

NOTE TO USERS

This reproduction is the best copy available.

UMI[®]



uOttawa

L'Université canadienne
Canada's university

**FACULTÉ DES ÉTUDES SUPÉRIEURES
ET POSTDOCTORALES**



**FACULTY OF GRADUATE AND
POSTDOCTORAL STUDIES**

Mark David Smith

AUTEUR DE LA THÈSE / AUTHOR OF THESIS

Ph.D. (Earth Sciences)

GRADE / DEGREE

Département of Earth Science

FACULTÉ, ÉCOLE, DÉPARTEMENT / FACULTY, SCHOOL, DEPARTMENT

**Stratigraphic and Geochemical Evolution of the Old Fort Point Formation, Southern Canadian
Cordillera: The Deep-Marine Perspective of Ediacaran Post-Glacial Environmental Change**

TITRE DE LA THÈSE / TITLE OF THESIS

William Arnott

DIRECTEUR (DIRECTRICE) DE LA THÈSE / THESIS SUPERVISOR

CO-DIRECTEUR (CO-DIRECTRICE) DE LA THÈSE / THESIS CO-SUPERVISOR

EXAMINATEURS (EXAMINATRICES) DE LA THÈSE / THESIS EXAMINERS

Ian Clark

Paul Gammon

**Nicholas Christie-Blick (Columbia
University, NY)**

Robert Rainbird

Gary W. Slater

Le Doyen de la Faculté des études supérieures et postdoctorales / Dean of the Faculty of Graduate and Postdoctoral Studies

**STRATIGRAPHIC AND GEOCHEMICAL EVOLUTION OF THE
OLD FORT POINT FORMATION,
SOUTHERN CANADIAN CORDILLERA:
THE DEEP-MARINE PERSPECTIVE OF
EDIACARAN POST-GLACIAL ENVIRONMENTAL CHANGE**

By

Mark David Smith

Thesis submitted to the
Faculty of Graduate and Postdoctoral Studies
University of Ottawa
In partial fulfillment of the requirements for the
Ph.D. degree in Earth Sciences

OTTAWA-CARLETON GEOSCIENCE CENTRE
UNIVERSITY OF OTTAWA
OTTAWA, CANADA

Thèse soumise à la
Faculté des études supérieures et postdoctorales
Université d'Ottawa
En vue de l'obtention d'un
Doctorat en sciences de la Terre

CENTRE GEOSCIENTIFIQUE D'OTTAWA-CARLETON
UNIVERSITÉ D'OTTAWA
OTTAWA, CANADA



Library and Archives
Canada

Published Heritage
Branch

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque et
Archives Canada

Direction du
Patrimoine de l'édition

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file *Votre référence*
ISBN: 978-0-494-61260-6
Our file *Notre référence*
ISBN: 978-0-494-61260-6

NOTICE:

The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.


Canada

University of Ottawa / Université d'Ottawa

The undersigned certify that they have read, and recommend to the Faculty of Graduate and Postdoctoral Studies for acceptance, a thesis entitled: "***Stratigraphic and geochemical evolution of the Old Fort Point Formation, southern Canadian Cordillera: the deep-marine perspective of Ediacaran post-glacial environmental change***" submitted by Mark David Smith in partial fulfillment of the requirements for the degree of Doctorate of Science.

Dr. R.W. (Bill) C. Arnott
Supervisor, University of Ottawa

Dr. Devinder Gandhi
Chairman of Committee, University of Ottawa

Dr. Ian Clark
University of Ottawa

Dr. Robert Rainbird
Geological Survey of Canada

Dr. Paul Gammon
Geological Survey of Canada

Dr. Nick Christie-Blick
Columbia University

Date: October 9TH, 2009

ABSTRACT

The ~608 Ma Old Fort Point Formation (OFP) is a unique, mixed siliciclastic and carbonate, stratigraphic marker that is exposed locally over an area of 35,000 km² within the Neoproterozoic Windermere Supergroup (WSG) of the southern Canadian Cordillera. The OFP accumulated in bathyal to upper abyssal settings along the ancient western continental margin of Laurentia. It comprises three lithostratigraphic members that can easily be distinguished from the enveloping strata of the deep-marine WSG. The Temple Lake and Geikie Siding members are generally uniform in thickness and lithofacies and are interpreted to reflect basin-wide, synchronous deposition. These basal Ediacaran transgressive and highstand deposits, respectively, accumulated during a post-glacial eustatic rise that essentially shutdown the supply of coarse-grained siliciclastic sediment into the deep-marine part of the Windermere basin. Regionally widespread bottom-water anoxia developed during the post-glacial highstand and is indicated by prominent enrichments in organic carbon and seawater redox-proxies (e.g. Mo, V/Cr). Subsequent regional tectonic uplift and related relative sea-level fall is indicated by the diachronous deposition of the Whitehorn Mountain Member. Newly created sediment transport pathways such as submarine canyons, controlled the timing, location, and composition of Whitehorn Mountain Member strata which accumulated mostly during the ensuing relative sea-level rise. Limestone units of the OFP are characterized by negative $\delta^{13}\text{C}$ values that stratigraphically-upward exhibit a positive ~12‰ shift, in addition to a 1 to 2‰ shift towards more negative values from shallow to deep water environments. These results are similar to other globally distributed, basal Ediacaran transgressive post-glacial carbonates related to melting of the ca. 635 Ma terminal Cryogenian glacial event, including correlative WSG strata exposed in the Mackenzie Mountains, northern Canadian Cordillera. The physical and isotopic characteristics of the OFP are interpreted to be most consistent with the hypothesis of post-glacial upwelling and oceanic stratification.

RÉSUMÉ

La formation Old Fort Point (OFP), ~ 608 Ma, du groupe néoprotérozoïque de Windermere (WSG), est un repère stratigraphique unique. Elle est composée de roches silicoclastiques et carbonatées et exposée localement sur 35 000 km² au sud de la Cordillère canadienne. La OFP s'est accumulée dans les régions bathyales et abyssales supérieures, le long de l'ancienne marge continentale à l'ouest du Laurentia. Elle comprend trois membres lithostratigraphiques, facilement distinguables à partir des strates enveloppantes du bassin de Windermere. L'épaisseur et les lithofaciès des membres Temple Lake et Geikie Siding sont généralement uniformes, reflétant une déposition synchrone pour l'ensemble du bassin. Ces dépôts, basaux Ediacaran transgressif et de haut niveau marin, se sont accumulés lors d'une montée eustatique post-glaciaire qui a littéralement cessé l'apport de sédiments grossiers silicoclastiques dans la région marine profonde du bassin Windermere. Les conditions anoxiques des eaux de fond, régionalement étendues et développées lors du cortège de haut niveau post-glaciaire, sont indiquées par des enrichissements proéminents du carbone organique et des données indirectes d'oxydo-réduction des eaux marines (p. ex. Mo, V/Cr). Le déclin du niveau marin relatif, associé au soulèvement tectonique régional subséquent, est indiqué par la déposition non synchrone du membre Whitehorn Mountain. De nouveaux chemins pour le transport des sédiments, tels des canyons sous-marins, contrôlent le rythme, l'emplacement et la composition des strates du membre Whitehorn Mountain, accumulées principalement lors de la remontée du niveau marin relatif. Le calcaire est généralement caractérisé par des valeurs négatives du $\delta^{13}\text{C}$ qui, en montant stratigraphiquement, démontrent un enrichissement (~12‰) additionnel à un appauvrissement (de 1 à 2‰), résultant d'une modification de l'environnement allant d'eaux peu profondes à profondes. Ces résultats sont semblables à d'autres dépôts basaux Ediacaran transgressif post-glaciaire carbonatés, distribués globalement et reliés à la fonte de l'évènement glaciaire Cryogénique terminal du ca. 635 Ma, incluant les strates corrélatives du WSG exposées dans les montagnes Mackenzie, au nord de la Cordillère canadienne. Les caractéristiques physiques et isotopiques de la OFP sont interprétées comme étant dès plus consistantes avec les hypothèses de la remontée post-glaciaire et la stratification océanique.

DEDICATION

To my parents for all their support over the years. Thank you for everything.



ACKNOWLEDGMENTS

Although there is only one name on the side of the binding, many people have contributed to this Ph.D. thesis. The first person to thank is my supervisor Bill Arnott for introducing me to the world of sedimentology and stratigraphy and allowing me the freedom (and financial support) to conduct the research that I felt was important to understanding the Old Fort Point Formation. The second important person to thank is Gerry Ross, formerly of the Geological Survey of Canada (GSC) and now full-time organic farmer for introducing me to the project and long-distance support. Thanks also go to the both of you for putting together the Windermere Consortium and all its sponsors, whcih allow many graduate students the opportunity to work fantastic projects in one of the most beautiful places in the world. I would also like to thank Drs. Ian Clark (University of Ottawa), Robert Rainbird (GSC), Paul Gammon (GSC) and Nick Christie-Blick for reading this rather lengthy document and serving on my committee.

I am grateful to all the various staff at the University of Ottawa and Carleton University: Wendi, Paul, Patricia and Gilles in the G. G. Hatch Stable Isotope Lab; George Mrazek for all the thin sections; Ron Hartree for XRF and XRD work; Peter Jones for microprobe analyses; and Hélène De Gouffe for all the administrative support. Also, a big thank you to Dr. André Desrochers for leading two very enjoyable field trips to the southern U.S and Anticosti Island, Québec.

Thank you to all the people who helped support me in the field: Parks Canada and BC Parks for allowing me to collect samples; Park Wardens Hal and Jim for providing shotgun escorts to keep away the grizzlies; Glen Stanley for use of the Eagle Valley back country lodge; Resorts of the Canadian Rockies for access to the Lake Louise Ski-Hill; and Yellowhead Helicopters and Canadian Mountain Holidays for safe and efficient helicopter rides.

Thanks go out to all the undergrads, grads and post-doc for being part of the journey over the many years: John H., Andre K., Paul F., Krystal, Juraj, Mike H.,

Benoit, André P., Nick, Ben, Lilian, Shann, Ernesto, Kenny, Viktor, Julien, Claude, John J., Martin, Mélanie C., Adam, Kelly, and many others I have forgotten to name.

Thanks again to my parents, the second one of these thesis things they have had to put up with and support instead of their son getting a job. Thank you also to the cats, Squeaker and Lyekka who constantly remind me how simple life is.

Thank you to Chelsea Hermus – I'm sorry things didn't work between us, but I know I am a better person because of our time together.

Thank you to Heather Sutherland for helping me understand my problems and teaching me how to deal with them when life bottomed out.

Thanks to Andres Altosaar – for being a great field assistant and even a better friend when one was needed. Thanks for everything buddy.

Merci beaucoup a Mélanie Mercier - for becoming part of my life (even if just for a short time) and sharing your vibrant nature with me.

Et un plus grande merci beaucoup et tout mon cœur a Pascale St-Germain. Thank you for taking a chance on me, staying patient with me and being there for me as I finished this thing up. Your smile and positivity are a continual inspiration and I am very happy that they are now a fixture of my life.

TABLE OF CONTENTS

ABSTRACT	ii
RÉSUMÉ	iii
DEDICATION	iv
ACKNOWLEDGMENTS.....	v
TABLE OF CONTENTS	vii
LIST OF TABLES	xiv
LIST OF FIGURES	xvi
LIST OF ABBREVIATIONS	xxxii
CHAPTER 1: Thesis Introduction	1
1.1 Thesis Rationale.....	1
1.2 Regional Geological Background.....	2
1.3 Previous Work	10
1.4 Thesis Organization	14
1.5 Statement of Contribution.....	15
CHAPTER 2: The Old Fort Point Formation: proposed stratigraphic formalization of a distinctive marker horizon and its three constituent members, Neoproterozoic Windermere Supergroup, southern Canadian Cordillera	18
2.1 Introduction	18
2.2 Regional geological setting	19
2.3 Stratigraphic correlations	21

2.4 Historical background	21
2.5 Proposed formal definition of the Old Fort Point Formation and its three members	28
2.5.1 Justification for name: Old Fort Point Formation.....	28
2.5.2 Designation of category and rank of units, selection and derivation of name, specification of principal reference section and stratotypes	32
2.5.2.1 Old Fort Point Formation.....	32
2.5.2.2 Temple Lake Member	33
2.5.2.3 Geikie Siding Member	33
2.5.2.4 Whitehorn Mountain Member	34
2.5.3 Description of lithologic units	36
2.5.3.1 Old Fort Point Formation.....	36
2.5.3.2 Temple Lake Member	36
2.5.3.2 Geikie Siding Member	37
2.5.3.3 Whitehorn Mountain Member	37
2.5.4 Definition of boundaries	38
2.5.5 Dimensions and regional correlations.....	39
2.5.6 Geological Age.....	40
2.6 Depositional model	41
2.7 Conclusions	42

CHAPTER 3: Transgression, anoxia, submarine canyon incision and highstand sand deposition along an ancient continental margin: the deep-marine Old Fort Point Formation (Ediacaran), southern Canadian Cordillera. 43

3.1 Introduction	43
3.2 Regional geological setting	44
3.3 Study area and methods.....	51
3.4 Old Fort Point Formation.....	54
3.5 Temple Lake Member.....	54
3.5.1 Lithofacies description.....	58
3.5.1.1 Siltstone (TLM-1)	58
3.5.1.2 Stratified sandstone (TLM-2)	58
3.5.1.3 Interbedded limestone and siltstone (TLM-3).....	61
3.5.1.4 Breccia (TLM-4)	63
3.5.1.5 Massive sandstone (TLM-5).....	65
3.5.2 Lithofacies associations and interpretations	65
3.5.2.1 Siltstone association	65
3.5.2.2 Rhythmic limestone-siltstone association.....	68
3.6 Geikie Siding Member	70
3.6.1 Lithofacies description.....	71

3.6.1.1 Mudstone (GSM-1).....	71
3.6.1.2 Breccia (GSM-2)	74
3.6.2 Lithofacies interpretations and associations	74
3.7 Whitehorn Mountain Member	76
3.7.1 Lithofacies description.....	77
3.7.1.1 Diamictite to breccia (WMM-1)	77
3.7.1.2 Laminated mudstone (WMM-2)	77
3.7.1.3 Sandstone (WMM-3).....	80
3.7.1.4 Quartz arenite (WMM-4).....	81
3.7.1.5 Calcareous arenite to arenaceous limestone (WMM-5).....	81
3.7.1.6 Limestone (WMM-6).....	84
3.7.1.7 Organic-rich mudstone (WMM-7)	84
3.7.1.8 Breccia to conglomerate (WMM-8).....	84
3.7.2 Lithofacies interpretations and associations	87
3.7.2.1 Heterolithic association	93
3.7.2.2 Quartzose siliciclastic and carbonate association	96
3.8 Depositional model of the Old Fort Point Formation.....	98
3.8.1 Temple Lake Member	101
3.8.2 Geikie Siding Member	105
3.8.3 Glacial Connection and Age Constraints.....	106
3.8.4 Whitehorn Mountain Member	108
3.9 Tectonic influence.....	113
3.10 Conclusions	118

CHAPTER 4: Deep-marine perspective of provenance, weathering and paleoredox conditions along the continental margin of Laurentia: insights from fine-grained sedimentary rocks of the Neoproterozoic Windermere Supergroup, southern Canadian Cordillera.....121

4.1 Introduction	121
4.2 Geological Setting.....	124
4.3 Stratigraphic Setting.....	126
4.4 Sampling and Analytical Methods	131
4.5 Results	134
4.5.1 Major elements.....	140
4.5.2 Large ion lithophile elements (LILE): Rb, Cs, Ba, Sr, Th, U, Pb.....	144
4.5.3 High-field strength elements (HFSE): Y, Zr, Hf, Nb, Ta.....	147
4.5.4 Transition trace elements (TTE): Cr, Co, Ni, Cu, Zn, Sc, V	148
4.5.5. Mo, Sb, As, TOC	149
4.5.6 Rare earth elements (REE)	150

4.6 Discussion.....	152
4.6.1 Effect of metamorphism.....	152
4.6.2 Mineralogy and sedimentary sorting.....	154
4.6.3 Provenance and tectonic setting.....	158
4.6.4 Paleoweathering and metasomatism	166
4.6.5 Paleoredox conditions	171
4.6.6 Deep-ocean anoxia	178
4.6.7 Neoproterozoic WSG geochemical evolution.....	180
4.7 Conclusions	186

CHAPTER 5: Carbonate paragenesis and isotope geochemistry of the Old Fort Point Formation, Windermere Supergroup, southern Canadian Cordillera: the deep-marine perspective of post-glacial Ediacaran environmental change.....189

5.1 Introduction	189
5.2 Regional geology and tectonic setting.....	191
5.3 Stratigraphy and sedimentology.....	195
5.4 Sampling and analytical methods.....	199
5.5 Petrography and geochemistry	201
5.5.1 Calcite 1 (CC1)	201
5.5.2 Calcite 2 (CC2)	205
5.5.3 Calcite 3 (CC3)	208
5.5.4 Calcite 4 (CC4)	211
5.5.5 Dolomite 1 (DOL1).....	211
5.5.6 Dolomite 2 (DOL 2).....	212
5.5.7 Ankerite (ANK)	212
5.5.8 Clasts of bladed-calcite crystal limestone (BLD CC).....	215
5.6 Stable isotope results	217
5.6.1 Carbonate: $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$	228
5.6.2 Organic residue: $\delta^{13}\text{C}$	236
5.6.3 Pyrite: $\delta^{34}\text{S}$	238
5.7 Carbonate paragenesis.....	242
5.8 $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ isotopic signatures.....	250
5.8.1 Carbonate: $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$	250
5.8.1.1 Effect of metamorphism	250
5.8.1.2 Effect of diagenesis.....	252
5.8.1.3 Preservation of the $\delta^{13}\text{C}$ carbonate signature.....	258
5.8.2 Organic residue: $\delta^{13}\text{C}$	260
5.8.3 Pyrite: $\delta^{34}\text{S}$	261
5.9 Discussion.....	265
5.9.1 Old Fort Point Formation (OFP): post-glacial depositional model.....	265

5.9.1.1 Temple Lake (TLM) and Geikie Siding (GSM) members	265
5.9.1.2 Whitehorn Mountain Member (WMM)	269
5.9.2 Windermere Supergroup (WSG): regional stratigraphic correlation of the glacial Cryogenian to post-glacial Ediacaran transition	270
5.9.3 Neoproterozoic post-glacial cap carbonate models	280
5.9.4 Deep-marine perspective of post-glacial cap carbonate deposition	282
5.10 Conclusions	290

CHAPTER 6: Thesis Summary	293

REFERENCES	299

APPENDICES	330

APPENDIX A: The Record of Neoproterozoic Glaciations in the Windermere

Supergroup, southern Canadian Cordillera.....	331

A.1 Chapter Summary	331
A.2 Introduction	332
A.2.1 Toby Formation	333
A.2.2 Vreeland Formation	333
A.2.3 Old Fort Point Formation.....	334
A.3 Structural Framework and Basin Setting.....	335
A.4 Stratigraphy	337
A.5 Glacigenic deposits and associated strata	339
A.5.1 Toby Formation	339
A.5.2 Vreeland Formation	341
A.5.3 Old Fort Point Formation.....	342
A.6 Boundary relations with overlying and underlying non-glacial units	344
A.6.1 Toby Formation	344
A.6.2 Vreeland Formation	344
A.6.3 Old Fort Point Formation.....	345
A.7 Chemostratigraphy	345
A.8 Other characteristics	346
A.9 Palaeolatitude and palaeogeography.....	347
A.10 Geochronological constraints	347

A.11 Discussion	348
A.11.1 Toby Formation	348
A.11.2 Vreeland Formation	349
A.11.3 Old Fort Point Formation	350
A.11.4 Regional Correlations	351

APPENDIX B: List of outcrop and sample locations from the southern Canadian Cordillera	359

APPENDIX C: Complete sample listing and descriptions	360

APPENDIX D: Stratigraphic section measurements and data from the Old Fort Point Formation, southern Canadian Cordillera	374

APPENDIX E: Outcrop gamma-radiation measurements from the Old Fort Point Formation, southern Canadian Cordillera.	375

APPENDIX F: Representative thin section photomicrographs of lithofacies from the three members of the Old Fort Point Formation and results of modal mineralogy point-counting of carbonate and fine-grained rocks.	376

APPENDIX G: List of paleocurrent measurements.	388

APPENDIX H: Major, trace and rare-earth element lithogeochemical analyses from fine-grained meta-sedimentary rocks of the Windermere Supergroup, southern Canadian Cordillera	389

APPENDIX I: Total %C analyses for carbonate CO₂.	406
APPENDIX J: Electron microprobe analyses of carbonate phases from the Old Fort Point Formation.	407
APPENDIX K: TOC (total organic carbon) and $\delta^{13}\text{C}_{\text{org}}$ analyses.	417
APPENDIX L: Duplicate carbonate $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analyses.	422
APPENDIX M: Pyrite $\delta^{34}\text{S}$ analyses and description.	423
APPENDIX N: Assignment #4: The Old Fort Point Formation.	425

LIST OF TABLES

Table 2.1: Section locations of the Old Fort Point Formation and its three members.	30
Table 3.1: Locations of Old Fort Point Formation stratigraphic sections.	53
Table 3.2: Lithofacies description of the Old Fort Point Formation.	55
Table 4.1: Locations of WSG sample locations in the southern Canadian Cordillera.	132
Table 4.2: Compositional average (avg.), standard deviation (2 σ), minimum (min.) and maximum (max.) values for stratal divisions of the WSG in the southern Canadian Cordillera. Notes: n = number of samples; n/a = not analyzed; b.d. = below detection limits. Stratal abbreviations are listed in the text.	135
Table 4.3: Correlation coefficients between major and selected trace elements for WSG mudstone samples ($n = 87$). Pearson's correlation coefficient (r) listed in upper right triangle of matrix, Spearman's rank order correlation coefficient (ρ) listed in lower left triangle of matrix. Correlation coefficients with p-values <0.001 are highlighted in bold: positive in red, negative in blue. Shapiro-Wilk's test (W) values are presented in the shaded diagonal that separates the two triangles.	138
Table 4.4: REE, Th/Sc, Cr/Th, and Eu/Eu* for average WSG mudstone ($n = 87$), mixing parameters and model results. Mixing endmembers are from Condie (1993). Abbreviations: Archean tonalite-trondhjemite-granodiorite (ATTG); Proterozoic tonalite-trondhjemite (PTTG); Archean granite (AG); Proterozoic granite (PG); and Late Archean andesite (LAA).	163
Table 4.5: Correlation coefficients between TOC and Mo with potential redox-proxies. Spearman's rank order correlation coefficient (ρ) are used and correlation coefficients with p-values <0.001 are highlighted in bold: positive in red, negative in blue. W = Shapiro-Wilk's test.	173
Table 5.1: Minimum (min.) and maximum (max.) values for carbonate phases of the OFP from electron microprobe analyses. n = number of analyses; b.d. = below detection limit.	202
Table 5.2: Results of carbon and oxygen isotopic analyses of OFP carbonate. Samples denoted by an asterisk (*) are previously unpublished data from G. M. Ross.	218

Table 5.3: Results of carbon and oxygen isotopic analyses of other WSG carbonates. Samples denoted by an asterisk (*) are previously unpublished data from G. M. Ross. Monk = Monkman Pass area, B.C.; VF = Vreeland Formation; FF = Framstead Formation; SMC = shallow-marine carbonate.	224
Table 5.4: Results of carbon isotopic analyses from organic residue in strata of the OFP. Samples denoted by an asterisk (*) are previously unpublished data from G. M. Ross.	226
Table 5.5: Results of sulfur isotopic analyses from pyrites in strata of the OFP and WSG. Samples denoted by an asterisk (*) are from Table 1 in Ross et al. (1995).	227

LIST OF FIGURES

Figure 1.1: Distribution of WSG strata in western North America (modified from Ross, 1991).	3
Figure 1.2: Simplified geological map of the WSG, southern Canadian Cordillera showing the main outcrops of the OFP (modified from Ross and Murphy, 1988).	5
Figure 1.3: Map of western Canada showing the five major sub-divisions of the Canadian Cordillera (modified from Reid et al., 2002), the distribution of WSG strata shown in black (modified from Ross, 1991) and overall study area located in the Foreland fold and thrust and Omineca belts.	6
Figure 1.4: Stratigraphic column for the WSG from the Cariboo-Purcell-Rocky Mountains in the southern Canadian Cordillera (modified from Ross et al. 1995). Rift and post-rift strata, paleogeographic environment and relative stratigraphic position of the OFP are shown. Ages shown in stratigraphic order are from McDonough and Parrish (1991), Lund et al. (2003), Kendall et al. (2004) and Colpron et al. (2002). Asterisk indicates the age is from correlative strata to the column. ..	8
Figure 1.5: Section photos of the Old Fort Point Formation in Alberta. A) JP1: Geikie Siding, Jasper National Park. B) LL1: Temple Lake, Lake Louise. C) LL4: Upper Boomerang, Lake Louise. D) LL5: Wolverine Bowl, Lake Louise. Arrows indicate upward stratigraphic direction.	11
Figure 1.6: Section photos of Old Fort Point Formation in British Columbia. A) – B) MR1: Vista Glacier, Mount Robson Provincial Park. C) MK1: McKale River area. D) PM1: Frances Creek, Purcell Mountains. E) CM1: Eagle Valley, Cariboo Mountains. Arrows indicate upward stratigraphic direction.	12
Figure 2.1: Simplified geological map of the WSG, southern Canadian Cordillera showing prominent outcrop localities of the OFP and correlatives (modified from Ross and Murphy, 1988). (Localities: A – Lake Louise; B – Jasper National Park; C – Mount Robson Provincial Park; D – McKale River; E – Frances Creek; F – Dogtooth Range; G – Monashee Mtns.; H – Selkirk Mtns.; I – Cariboo Mtns.)	20
Figure 2.2: Stratigraphic nomenclature of the WSG, southern Canadian Cordillera. Sources of information include: 1) Campbell et al. (1973), Ferguson (1994), Ross and Ferguson (2003a, 2003b); 2) Grasby and Brown, 1993; 3) Kubli (1990), Kubli and Mountjoy (1992, 1994), Warren (1996, 1997); 4) McDonough (1989, 1994), McMechan and Hein (1989); 5) Charlesworth and Remington (1961), Charlesworth et al. (1967); 6) Walcott (1910), Gussow (1956, 1957), Aitken (1969).	22

Figure 2.3: A) Location map of key stratigraphic sections. B) OFP Type locality, Old Fort Point Landmark, Jasper National Park.	25
Figure 2.4: A) OFP principal reference section and GSM unit stratotype, Geikie Siding outcrop, Jasper National Park. B) TLM unit stratotype, near Temple Lake, Lake Louise. Note WMM is thinly (<0.5 m) developed here and difficult to distinguish from underlying GSM or overlying fine-grained Miette Group. C) WMM unit stratotype, “Upper Boomerang (#64) Ski Run, Lake Louise Ski Resort.	31
Figure 2.5: Schematic stratigraphic section of the OFP and its three members illustrating main lithofacies and sedimentary features present.	35
Figure 3.1: Distribution of WSG strata in western North America (modified from Ross 1991).	45
Figure 3.2: Simplified geological map of the WSG, southern Canadian Cordillera showing prominent outcrop localities of the OFP (modified from Ross and Murphy, 1988). (Localities: A – Lake Louise; B – Jasper National Park; C – Mount Robson Provincial Park; D – McKale River; E – Frances Creek; F – Dogtooth Range; G – Monashee Mountains; H – Selkirk Mountains; I – Cariboo Mountains).....	46
Figure 3.3: Stratigraphic column for the WSG from the Cariboo-Purcell-Rocky Mountains in the southern Canadian Cordillera (modified from Ross et al. 1995). Rift and post-rift strata, paleogeographic environment and relative stratigraphic position of the OFP are shown. Ages shown in stratigraphic order are from McDonough and Parrish (1991), Lund et al. (2003), Kendall et al. (2004) and Colpron et al. (2002). Asterisk indicates the age is from correlative strata to the column.	47
Figure 3.4: A) to F) Representative lithofacies photos of variably-coloured TLM-1 siltstone. A) JP1: T ₄ to T ₆ turbidites. B) LL5: T ₀ to T ₆ turbidites. C) MR1: T ₃ to T ₆ turbidites. D) CM1: Contact between mud-rich Middle Kaza Group (MKG) and silt-rich, carbonate-cemented TLM. Arrow indicates upward stratigraphic direction. E) LL5: T ₀ to T ₆ turbidites. F) CM1: T ₃ to T ₆ turbidites. G) – H) LL8: Discoid structures with concentric wrinkles of possible biological origin. G) Example of epirelief with 5-point star-like figure. H) Example of hyporelief.....	59
Figure 3.5: A) to F) Representative lithofacies photos of TLM-2 stratified sandstone. A) LL5: Tbc turbidite with 3D ripple-top. Pencil is ~15 cm long and is pointed in the direction of flow. B) JP1: Planar laminated Tb turbidite. C) MR: Interstratified TLM-2 Tb turbidites and TLM-1 siltstone. Ruler is 50 cm. D) PM1: Ripple-stratified Tc bed and planar laminated Tb turbidite. E) CM1: Laterally-extensive, repetitive T(b)cd basinal turbidites. Arrow indicates upward stratigraphic direction. F) CM1: Two, stacked Tbc turbidites. Ruler is 50 cm.....	60

Figure 3.6: A) to G) Representative lithofacies photos of TLM-3 interbedded limestone and siltstone. A) LL1: T_c limestone turbidite showing ripple trough. B) LL1: Tbc limestone turbidites interbedded with siltstone. Ruler is ~35 cm. C) LL5: Tde limestone turbidite overlain by T(a)bcd very-fine grained sandstone turbidite. D) PM1: Tbc limestone turbidites interbedded with siltstone. E) JP1: TLM-3 purple to green colour transition. Note colour change is not parallel to bedding. Arrow indicates upward stratigraphic direction. Ruler is 100 cm. F) MR1: Tbc limestone (grey) turbidites interbedded with siltstone (red-brown). Ruler is 100 cm. G) CM1: Tbc limestone turbidites interbedded with siltstone. Ruler is 100 cm. 62

Figure 3.7: A) to F) Representative lithofacies photos of TLM-4 breccia. A) LL5: basal slump or slide scar surfaces in TLM-1 siltstone. Ruler is 100 cm. B) LL5: large, deformed slide block of TLM-3 in strata of TLM-1 and TLM-2. Ruler is 100 cm. C) LL1: ptymatically-deformed limestone clasts. Ruler is ~50 cm. D) LL1: lenticular bed geometry which grades laterally into a TLM-3 limestone bed. Ruler is 20 cm. E) LL5: poorly-developed imbrication in debris flow deposit. Ruler is ~50 cm. F) LL5: debris flow deposit in TLM-3 strata. Ruler is 100 cm. 64

Figure 3.8: A) to F) Representative lithofacies photos of GSM. A) and B) JP1: Interbedded siltstone and organic-rich mudstone. Ruler is ~30 cm. C) MR1: Recessive nature of GSM compared to strata of underlying TLM and mudstone units of the overlying Middle Miette Group (MMG). D) MR1: Contact between mudstone units of the GSM and overlying Middle Miette Group (MMG). GSM is finer-grained and more recessive with the GSM-WMM-MMG contact marked by a decrease in gamma-ray counts, total organic carbon content and selected trace elements (e.g. molybdenum) E) PM1: Carbonate-cemented Tbc turbidite sandstone with basal scour surface. F) PM1: Carbonate-cemented sandstone Tbc turbidite with ripple-top. Pencil is ~15 cm and points in the direction of flow. Arrows indicate upward stratigraphic direction. 72

Figure 3.9: A) to G) Representative lithofacies photos of GSM. A) CM1: Mudstone (pelite) interbedded with limestone. Ruler is 50 cm. B) CM1: Mudstone (pelite) with interbedded limestone bed. C) – D) CM1: Sharp contact between GSM and overlying fine-grained carbonate-rich units of WMM. E) CM1: Mudstone (pelite) interbedded with Tbc turbidites of fine-grained sandstone. Ruler is 100 cm. F) CM1: Gradational contact between GSM and underlying TLM. Ruler is 100 cm. G) LL1: Gradational contact between GSM and underlying TLM marked by dark limestone beds. Ruler is 50 cm. Arrows indicate upward stratigraphic direction. 73

Figure 3.10: A) to G) Representative lithofacies photos of WMM-1 diamictite to breccia. A) LL4: Debris flow dominated by lenticular carbonate clasts. Hammer is ~35 cm. B) LL4: Thick amalgamated beds near base of WMM. Hammer is ~35 cm. C) LL4: Debris flow marking contact

between WMM and overlying Hector Formation (Middle Miette Group). Ruler is ~50 cm. D) JP3: Debris flow dominated by grey limestone clasts. Ruler is 100 cm. E) LL4: Block of WMM-1 with cm-sized angular carbonate clasts. Pencil is ~15 cm. F) LL4: Debris flow near top of WMM dominated by grey limestone clasts. Ruler is 100 cm. G) JP3: Debris flow with large, (up to 1 m) elongated carbonate clasts. Fieldbook is ~20 cm. Photos A), B) and E) are courtesy of G. M. Ross.....78

Figure 3.11: A) to D) Representative lithofacies photos of WMM-2 laminated mudstone. Ruler is ~40 cm. A) LL4: T₃ to T₆ turbidites illustrating purple and green redox changes. B) LL4: Repetitive T₃ turbidites with rare example of scour surface. Ruler is 50 cm. C) LL2: overturned slab with current ripple formsets. Ruler is 100 cm. D) JP3: isolated WMM-3 Tbc turbidite in WMM-2 strata. Ruler is ~45 cm. E) to F) Representative lithofacies photos of WMM-3 sandstone. E) LL4: Ripple cross-stratified Tc turbidite. F) PM1: Planar laminated Tb turbidite.....79

Figure 3.12: A) to F) Representative lithofacies photos of WMM-4 quartz arenite. A) PM1: Thick, amalgamated Ta turbidites interbedded with Tbc turbidites. B) PM1: Two, ~5 m thick WMM-4 Ta turbidites (light-coloured) encompassed by WMM-5 strata (dark-coloured). C) MK1: WMM-4 Ta or S2-S3 turbidite sharply overlying a WMM-8 S1 breccia. Ruler is ~50 cm. D) MK1: Preferential carbonate-cementation within Ta turbidites near contact between WMM and overlying MMG (Middle Miette Group). Ruler is 100 cm. E) – F) CM1: Basinal examples of thick, repeating WMM-4 Ta turbidites. Arrows indicate upward stratigraphic direction.....82

Figure 3.13: A) to G) Representative lithofacies photos WMM-5 (also WMM-4 and WMM-6). A) MK1: Thin calcareous arenite interbedded with planar laminated Tb(c) arenaceous limestone turbidites. Ruler is 50 cm. B) PM1: Thin calcareous arenite interbedded with planar laminated Tb(c) arenaceous limestone turbidites. C) PM1: Onlap of beds, possibly in small-scale erosional feature. Ruler is 50 cm. D) Interbedded Tb(c) turbidites. E) Tbc turbidites. F) PM1: T(a)b calcareous arenite turbidites interbedded with planar laminated Tb(c) arenaceous limestone turbidites. G) CM1: Contact between carbonate-rich WMM and generally non-calcareous overlying Upper Kaza Group (UKG). Ruler is 100 cm. Arrows indicate upward stratigraphic direction.....83

Figure 3.14: A) to D) Representative lithofacies photos of WMM-6 limestone (and WMM-5). A) PM1: Planar-laminated Td limestone turbidite. B) PM1: Example of metre-scale upward thinning of limestone beds. C) CM1: Sharp contact between WMM carbonate-rich strata and underlying GSM organic-rich mudstone (pelite). Arrow indicates upward stratigraphic direction. D) CM1: WMM-6 limestone interbedded with thin Tbc turbidites. Ruler is 50 cm. E) to F) Representative lithofacies photos of WMM-7 organic-rich mudstone (also WMM-5 and WMM-6). E) PM1: WMM-7 mudstone

interbedded with WMM-5 calcareous arenite and WMM-6 limestone. F) PM1: WMM-7 mudstone interbedded with WMM-5 Tb turbidites.....85

Figure 3.15: A) to F) Representative lithofacies photos of WMM-8 breccia to conglomerate. A) PM1: Debris flow or R1 turbidite with quartz-sand rich matrix and WMM-6 limestone clasts. B) JP1: Debris flow or S1 turbidite with quartz-sand rich matrix and WMM-6 limestone clasts. Ruler is 50 cm. C) MK1: Example of prominent erosional surface associated and overlying WMM-8 debris flow deposits. Irregular top contact of WMM-8 units also created topography for subsequent turbidites. Note person for scale in bottom left corner. D) LL4: WMM-8 S1 breccia overlain directly by WMM-3 Tb turbidite sandstone. D) PM1: Lenticular bed geometry for WMM-8 mass flow. E) and F) MK1: Lenticular bed geometry for WMM-8 mass flow. Arrows indicate upward stratigraphic direction. .86

Figure 3.16: A) to F) Representative photos of clast types from WMM-8 breccia to conglomerate. A) MK1: Common, sub-rounded, bimodal clast assemblage of local WMM-6 limestone and brown sandy dolostone from shallower carbonate environments. B) LL4: Dolomitized microbial laminite. C) MK1: Large, metre-sized, diverse assemblage of clasts in basal debris flow. D) MK1: Beige-coloured, wave-ripple cross-stratified dolostone. E) LL2: Limestone clast with bladed-calcite crystals. Pencil tip is ~ 1 cm. F) PM1: Limestone in a siltstone clast. Penny is ~ 2 cm. Photos E) and F) courtesy of G. M. Ross. 88

Figure 3.17: A) to G) Representative photos of soft-sediment deformation features observed in WMM strata. A) LL4: Convolute bedding in WMM-2 laminated mudstone. Ruler is 50 cm. B) PM1: Sand-on-sand dewatering structures in WMM-3 sandstone. C) CM1: Basal load structures and “sinking dune” within WMM-4 to WMM-6 strata. Ruler is 50 cm. D) CM1: Sand-on-sand basal load structures in WMM-4 with preferential carbonate-cementation in more stratified turbidite bed. Ruler is 50 cm. E) LL4: Block of WMM-2 laminated mudstone exhibiting soft-sediment folds. F) PM1: “wrap-over lamination” in WMM-3 sandstone which laterally grades into planar-laminated Tb turbidite. Arrow indicates upward stratigraphic direction. G) CM1: Basal load structure within interbedded WMM-4 to WMM-6 strata. Ruler is 100 cm.....89

Figure 3.18: A) Simplified geological map of the Lake Louise area, Alberta showing outcrop localities of the OFP and cross-section location. Modified from Price et al. (1980a, b). B) Simplified stratigraphic columns of the OFP in the Lake Louise area illustrating the correlation of the lower two members (TLM + GSM), prominent incision event and deposition of the WMM in a submarine canyon. C) LL5 section (Wolverine Bowl) showing TLM and GSM. D) LL4 section (Upper Boomerang) showing only WMM where the TLM and GSM are completely eroded. Arrows indicate upward stratigraphic direction.....91

Figure 3.19: Simplified stratigraphic columns of the OFP and correlated cross-section in an east to west direction, along a basin-slope to basin-floor transect from Jasper National Park to the Cariboo Mountains. In certain basin-slope settings, prominent incision events are evident with the complete removal of the lower two members (TLM and GSM) and deposition of the WMM in submarine canyons. Stratigraphic column MK1 is projected into the the cross-section line of Jasper National Park to the Cariboo Mountains. Location map is modified from Figure 3.2..... 99

Figure 3.20: Schematic depositional model, relative sea-level curve and sequence stratigraphic framework of the OFP. Abbreviations: WSG – Windermere Supergroup; MMG – Middle Miette Group; MKG – Middle Kaza Group; UKG – Upper Kaza Group; HTC – Horsethief Creek Group; TST – transgressive systems tract; CS – condensed section; HST – highstand systems tract; FSST – falling-stage systems tract; LST – lowstand systems tract; BSFR – basal surface of forced regression; MFS – maximum flooding surface; MRS – maximum regressive surface; SB – sequence boundary. (Localities: A – Lake Louise; B – Jasper National Park; C – Mount Robson Provincial Park; D – McKale River; E – Frances Creek; I – Cariboo Mountains)..... 102

Figure 3.21: Simplified stratigraphic column of the anomalously thick OFP section (>450 m) at Frances Creek (PM1) in the Purcell Mountains, and for comparative purposes, stratigraphic columns at Temple Lake (LL1) and McKale River (MK1). At Frances Creek, the TLM and GSM are significantly thicker and lack the typical upward gradation from limestone-siltstone rhythmites to organic-rich mudstone. This locality is interpreted to be a local area of unusually high accommodation produced by growth faults that became active following deposition of the TLM. Note the overall similarity of the lower part of the TLM at PM1 to LL1 and the WMM at PM1 to MK1. Location map is modified from Figure 3.2. 115

Figure 4.1: Location of study area and simplified geological map of the WSG, southern Canadian Cordillera (modified from Ross and Murphy, 1988). Sample localities: A – Lake Louise; B – Jasper National Park; C – Mount Robson Provincial Park; D – McKale River; E – Frances Creek, Purcell Mountains; F – Cariboo Mountains. SRMT: Southern Rocky Mountain Trench. 122

Figure 4.2: Stratigraphy of the WSG, southern Canadian Cordillera (from Chapter 2 and references therein). OFP is used across the Windermere basin as opposed to other terminology (Chapter 2). Notes: *n* = number of samples collected for stratal division; no thickness implied in figure..... 128

Figure 4.3: Stratigraphic column for the WSG from the Cariboo-Purcell-Rocky Mountains in the southern Canadian Cordillera (modified from Ross et al. 1995). Rift and post-rift strata, paleogeographic environment and relative stratigraphic position of the OFP are shown. Ages shown

in stratigraphic order are from McDonough and Parrish (1991), Lund et al. (2003), Kendall et al. (2004) and Colpron et al. (2002). Asterisk indicates the age is from correlative strata to the column.

.....129

Figure 4.4: Sedimentary geochemical classification after Herron (1988) for WSG samples ($n = 87$).

Legend abbreviations: OFP = Old Fort Point Formation; WMM = Whitehorn Mountain Member; GSM = Geikie Siding Member; IF = Isaac Formation, Cariboo Group; UKG = Upper Kaza Group; MKG = Middle Kaza Group; UMG = Upper Miette Group; MMGA = Middle Miette Group above OFP; MMGB = Middle Miette Group below OFP; SRMT = Southern Rocky Mountain Trench; NASC = North American Shale Composite (Gromet et. al., 1984); and PAAS = Post-Archean Australian Shale (Taylor and McLennan, 1985).....141

Figure 4.5: Major element (wt%) diagrams of $\text{SiO}_2/\text{Al}_2\text{O}_3$ vs.: A) Fe_2O_3 ; B) TiO_2 ; C) MgO ; D) MnO ; E) Na_2O ; F) K_2O ; G) CaO ; and H) P_2O_5 . Legend of symbols is the same as Fig. 4.4.....142

Figure 4.6: Selected major (wt%) element diagrams: A) $\text{SiO}_2/\text{Al}_2\text{O}_3$ vs. $\text{K}_2\text{O}/\text{Na}_2\text{O}$; B) $\text{SiO}_2/\text{Al}_2\text{O}_3$ vs. $\text{Na}_2\text{O}/\text{TiO}_2$; C) Al_2O_3 vs. K_2O ; D) Al_2O_3 vs. TiO_2 ; E) Fe_2O_3 vs. MgO ; F) Fe_2O_3 vs. MnO ; G) K_2O vs. Na_2O ; and H) CaO vs. P_2O_5 . Legend of symbols is the same as Fig. 4.4.....143

Figure 4.7: Selected major (wt%) and trace (ppm) element diagrams: A) Al_2O_3 vs. Ba; B) Al_2O_3 vs. Rb; C) K_2O vs. Ba; D) K_2O vs. Rb; E) CaO vs. Sr; F) Na_2O vs. Sr; G) Fe_2O_3 vs. Ni; and H) TiO_2 vs. Cr. Legend of symbols is the same as Fig. 4.4.....145

Figure 4.8: Spider diagram of selected trace elements (Rb, Ba, Sr, Th, U, Zr, Nb, Cr, Ni, Sc, V, Mo) normalized to Post-Archean Australian Shale (PAAS) (Taylor and McLennan, 1985). Legend of symbols is the same as Fig. 4.4.....146

Figure 4.9: Spider diagram for rare earth elements (REE) normalized to Post-Archean Australian Shale (PAAS) (Taylor and McLennan, 1985). Legend of symbols is the same as Fig. 4.4.....151

Figure 4.10: Cluster analysis dendrogram of TOC and selected major and trace elements with three main clusters and their interpreted mineral associations. The dendrogram was generated using the Spearman rank order correlation coefficient as the distance matrix and amalgamated/agglomerated by the unweighted pair group average (uses mean distances). Strong correlations show low linkage distances (similarity ~ 1) between amalgamated element clusters whereas a lack, or negative correlation results from high distance linkages (similarity ~ 0). Presentation of the geochemical data in this fashion can be effective for understanding elemental associations that are linked with significant mineral phases beyond the correlation coefficients. 155

Figure 4.11: Sedimentary sorting diagrams: A) Plot of Zr/Sc vs. Th/Sc after McLennan et al. (1993). B) Plot of Ti vs. Nb. SRMT = Southern Rocky Mountain Trench. Legend of symbols is the same as Fig. 4.4.	157
Figure 4.12: Provenance diagrams: A) Plot of Cr/Th vs. Th/Sc. B) Plot of Eu/Eu* vs. Th/Sc. Mixing end members are from Condie (1993). Abbreviations: Archean tonalite-trondhjemite-granodiorite (ATTG); Proterozoic tonalite-trondhjemite (PTTG); Archean granite (AG); Proterozoic granite (PG); and Late Archean andesite (LAA). Legend of symbols is the same as Fig. 4.4.	160
Figure 4.13: REE spider diagrams normalized to Post-Archean Australian Shale (PAAS) (Taylor and McLennan, 1985) showing results of mixing calculations (Table 4.5). A) Average WSG mudstone east of the SRMT. B) Average WSG mudstone west of the SRMT. Shaded regions represent respective average mudstone value $\pm 2\sigma$. End member compositions are from McLennan et al. (1993).....	164
Figure 4.14: A) Molar A - CN - K ternary diagram illustrating CIA (Chemical Index of Alteration) values. Only top 60% of diagram is shown. Potential source components are indicated, including WINMIX determined in this study and igneous end members from Condie (1993). Predicted weathering trend-line from WINMIX is shown as well as range of CIA values corrected for effects of K-metasomatism. A = molar Al_2O_3 ; CN = molar CaO^* (non-carbonate) + molar Na_2O ; K = molar K_2O . Mineral abbreviations include: plag = plagioclase feldspar; Kspar = potassium feldspar; musc = muscovite; ill = illite; kaol = kaolinite. Legend of symbols is the same as Fig. 4.4.	168
Figure 4.15: Paleoredox diagrams with empirically defined WSG cutoffs for interpreted bottom-water anoxic conditions: A) Plot of Mo (ppm) vs. TOC (wt%). B) Plot of Mo (ppm) vs. V/Cr. Legend of symbols is the same as Fig. 4.4.....	176
Figure 4.16: Paleoredox diagrams illustrating elevated V contents not associated with detrital mineral fraction. A) Plot of Ti (ppm) vs. V (ppm). B) Plot of Ti (ppm) vs. V/Cr. Legend of symbols is the same as Fig. 4.4.	177
Figure 4.17: Conceptual geochemical evolution model of post-rift WSG strata. Geochemical profiles of Th/Sc and Cr/Th are presented to show WSG sediment provenance. Average values for WSG mudstone east and west of the SRMT are indicated by dashed line in columns showing the ratios Th/Sc (0.83 and 1.06, respectively) and Cr/Th (4.50 and 6.90, respectively). Weathering conditions are represented by the geochemical profile of CIA-K (Chemical Index of Alteration, corrected for K-metasomatism). Dashed line is placed at a CIA-K value of 78, which for the WSG may indicate the transition from hot/humid to cold/arid conditions in hinterland continental settings. Geochemical profiles of Mo (ppm) and TOC (%) are displayed for paleoredox proxies. Dashed line placed at Mo = 1 represents interpreted empirical cutoff in WSG sedimentary rocks for interpreted anoxic	

conditions. Dashed line placed at TOC = 0.25% is the interpreted cutoff between background, non-organic WSG deposition and organic-rich deposition. Relative timing of deposition is constrained to younger than 684 Ma from correlative rift-related volcanic rocks in Idaho (Lund et al., 2003), and older than 569 Ma based on the timing of volcanic rocks associated with the late Ediacaran rift-event (Colpron et al., 2002). Minimum timing of deposition for the OFP is constrained by an Re-Os whole rock isochron age of 607 ± 4.7 Ma from organic-rich mudstone of the GSM (Kendall et al., 2004). Total stratal thickness is approximate and represents a composite section measured from the three locations (Mount Quanstrom, Eagle Valley, Castle Creek) in the Cariboo Mountains using known marker horizons (Chapter 3; Meyer, 2004; Ross and Arnott, 2007). Also shown are interpreted relative sea-level (RSL) curve, potential timing of glacial events and interpreted development of anoxic deep-ocean conditions. Stratal abbreviations: OFP = Old Fort Point Formation (Whitehorn Mountain Member: red-brown and blue; Geikie Siding Member: black; Temple Lake Member: purple); IF = Isaac Formation, Cariboo Group; UKG = Upper Kaza Group; MKG = Middle Kaza Group; UMG = Upper Miette Group; MMGA = Middle Miette Group above OFP; MMGB = Middle Miette Group below OFP; SRMT = Southern Rocky Mountain Trench. Yellow are sandstone-dominated units, grey are mudstone-dominated units and blue are carbonate-dominated units. Closed symbols are samples collected west of the SRMT, open symbols collected east of the SRMT. Legend of symbols is the same as Fig. 4.4. 182

Figure 5.1: Simplified regional geological map of the WSG and study locations in the southern Canadian Cordillera, western Canada (modified from Ross and Murphy, 1988; Ross, 1991). OFP sample localities: A – Lake Louise, Banff National Park (LL); B – Jasper National Park (JP); C – Mount Robson Provincial Park (MR); D – McKale River (MK); E – Frances Creek, Purcell Mountains (PM); F – Cariboo Mountains (CM). 192

Figure 5.2: Stratigraphic column for the WSG from the Cariboo-Purcell-Rocky Mountains in the southern Canadian Cordillera (modified from Ross et al. 1995). Rift and post-rift strata, paleogeographic environment and relative stratigraphic position of the OFP are shown. Ages shown are discussed in the text and are from McDonough and Parrish (1991), Lund et al. (2003), Kendall et al. (2004) and Colpron et al. (2002). Asterisk indicates the age is from correlative strata to the column. 193

Figure 5.3: A) to F) Photos of distinctive TLM limestone-siltstone rhythmites from the southern Canadian Cordillera. A) LL1: purple siltstone and pink limestone. B) JP1: green siltstone and pink to grey limestone. Ruler is 100 cm. C) MR1: red-brown siltstone and white limestone. D) MR1:

stratified Tbcd turbidites with pyrite. Ruler is 16 cm. E) CM1: grey siltstone and white to dark grey limestone. Ruler is 50 cm. F) PM1: red-brown siltstone and dark grey limestone. Ruler is 50 cm. G) Photo of WMM dark grey limestone interbedded with quartz-rich siliciclastics. Arrows indicate stratigraphic upward direction.....197

Figure 5.4: Ternary diagram illustrating mineralogical compositions in MgCO_3 - CaCO_3 - FeCO_3 space of OFP carbonate phases analyzed on the electron microprobe. Note that only the upper 60% of the diagram is displayed.....203

Figure 5.5: A) to E) Elemental cross-plots of calcite phases. A) CaCO_3 vs. Sr. B) FeCO_3 vs. Sr. C) MgCO_3 vs. FeCO_3 . D) MgCO_3 vs. Mn/Sr. E) FeCO_3 vs. MnCO_3 . F) to H) Elemental cross-plots of dolomite and ankerite phases. F) FeCO_3 vs. MnCO_3 . G) MgCO_3 vs. FeCO_3 . H) MgCO_3 vs. MnCO_3 . Legend is the same as in Figure 5.4.....204

Figure 5.6: A) to F) Representative stained thin sections photomicrographs of CC1 and CC2. Pink to red coloured staining indicated iron-poor calcite phases and purple to royal blue staining indicates iron-rich calcite phases. A) LL5: TLM. B) LL1: TLM. C) JP1: TLM. D) MR1: TLM. E) JP1: GSM. F) CM1: GSM. 206

Figure 5.7: A) to H) Representative backscatter electron (BSE) images of carbonate phases CC1 (dark) and CC2 (light) from limestone units of the OFP. A) LL1: TLM. B) JP1: TLM. C) MR1: TLM. D) LL1: GSM. E) JP1: GSM. F) MK1: WMM. G) CM1: TLM. H) CM1: WMM. Note the increasing degree of recrystallization (diagenetic) with increasing stratigraphic height (TLM → GSM → WMM) and metamorphic grade (east to west: LL → JP → MR → MK → CM).....207

Figure 5.8: A) to C) Representative stained thin section photomicrographs of carbonate cement phase CC3. Pink to red coloured staining indicated iron-poor calcite phases, purple to royal blue staining indicates iron-rich calcite phases, no staining indicates iron-poor dolomite and light blue to turquoise staining indicates iron-rich dolomite. A) LL5: TLM. B) CM1: TLM. C) LL1: TLM, note replacement of DOL2 by CC3. D) to F) Representative stained thin section photos of cross-cutting vein CC4. D) LL1: TLM, CC4 cuts across clasts of CC1 + CC2 and breccia matrix where DOL2 is replaced by CC3. E) LL1: TLM. F) LL1: TLM.....209

Figure 5.9: A) to E) Representative BSE images of CC3. A) LL1: TLM, diagenetic barite and hematite present. B) LL1: TLM, replacement of DOL2 by CC3 and corrosion of former ilmenite grain. C) LL5: TLM, contact between mud- to silt-sized calcite-rich suspension fallout bed (CC1 + CC2) and overlying very fine sand-sized siliciclastic bed deposited by tractional processes and cemented by CC3. D) and E) LL5: TLM, CC3 zonation. F) to H) Representative BSE images of cross-cutting vein CC4 phase. F) LL1: TLM. G) LL1: GSM. H) CM1: GSM.....210

Figure 5.10: A) to F) Representative stained thin section photomicrographs of dolomite (DOL2) from the OFP. Pink to red coloured staining indicated iron-poor calcite phases, purple to royal blue staining indicates iron-rich calcite phases, no staining indicates iron-poor dolomite and light blue to turquoise staining indicates iron-rich dolomite. A) JP1: TLM, DOL2 cementation in siliciclastic-dominated parts of turbidite beds (both lower and ripple-stratified upper bed). B) LL1: TLM, DOL2 is replaced by CC3 between clasts of CC1 + CC2. C) LL5: TLM, DOL2 crystal size and degree of cementation is controlled by grain-size of siliciclastic matrix. D) MR1: TLM, DOL2 replaced by CC3. E) CM1: TLM. F) LL4: WMM. 213

Figure 5.11: A) to G) Representative BSE images of dolomite phases from the OFP. A) MR1: TLM, DOL1 core replaced by DOL2, which is then replaced by CC3. B) LL1: TLM, replacement of DOL2 by CC3. C) JP1: TLM, euhedral DOL2 displaying zonation. D) – E) JP1: TLM, DOL2 replacement by CC3. F) MR1: TLM, ANK rims encompassing DOL2 crystals. G) LL5: TLM, DOL2 replacement by CC3. H) LL5: TLM, large filament of diagenetic hematite. 214

Figure 5.12: Representative images from clasts of bladed-calcite crystal limestone in WMM breccia at LL4. A) Clast in outcrop. Photo courtesy of G. M. Ross. B) to D) Stained thin section photomicrographs showing bladed and “fan” morphology with infilling of siliciclastic detritus between the blades. Pink to red coloured staining indicated iron-poor calcite phases. E) to G) BSE images showing mottled texture within bladed calcite crystals. Arrows indicate stratigraphic-upward direction in BSE images. 216

Figure 5.13: Simplified stratigraphic columns of the OFP, correlated cross-section and stable isotopic profiles ($\delta^{13}\text{C}_{\text{org}}$; carbonate $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) of the three members of the OFP. Cross-section is in an east to west direction, along a paleogeographic slope to basin-floor transect and uses the top of the GSM as a datum. Sections from Jasper National Park and Mount Robson area are composite sections for display purposes and include analyses from more than one locality. The carbonate $\delta^{13}\text{C}$ profile through the TLM (and GSM in the Cariboo Mountains) consistently shows a stratigraphically-upward 3‰ shift towards more positive values. The TLM also displays a negative ~1.5‰ shift from lower slope to basin floor depositional environments. In the Jasper region, the negative ~2.5‰ shift in the GSM corresponds to a prominent negative shift in the $\delta^{13}\text{C}_{\text{org}}$ values. The WMM in the Cariboo Mountains exhibits a stratigraphically-upward 4 to 5‰ shift towards near-zero $\delta^{13}\text{C}$ values in limestone units. Conversely, the carbonate $\delta^{18}\text{O}$ values appear homogenized at each geographic region, with increasing negative values corresponding to the increase in metamorphic grade from east to west. 229

Figure 5.14: Simplified stratigraphic columns of the OFP, correlated cross-section and stable isotopic profiles ($\delta^{13}\text{C}_{\text{org}}$; carbonate $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) of the three members of the OFP in the Lake Louise area. Cross-section illustrates the correlation of the lower two members (TLM + GSM), prominent incision event and deposition of the WMM in a submarine canyon. The carbonate $\delta^{13}\text{C}$ profiles show a similar positive shift of approximately 4 to 5‰ through the TLM with a negative 2 to 3‰ shift in the GSM which corresponds to a prominent negative shift in the $\delta^{13}\text{C}_{\text{org}}$ values. $\delta^{18}\text{O}_{\text{carb}}$ values appear homogenized throughout the area with the exception of shallow-marine clasts from WMM breccia units at LL4 (not displayed, see Table 5.3).	231
Figure 5.15: Simplified stratigraphic columns of the OFP from McKale River and Purcell Mountains and stable isotopic profiles ($\delta^{13}\text{C}_{\text{org}}$; carbonate $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$). The section from Frances Creek in the Purcell Mountains consists of an anomalously thick succession of the TLM and GSM strata related to syn-sedimentary growth faulting. Also, note the abnormally positive carbonate $\delta^{13}\text{C}$ values from TLM limestone rhythmites. Although separated by >500 km (palinspastically unrestored), the carbonate $\delta^{13}\text{C}$ profile through the WMM shows stratigraphically-upward, positive shift toward near-zero values (McKale River 2 to 3‰; Purcell Mountains ~6‰) like the WMM in the Cariboo Mountains (Fig. 5.13). The $\delta^{13}\text{C}_{\text{org}}$ profile appears to show a similar trend. Carbonate $\delta^{18}\text{O}$ values show similar homogenization from regional metamorphism with the exception of some WMM analyses from the Purcell Mountains section.	233
Figure 5.16: Isotopic cross-plots of $\delta^{18}\text{O}$ vs. $\delta^{13}\text{C}$. A) Carbonate phases CC1 + CC2, CC2-WMM and BLD CC. B) Carbonate phases CC3, CC4 vein, DOL2, ANK, CC-SMC and DOL-SMC.	237
Figure 5.17: Histogram plot of sulfur isotopic analyses of pyrite from the OFP, divided up into its three constituent members. Plot includes analyses from this study and those previously published by Ross et al. (1995).	239
Figure 5.18: Schematic stratigraphic section of the OFP (Chapter 2), its three constituent members, sulfur stable isotopic profiles from sampled locations and a composite profile of all analyzed $\delta^{34}\text{S}_{\text{py}}$ values. Note the variability in isotopic values from slope strata the lower two members (TLM - GSM). Isotopic profile from Cariboo Mountains also includes results previously published by Ross et al. (1995).	240
Figure 5.19: A) BSE image of electron microprobe chemical traverse of zoned dolomite crystal containing DOL1, DOL2 and ANK from MR1. B) Chemical analyses of Ca-normalized trace element ratios illustrating distinct chemical differences in diagenetic (DOL1 and DOL2) and metamorphic (ANK) phases.	245

Figure 5.20: A) Relative paragenetic timing of OFP carbonate phases. B) Schematic diagrams (1 to 5) illustrating paragenetic timing observed in a TLM limestone breccia unit: 1) Turbidity current transport of CC1 from upslope staging area and deposition in the deep ocean; 2) Early burial and lithification whereby CC2 cement encompasses grains of CC1, DOL1 cementation in the siliciclastic bed (not observed in TLM breccia) with extensive replacement by DOL2 soon after; 3) Slope collapse and burial by younger turbidites, CC3 cement replaces DOL2 in siliciclastic units and breccia matrix; 4) Continued diagenetic cementation during burial (CC3) and compaction (CC4); 5) Regional metamorphism and recrystallization of DOL2 to ANK (not observed in TLM breccia). C) to D) Representative stained thin section photomicrographs from TLM breccia unit. Pink to red coloured staining indicated iron-poor calcite phases, purple to royal blue staining indicates iron-rich calcite phases, no staining indicates iron-poor dolomite and light blue to turquoise staining indicates iron-rich dolomite. 248

Figure 5.21: A) – B) Cross plots of $\delta^{13}\text{C}$ isotopic analyses and corresponding averaged trace-element analyses from the electron microprobe. A) $\delta^{13}\text{C}$ vs. FeCO_3 . B) $\delta^{13}\text{C}$ vs. MnCO_3 254

Figure 5.22: A) Example of a TLM limestone bed from CM1 illustrating physical, chemical and isotopic changes that take place during burial diagenesis. Outcrop photo of the bed (dashed box) showing upward colour change from dark grey to white. Ruler is 50 cm. Photomicrograph showing upward change in staining characteristics from purple to red and locations of electron microprobe analyses. Plots that show the upward decrease in FeCO_3 content, and positive shift in $\delta^{13}\text{C}$ values. B) GSM limestone bed from CM1 showing a positive shift in $\delta^{13}\text{C}$ from a CC3 cemented to a CC1 + CC2 bed, then a negative shift in the overlying CC3 cemented bed. C) $\delta^{13}\text{C}$ isotopic values from a TLM limestone (CC1 + CC2) - siltstone (CC3) couplet from MR1. D) $\delta^{13}\text{C}$ isotopic values from a TLM limestone (CC1 + CC2) bed and cross-cutting CC4 vein LL1.....255

Figure 5.23: Schematic cartoon illustrating deposition of the three members of the OFP, position of relative sea-level and carbon isotopic profile. Numbered locations on shelf – slope – basin profile refer to paleogeographic locations of the OFP: 1) Mid-slope, Lake Louise (LL) and Purcell Mountains (PM); 2) Lower slope, Jasper (JP); 3) Base of slope, Mount Robson (MR), McKale River (MK); and 4) Basin-floor, Cariboo Mountains. Abbreviations: HST – highstand systems tract; LST – lowstand systems tract; TST – transgressive systems tract; BSFR – basal surface of forced regression; MFS – maximum flooding surface; MRS – maximum regressive surface; SB – sequence boundary. Note: diagenetically altered values in the TLM from the Frances Creek locality are not plotted. 266

Figure 5.24: A) Outcrop distribution of the WSG in the Canadian Cordillera showing locations of the Mackenzie Mountains, Monkman Pass area and southern Canadian Cordillera (modified from Ross,

1991). B) Stratigraphic columns with corresponding nomenclature for WSG Cryogenian to Ediacaran strata (glacial to post-glacial transition) from the three regions of the Canadian Cordillera. C) Schematic representation showing a conceptual shelf to basin profile of rift to post-rift WSG strata in the Canadian Cordillera. Figure is re-drafted using information originally presented in McMechan (1987, 2000), Ross et al. (1995), Ross (2000), James et al. (2001) and Hoffman and Halverson (submitted). No absolute thicknesses for strata or distances are implied in the schematic representation. Maximum age constraint of 755 ± 18 Ma for deposition in the Mackenzie Mountains area is from a leucogranite clast in the Sayunei Formation (Ross and Villeneuve, 1997). Age constraints in the southern Canadian Cordillera include: local basement, which ranges from 742 to 728 Ma (Evenchick et al., 1984; Scammell and Parrish, 1988; McDonough and Parrish, 1991); interpreted Irene Formation volcanic correlatives from Idaho, USA ranging from 709 to 684 Ma (Lund et al., 2003; Fanning and Link, 2003); and 607.8 ± 4.7 Ma from the GSM of the OFP (Kendall et al., 2004). 271

Figure 5.25: Schematic stratigraphic columns and correlation of Cryogenian to Ediacaran, glacial to post-glacial WSG strata in the Canadian Cordillera from the Mackenzie Mountains, Monkman Pass area and southern Canadian Cordillera. Each location represents a different paleogeographic position on a conceptual shelf to basin profile. Approximate total thickness of each schematic column is provided, with relative thickness of each geological unit roughly represented in the figure; however, no absolute thickness is implied in any of the columns. Schematic column of the Monkman Pass area is re-drafted using information from McMechan (2000) and the Mackenzie Mountains from James et al. (2001), Hoffman et al. (2007), Shen et al., (2008) and Hoffman and Halverson (submitted). Timing of the Icebrook Formation (Stelfox Member) is interpreted to be ca. 635 Ma based on global correlation with other well-constrained glaciogenic deposits (e.g. Condon et al., 2005; Hoffman et al., 2007). Age of the GSM in the OFP is constrained by the Re-Os isochron of 607.8 ± 4.7 Ma (Kendall et al., 2004). Diamictite of the Icebrook Formation is correlated with Vreeland Formation and coarse-grained arkosic turbidites of the Windermere Supergroup. The Ravensthorpe Formation dolostone is correlated with the basal TLM siliciclastic siltstone and the overlying Hayhook Formation is correlated with the TLM limestone rhythmites to the Hayhook Formation. Robust regional correlation of the discontinuous limestone overlying diamictite of the Vreeland Formation remains equivocal. The ~608 Ma organic-rich GSM is interpreted to correlate to the pyrite-rich zone at the top of the Vreeland Formation and the lower part of the Sheepbed Formation with $\text{FeHR}/\text{FeT} > 0.38$ (Shen et al., 2008). The maximum flooding surface is located within these units (green line). The WMM correlates to the Framstead Formation. The deep-marine erosion surface (sequence boundary – red line) of the WMM is interpreted to correlate with the basal contact of the Framstead Formation.

Clasts of bladed calcite-crystals similar to the Hayhook Formation are in overlying strata of the WMM and Framstead Formation. The sequence boundary (red line) separating the OFP and overlying WSG strata is marked by a shift in the FeHR/FeT ratio from anoxic to oxic conditions (Canfield et al., 2008, supplementary data) and may correlate to a similar FeHR/FeT shift recorded in the Sheepbed Formation (Shen et al., 2008). Old Fort Point Formation: TLM – Temple Lake Member; GSM – Geikie Siding Member; WMM – Whitehorn Mountain Member. WSG – Windermere Supergroup; PKS – Paksumo Formation; VRL – Vreeland Formation; FRM – Framstead Formation; KEE – Keele Formation; ICE – Icebrook Formation; RAV – Ravensthorpe Formation; HAY – Hayhook Formation; SHP – Sheepbed Formation. Ba – barite crusts) 276

Fig. A.1: Generalized geological map showing outcrop distribution of Windermere Supergroup in western Canada and specific outcrop localities (A – K) discussed in the text (modified from Ross *et al.* 1995). A comprehensive list of outcrop locations for the Toby Formation can be found in Aalto (1971) and Reesor (1973). Outcrop localities for the Vreeland Formation are from McMechan (2000) and for the OFP from Ross & Murphy (1988) and Smith (2009). 353

Fig. A.2: Comparative stratigraphic columns for the Windermere Supergroup from the Monkman Pass area and the Cariboo-Purcell-Rocky Mountains (modified from Ross et al. 1995). Nomenclature of rift and post-rift strata (Kaza-Cariboo, Horsethief Creek and Miette groups refer to similar strata, depending on location within the region), relative stratigraphic position of the glaciogenic Toby, Vreeland and Old Fort Point formations and proposed correlation between the basal Framstead and Old Fort Point formations are shown. Ages shown are discussed in the text and in stratigraphic order, are: Malton Gneiss (McDonough & Parrish 1991); rift-related volcanic rocks from Idaho (Lund et al. 2003; Fanning & Link 2004); Old Fort Point Formation (Kendall et al. 2004); and Hamill Group volcanic rocks (Colpron et al. 2002). Bracketed ages indicate that the ages are not from rocks of the southern Canadian Cordillera, but rather interpreted correlatives of the Irene Formation. 354

Fig. A.3: Stratigraphic columns of the Toby Formation from the Mount Brewer and Paradise Mine localities (~ 50° 28' N, 116° 18' W) with lithofacies representative of other outcrops; however, their lateral continuity, stratigraphic thickness and stratigraphic distribution vary widely across the Purcell Mountains. Note the different scales used in each log. Facies codes used: first letter corresponds to D-diamictite, G-Conglomerate, S-sandstone, F-fine-grained facies; second letter in diamictite and conglomerate refers to the following: m-matrix supported, c-clast-supported. Third letter in code refers to sedimentary structure as follows: m-massive, l-laminated, d-deformed, r-rippled, h-horizontally-bedded, s-stratified. 355

Fig. A.4: Stratigraphic columns of the Vreeland Formation near Mount Vreeland in the Snake Indian thrust sheet, and Paksumo Pass in the Wapiti thrust sheet, modified from McMechan (2000). St-cross-trough bedded sandstone; Fld- laminated fine-grained facies with lonestones. See Fig. 3 for other facies codes. 357

Fig. A.5: Stratigraphic columns of the Old Fort Point Formation, simplified from Smith (2009). At the Geikie Siding section in Jasper National Park, the regionally widespread lower two members are exposed and overlain sharply by a thinly developed upper member. The Re-Os isochron age was obtained from the middle member at this section (Kendall *et al.* 2004). At the Upper Boomerang section on the Lake Louise Ski Resort, only a thickly developed Upper Member is exposed with complete erosion of the lower two members. Str-stratified (ripple cross-laminated and cross-bedded). See Fig. 3 for other facies codes. 358

LIST OF ABBREVIATIONS

AAPG	American Association of Petroleum Geologists
AG	Archean granite
ATTG	Archean tonatite-trondhjemite-granodiorite
b.d.	below detection limits
bsfr	basal surface of forced regression
BSR	bacterial-sulfate reduction
CFES	Canadian Federation of Earth Scientists
CIA	Chemical Index of Alteration
CM	Cariboo Mountains
CS	condensed section
CSPG	Canadian Society of Petroleum Geologists
EF	Enrichment Factor
FSST	falling-stage systems tract
GSA	Geological Society of America
GSC	Geological Survey of Canada
GSM	Geikie Siding Member
HFSE	High Field Strength Element
HREE	Heavy Rare Earth Element
HST	highstand systems tract
ICP-MS	Induced coupled mass spectrometry
IF	Isaac Formation
IGCP	International Geoscience Programme
IRD	ice-rafted debris
JP	Jasper National Park
LAA	Late-Archean andesite
LILE	Large Ion Lithophile Element
LL	Lake Louise, Banff National Park

LREE	Light Rare Earth Element
LST	lowstand systems tract
Ma	million years (datum)
mfs	maximum flooding surface
MK	McKale River
MKG	Middle Kaza Group
MMG	Middle Miette Group (undifferentiated)
MMGA	Middle Miette Group (above OFP)
MMGB	Middle Miette Group (below OFP)
MR	Mount Robson Provincial Park
mrs	maximum regressive surface
MSWD	mean squared weighted deviation
Myr	million years (duration)
n.a.	not analysed
NASC	North American Shale Composite
NSERC	National Science and Engineering Research Council
OFP	Old Fort Point Formation
OGS	Ontario Graduate Scholarship
PAAS	Post Archean Australian Shale
PG	Proterozoic granite
PIA	Plagioclase Index of Alteration
PM	Purcell Mountains
PTTG	Proterozoic tonatite-trondhjemite-granodiorite
REE	Rare Earth Element
Re-Os	rhenium – osmium
SB	sequence boundary
SHRIMP	sensitive high resolution ion microprobe
Sm-Nd	samarium – neodymium
SRMT	southern Rocky Mountain Trench

TLM	Temple Lake Member
TOC	total organic carbon
TST	transgressive systems tract
TTE	Transition Trace Element
UKG	Upper Kaza Group
UMG	Upper Miette Group
U-Pb	uranium – lead
UTM	universal transmercator grid
WMM	Whitehorn Mountain Member
WSG	Windermere Supergroup
XRD	x-ray diffraction
XRF	x-ray fluouresence

CHAPTER 1: Thesis Introduction

1.1 THESIS RATIONALE

The concept of Neoproterozoic global glaciation extending to tropical latitudes coupled with extreme geochemical perturbations associated with the deep freeze and subsequent major meltdown has increasingly captured the attention of scientists over the last 10+ years, resulting in an explosion literature devoted to these rocks. The terminal Neoproterozoic (~750 to 542 Ma) was a dynamic period in Earth history with the dispersal of the supercontinent Rodinia, evidence for great glaciations, changes in geochemical cycles and the emergence of metazoan life forms. The manner in which these processes interacted during the final 200 Myr of the Precambrian is hotly contested in the earth sciences with many contrasting hypotheses (e.g. snowball Earth, oceanic stratification upwelling, gas hydrate destabilization, plumeworld) proposed to explain the existing geological and geochemical record (see recent review in Fairchild and Kennedy, 2007 and references therein).

The Old Fort Point Formation (OFP) is a distinctive regional marker in the Neoproterozoic Windermere Supergroup (WSG) of the southern Canadian Cordillera. Its unique sedimentological and stratigraphic attributes set it apart from the monotonous thick succession of fine- and coarse-grained feldspar-rich turbidites typical of the WSG and led to its recognition by several authors as a significant and correlatable horizon (Ross and Murphy, 1988). It provides a key element in reconstructing the WSG sedimentary basin and linking it with coeval global events. The OFP has been interpreted as a post-glacial deep-water succession equivalent to better studied cap carbonate strata exposed in the northern Canadian Cordillera (Ross et al., 1995), which overlie diamictite deposits linked to the ca. 635 Ma terminal Cryogenian glaciation event (Hoffman et al., 2004; Condon et al., 2005).

This major eustatic rise attributed to glacial melting terminated coarse clastic input into the basin and is interpreted to have facilitated the subsequent development of anoxic bottom-water conditions (Ross and Murphy, 1988). A recent Re-Os age of 607.8 ± 4.7 Ma (Kendall et al. 2004) for the OFP places it in the newly defined Ediacaran Period (Knoll et al., 2004, 2006) and broadly correlates it with other basal Ediacaran post-glacial cap carbonate deposits.

Although the OFP has been described from many locations in the southern Canadian Cordillera, and its importance as a regional stratigraphic marker recognized, there is no single study that has specifically focused on the detailed sedimentology and stratigraphy of the OFP on a regional scale. This Ph.D. study is the first comprehensive project on the deep-marine OFP integrating sedimentology, stratigraphy, stable isotopes and geochemistry in order to evaluate its sedimentation processes, paleoenvironments of deposition, and the geochemical characteristics of Ediacaran seawater. The significance of this research is that it is the first to study a deep-marine equivalent of post-glacial, shallow-water cap carbonate strata previously studied in the northern Canadian Cordillera, and other locations around the world. In a global context, the deep-marine OFP potentially preserves a more complete record of paleo-oceanographic changes compared to previous studies in shallow-water settings, and thus, the physical and chemical data obtained from this project will provide a unique dataset from a previously un-researched part of the Neoproterozoic global ocean system potentially adding new insight into the many working hypotheses.

1.2 REGIONAL GEOLOGICAL BACKGROUND

The Neoproterozoic WSG is impressive in its widespread distribution across western North America (Fig. 1.1). Strata crop out discontinuously in northwestern Mexico and throughout the western United States, forming a fairly continuous outcrop belt in southwestern Canada as it extends northwards to the Yukon-Alaska

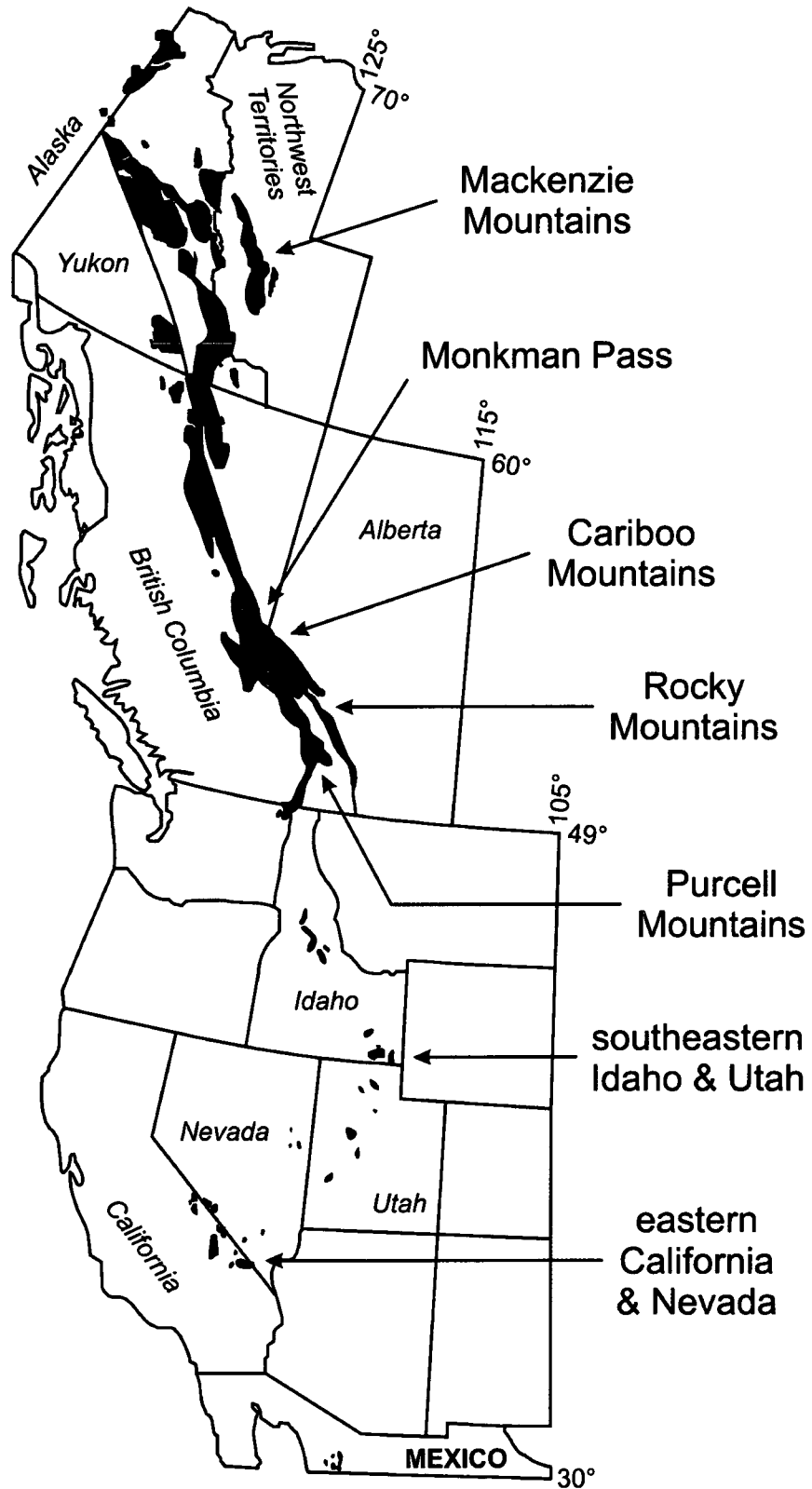


Figure 1.1: Distribution of WSG strata in western North America (modified from Ross, 1991).

border region; a total distance of more than 4000 km (e.g. Ross et al. 1989; Link et al., 1993). In the southern Canadian Cordillera, the WSG is a nearly 9 km-thick, unconformity-bounded succession (ca. 740-728 Ma to 569 Ma) consisting primarily of deep-marine meta-sedimentary rocks, exposed locally over an area of 35,000 km² in a series of thrust sheets and structural culminations associated with the mostly Mesozoic Cordilleran orogen. (e.g. Ross and Arnott, 2007) (Fig. 1.2).

The Canadian Cordillera has been divided into five northwest-southeast trending, morphogeological belts based on rock type, structural domains, metamorphic attributes and physiographic features (e.g. Monger et al., 1982; Fig. 1.3). From east to west, they are the Foreland fold and thrust belt, Omineca belt, Intermontane belt, Coast belt and Insular belt, with their boundaries delineated along major geological features. The present geological configuration of these belts is the result of collision and accretion of allochthonous terranes against the margin of the ancestral North American craton and its amalgamation history continues to be a source of debate (e.g. Reid et al., 2002). These events led to crustal thickening, thrust faulting, folding and metamorphism of both the accreted terranes and older rocks along the continental margin (Reid et al., 2002). Much of the deformation is associated with protracted intracontinental strike-slip faulting and extension, with substantial displacement and reconfiguration of the older North American rocks (Gabrielse, 1985). The Tintina – northern Rocky Mountain trench fault is one of these structural lineaments and it has been proposed that its slip motion continues into the southern Rocky Mountain trench (SRMT) (e.g. Pope and Sears, 1997). Although local strike-slip fault zones are observed in the SRMT, they do not accommodate major displacements (e.g. McDonough and Simony, 1989) and structural studies show little offset across the trench (McMechan and Price, 1982; Gal and Ghent, 1990).

Although all WSG strata were subjected to deformation during the Cordilleran Orogeny, extensive tracts of sub-greenschist to greenschist grade exist in the southern Canadian Cordillera, including: east of the SRMT in the Rocky

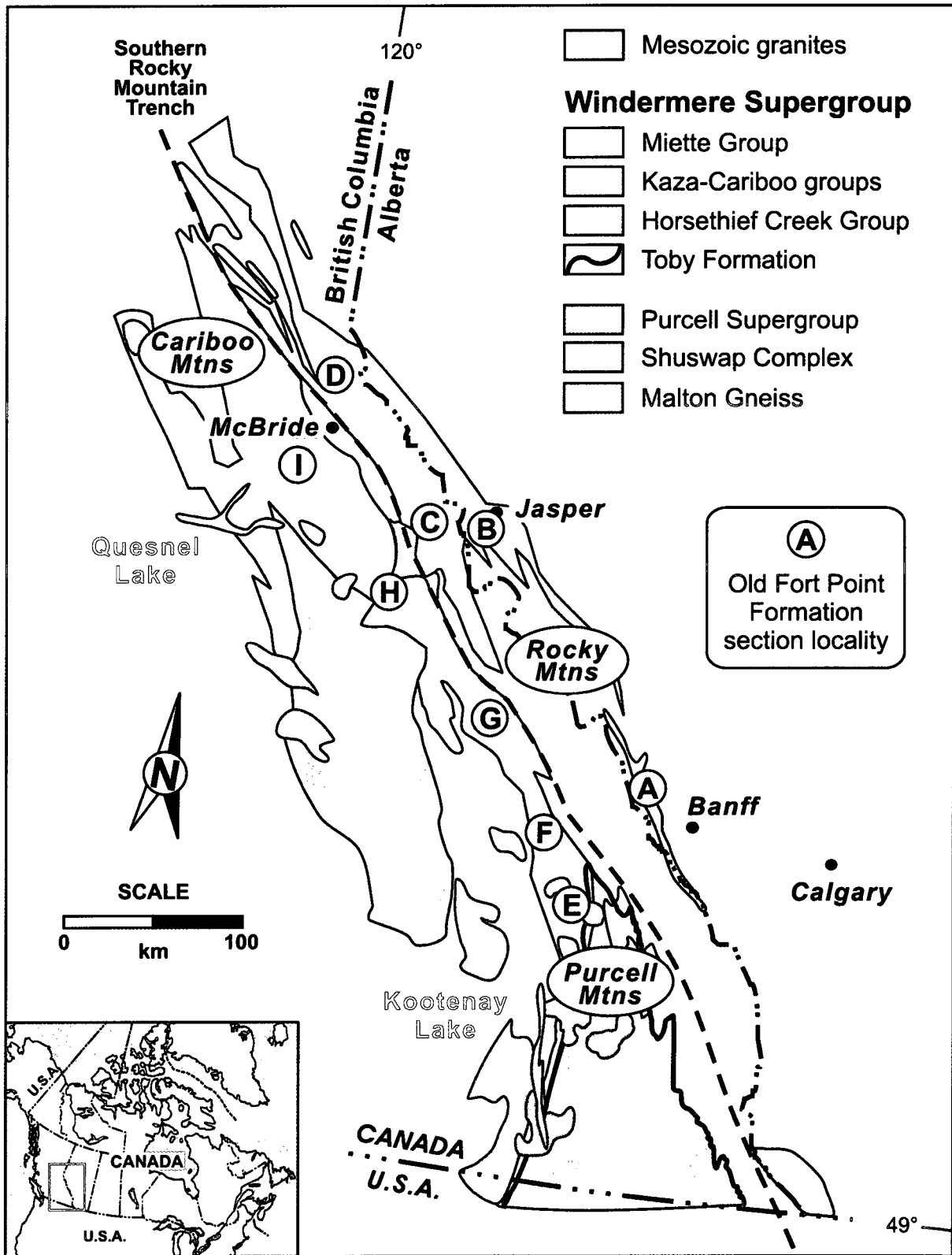


Figure 1.2: Simplified geological map of the WSG, southern Canadian Cordillera showing the main outcrops of the OFP (modified from Ross and Murphy, 1988).

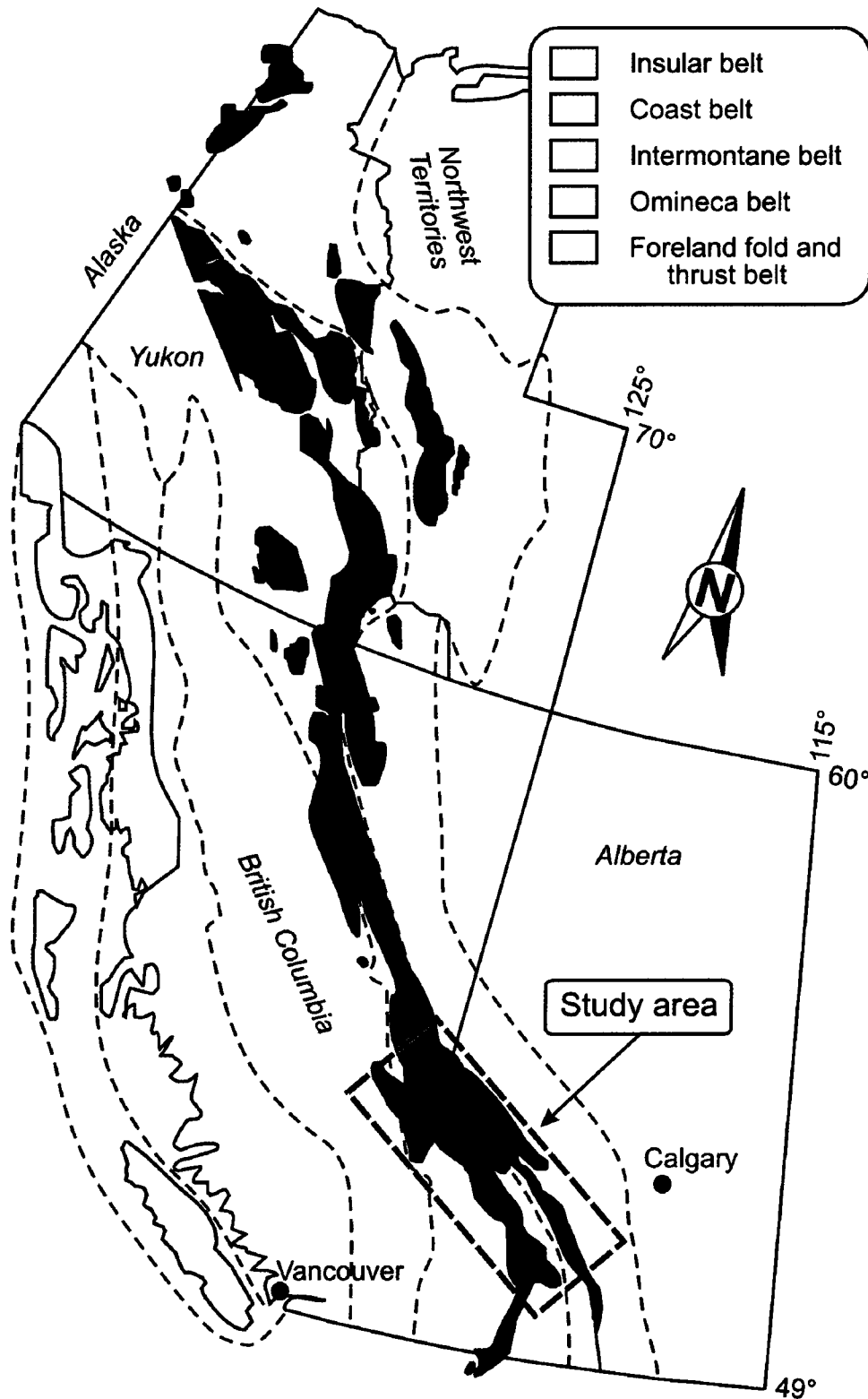


Figure 1.3: Map of western Canada showing the five major sub-divisions of the Canadian Cordillera (modified from Reid et al., 2002), the distribution of WSG strata shown in black (modified from Ross, 1991) and overall study area located in the Foreland fold and thrust and Omineca belts.

Mountains, Foreland fold and thrust belt (Lake Louise, Jasper, Mount Robson, McKale River); and west of the SRMT in the Omineca belt (northern Cariboo and eastern Purcell Mountains). At these locations, primary sedimentary textures and structures are preserved because of the low metamorphic grade and relatively uncomplicated tectonic deformation. Sedimentological studies in these areas have allowed the development of a consistent internal stratigraphy of the WSG and reconstruction of the Windermere basin in southwestern Canada (Ross and Murphy, 1988; Ross et al. 1989, 1995; Ross, 2000).

The WSG is interpreted to have accumulated in a two-phase tectonic model: the first rift phase during break-up of the supercontinent Rodinia, and the second during subsequent post-rift thermal relaxation (Stewart, 1972; Ross, 1991) (Fig. 1.4). At the base of the WSG, the Toby Formation overlies unconformably the Mount Nelson Formation of the Purcell Supergroup (Aalto, 1971; Root, 1987) (Fig. 1.4). It consists mainly of diamictite, which underlies and is intercalated with volcanic rocks of the Irene Formation. These basal units of the WSG are variable in thickness, limited in their areal extent, and restricted largely to the Purcell Mountains region. They are interpreted to have accumulated during the active rift phase with deposition controlled by syn-sedimentary faulting (Aalto, 1971; Root, 1987; Warren, 1997). No direct geochronological control is currently available to constrain the timing of the rift event in the southern Canadian Cordillera. The local maximum depositional age is constrained by U-Pb zircon dates ranging from 740 to 728 Ma from older crystalline basement rocks in the Canadian Cordillera (Evenchick et al. 1984; Parrish and Scammell 1988; McDonough and Parrish, 1991). Potential rift-related volcanic correlatives of the Irene Formation have been dated elsewhere from northern British Columbia and Idaho ranging from 762 to 684 Ma (Devlin et al. 1988; Ferri et al. 1999, Lund et al., 2003; Fanning and Link 2004).

The post-rift WSG succession represents one of the world's most expansive ancient laboratories of deep-marine sedimentary rocks (Fig. 1.4). In the southern Canadian Cordillera, the Horsethief Creek Group (Purcell Mountains), Kaza and

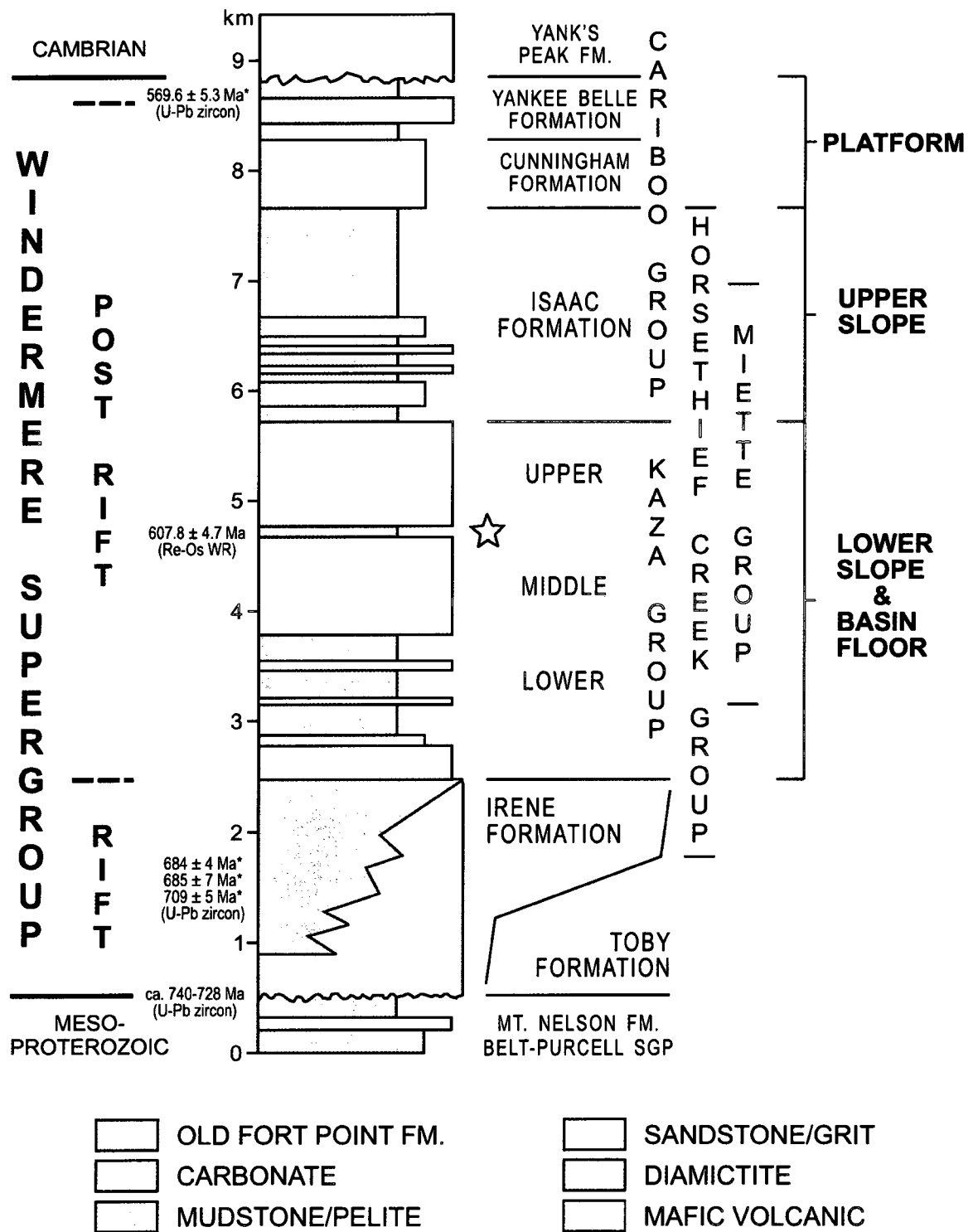


Figure 1.4: Stratigraphic column for the WSG from the Cariboo-Purcell-Rocky Mountains in the southern Canadian Cordillera (modified from Ross et al. 1995). Rift and post-rift strata, paleogeographic environment and relative stratigraphic position of the OFP are shown. Ages shown in stratigraphic order are from McDonough and Parrish (1991), Lund et al. (2003), Kendall et al. (2004) and Colpron et al. (2002). Asterisk indicates the age is from correlative strata to the column.

Cariboo groups (Cariboo Mountains) and Miette Group (Rocky Mountains) all refer to parts of the same ~5 km thick sedimentary pile, which stratigraphically upward consists of a continental-scale, basin-floor to basin-slope to outer shelf stratal succession (e.g. Ross et al. 1989; 1995; Ross and Arnott, 2007) (Fig. 1.4). Lithologies of the strata of the WSG are dominated by coarse-grained arkosic sandstone and granule conglomerate intercalated with mudstone-dominated intervals and minor carbonate (e.g. Ross et al., 1989; 1995; Ross and Arnott, 2007). The Vreeland Formation of the Misinchinka Group in north-central British Columbia, however, is an exception, being composed mainly of glaciogenic diamictite that undergo a lateral facies change into typical turbidites of the WSG in both a westward and southward direction (McMechan, 1987; McMechan and Thompson 1995a; McMechan, 2000).

Within the Windermere basin, the overall monotony of immature turbidites of the Horsethief Creek, Miette and Kaza groups is interrupted by the predominantly fine-grained, regionally widespread OFP (e.g. Ross and Murphy, 1988) (Fig. 1.4). The minimum timing of deposition of the OFP is constrained from a Re-Os isochron age of 607.8 ± 4.7 Ma from organic-rich mudstone of the Geikie Siding Member (GSM) in the Jasper area, Alberta (Kendall et al. 2004) placing it in the newly defined Ediacaran Period (Knoll et al., 2004, 2006). The OFP is overlain by coarse-grained feldspar-rich basin-slope to basin-floor turbidites, suggesting a return to more typical sedimentation patterns and mineralogical compositions. These deposits form a kilometre-scale upward-shoaling trend that culminates in mudstone-dominated upper slope units and shelf platform carbonates, and is interpreted to represent the long-term progradation of the continental margin of Laurentia as the rate of thermal subsidence decreased (e.g. Ross et al. 1989; Ross, 1991; Ross et al., 1995; Ross and Arnott, 2007).

A locally subtle, but significant regional unconformity marks the end of WSG deposition and the beginning of a latest Neoproterozoic to Cambrian rift-drift succession with the clastic and volcanic sediments of the upper Cariboo, Hamill and Gog groups. The timing of this event is well-constrained from a U-Pb zircon age of

569.6 $\pm$ 5.3 Ma from synrift felsic volcanic rocks of the Hamill Group that unconformably overlie the WSG (Colpron et al., 2002). Regional uplift associated with this rift-event has resulted in significant sub-Cambrian erosion in the southern Canadian Cordillera, which perhaps is responsible for the lack of preserved shallow-water WSG strata in the eastern outcrops (Ross and Murphy, 1988; Ross et al., 1995).

Approximate water depths for deposition of the basin-slope to basin-floor WSG are interpreted to range from upper bathyal (~500 m) to upper abyssal plain (~3000 m) settings. This interpretation is based on two main observations: 1) preservation of turbidite sedimentary structures that show no evidence for re-working by storms which would imply deposition above storm wave base (~300 m); and 2) an uninterrupted, ~3 km upward-shoaling stratigraphic succession from basin-floor to basin-slope to platform sedimentary deposits suggestive of progressive filling of accommodation as the rate of sedimentation gradually outpaces the rate of thermal subsidence along the continental passive margin. This water depth range (500 to 3000 m) for deposition of the WSG (including OFP) and overall succession thickness are consistent with other modern, deep-water passive margin analogues (e.g. Damuth and Flood, 1985).

1.3 PREVIOUS WORK

The unique physical characteristics of the OFP and its utility as a regional stratigraphic marker in an otherwise monotonous, thick succession of fossil-poor Neoproterozoic sedimentary rocks have ensured its mention in numerous local studies for nearly 100 years (Fig. 1.5, 1.6). The first report of lithologies of the OFP was by Charles Doolittle Walcott (Walcott, 1910) of Burgess Shale fame from the Lake Louise area (formerly named Laggan) using the distinctive purple and green colours to mark the basal Hector Formation. This research in the Lake Louise area was followed up by William Carruthers Gussow (Gussow, 1956, 1957) and in the

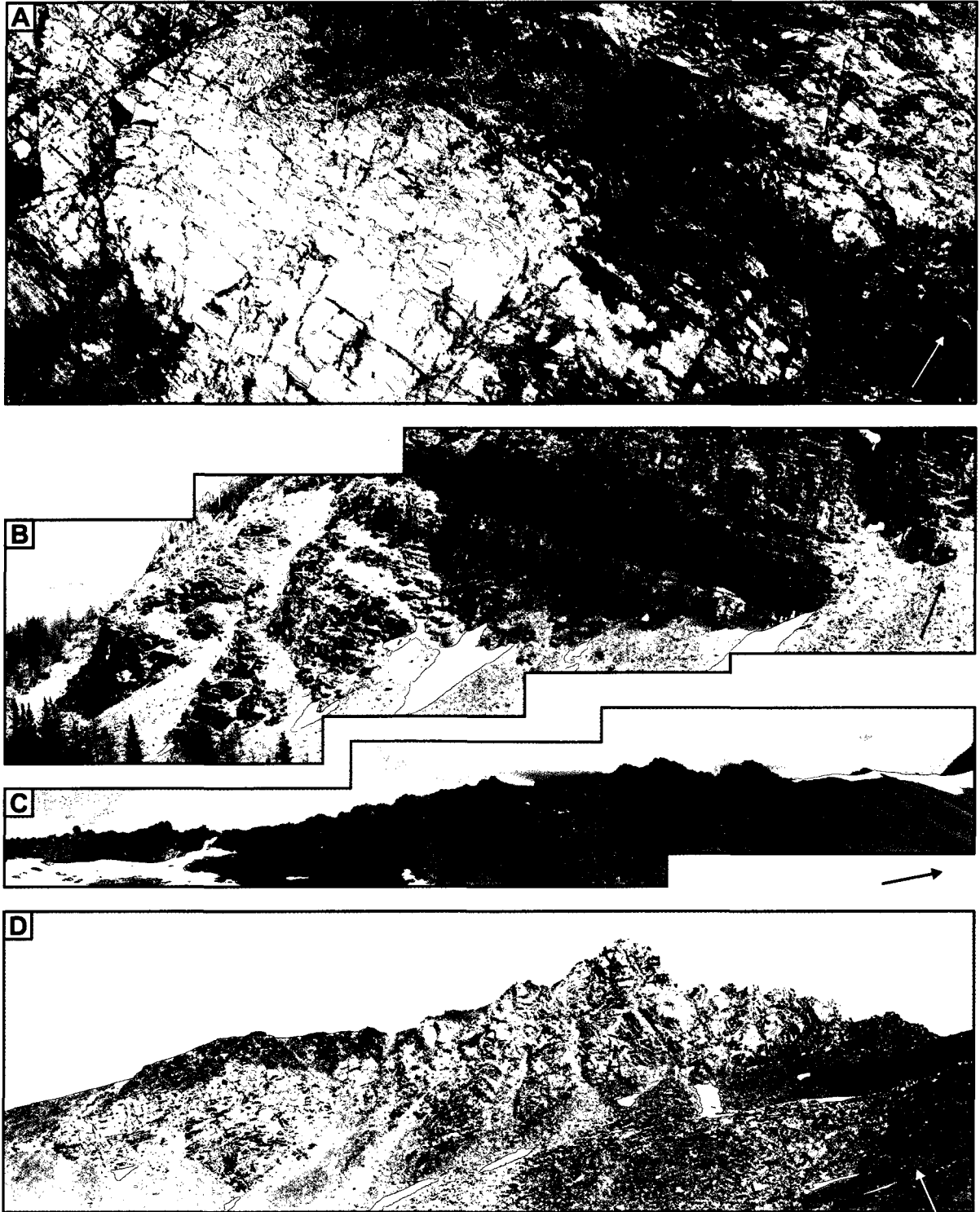


Figure 1.5: Section photos of the Old Fort Point Formation in Alberta. A) JP1: Geikie Siding, Jasper National Park. B) LL1: Temple Lake, Lake Louise. C) LL4: Upper Boomerang, Lake Louise. D) LL5: Wolverine Bowl, Lake Louise. Arrows indicate upward stratigraphic direction.

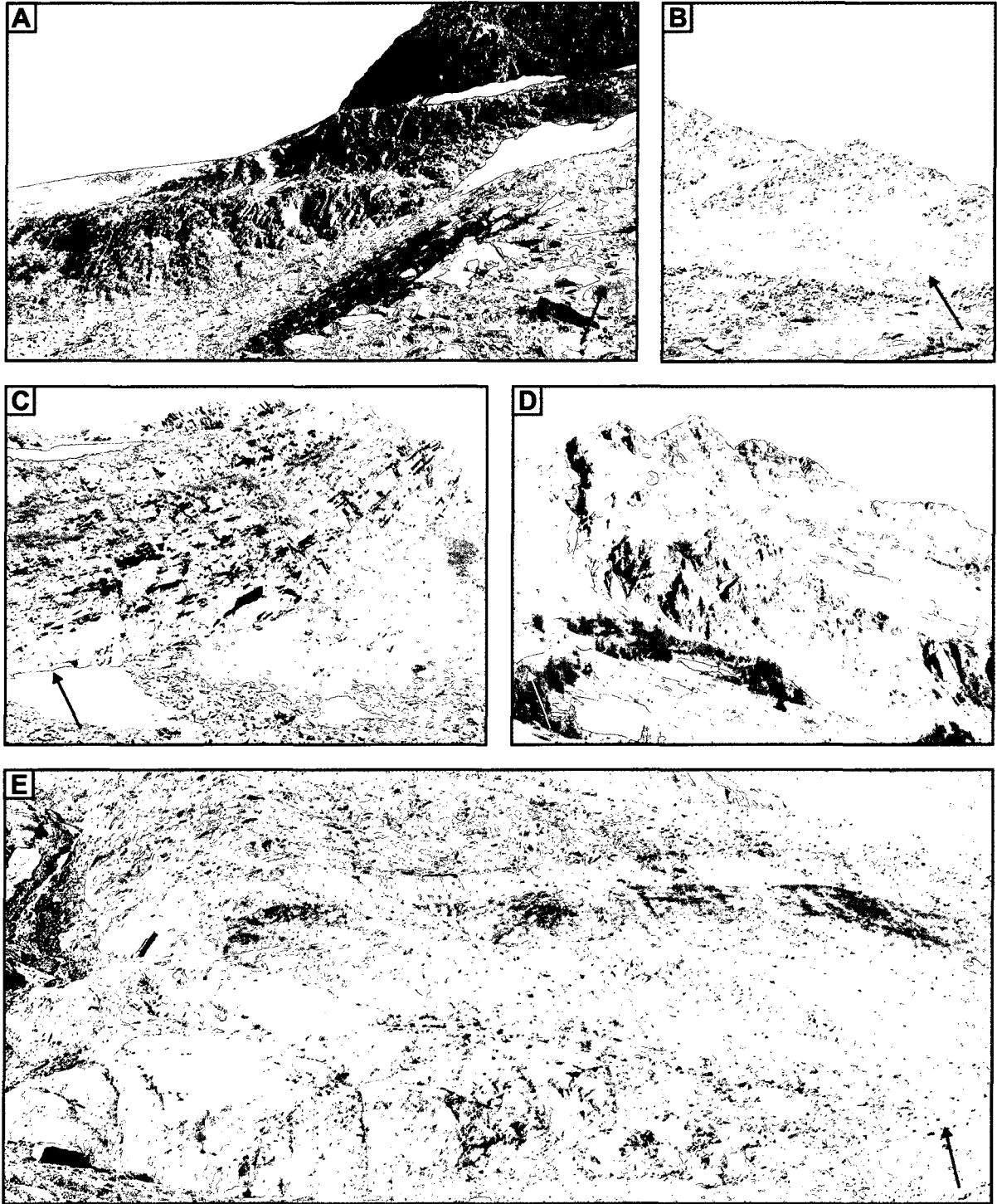


Figure 1.6: Section photos of Old Fort Point Formation in British Columbia. A) - B) MR1: Vista Glacier, Mount Robson Provincial Park. C) MK1: McKale River area. D) PM1: Frances Creek, Purcell Mountains. E) CM1: Eagle Valley, Cariboo Mountains. Arrows indicate upward stratigraphic direction.

1960s by Jim Aitken (Aitken, 1969) of the Geological Survey of Canada (GSC) who also correctly placed, and recognized the magnitude of erosion along the Precambrian – Cambrian angular unconformity. Additional reconnaissance or regional mapping in the southern Canadian Cordillera of Alberta and British Columbia was conducted by numerous authors with casual mention of lithologies consistent with the OFP (Walcott, 1913; Walker, 1926; Allan et al., 1932; Evans, 1933; Mountjoy, 1962, 1971; Reesor, 1957, 1973; Campbell et al., 1973; Mountjoy and Price, 1980; Price et al., 1980a, 1980b).

Dr. Henry Charlesworth and graduate students from the University of Alberta carried out the first detailed structural and stratigraphic mapping of the Precambrian Miette Group within Jasper National Park. The name Old Fort Point Formation was first informally defined in a fieldtrip guidebook (Charlesworth and Remington, 1960) with the name “Old Fort Point” coming from a prominent local landmark south of the Jasper townsite where accessible exposures of the unit are located. The M.Sc. of Evans (1961) focused on mapping the OFP at the landmark with the Ph.D. of Weiner (1966) completing a more regional structural study across Jasper National Park. Compilation and formal definition of the OFP, including proposed regional correlations between Jasper, Lake Louise and southern British Columbia, were first published in Charlesworth et al. (1967). For over 30 years, the landmark formed the mapping project assignment for the University of Alberta 2nd year geology field school with a noteworthy map and report being completed in 1995 (French, Dashtgard and Smith, 1995; Appendix L).

The significance of the OFP became apparent in the 1980s as it was consistently recognized across southern Canadian Cordillera in graduate theses (and subsequent publications) focused mostly on regional mapping and structural interpretation (e.g. Pell, 1984; Carey, 1984; Forest, 1985; Kubli, 1986; Murphy, 1986; Deschesne, 1990; McDonough, 1989; Grasby, 1991; Warren, 1997). It was from these studies that a number of location-specific, informal names for the OFP developed including “Kaza Group Marker”, “Baird Brook Division”, “Comedy Creek unit”,

and “upper and lower Markers”. At the same time, mapping by Dr. Gerald M. Ross of the Geological Survey of Canada (GSC) examined the Windermere succession from a sedimentological perspective and recognized the stratigraphic and global significance of the OFP (Ross and Murphy, 1988; Ross et al., 1995). The recent M.Sc. of Kendall (2003) and subsequent publication (Kendall et al., 2004) dated the GSM of the OFP by the Re-Os method.

1.4 THESIS ORGANIZATION

This Ph.D. thesis is organized into four main chapters, each as a stand alone paper intended for modification and publication at a future date. Chapter 2 outlines the criteria for proposed stratigraphic formalization of the OFP and its three members according to the North American Stratigraphic Code (NASC). Chapter 3 describes the detailed lithofacies and associations of the OFP and assembles them into a consistent sequence stratigraphic depositional model. These two chapters complement one another and are meant to be published together in the same volume. Chapter 4 presents the regional mudstone geochemistry of the WSG, southern Canadian Cordillera and interpretations of provenance, tectonic setting, weathering and paleoredox conditions. Chapter 5 examines the paragenesis of the OFP carbonate units, its stable isotopic geochemistry ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$, $\delta^{34}\text{S}$), regional WSG stratigraphic correlations, and integrates the deep-marine perspective into current models of basal Ediacaran cap carbonate deposition. A brief summary of overall dissertation conclusions from the previous four chapters forms the contents of Chapter 6. In addition, Appendix A is a stand-alone paper entitled: *The record of Neoproterozoic glaciations in the Windermere Supergroup, southern Canadian Cordillera* (M. D. Smith, E. Arnaud, R. W. C. Arnott and G. M. Ross). It has been reviewed and accepted as part of the forthcoming Geological Society of London Memoir of the International Geoscience Programme (IGCP) 512 whose goals are to provide a new global synthesis on Neoproterozoic ice ages (www.igcp512.org). Additional data

associated with each paper and the Ph.D. thesis are presented in the various appendices located at the end of the dissertation.

1.5 STATEMENT OF CONTRIBUTION

This Ph.D. thesis is the product of approximately 6 months of fieldwork over the summers of 2003 to 2005. Six separate regions of high-quality exposure of the OFP and encompassing WSG strata were examined in Alberta and British Columbia of the southern Canadian Cordillera. A total of 17 geologic sections, ranging from approximately 25 to 500 m were measured (centimetre- or decimetre-scale) accompanied by detailed bed-by-bed observations of physical sedimentary structures, bed thickness and stratigraphic characteristics (Appendix D). Outcrop gamma-radiation measurements were collected using a handheld spectrometer from each section (Appendix E). Representative samples were collected and analysed from each section including: 155 petrographic thin sections, 38 polished sections for microprobe analyses; 97 whole-rock geochemical analyses; 181 total organic carbon (TOC) analyses; 122 carbon isotopic analyses from organic residue; 303 oxygen and carbon isotopic analyses from carbonate; and 65 sulfur isotopic analyses from pyrite (Appendices C, F, H, I, J, and K). Nearly all subsequent sample preparation and analytical work (e.g. washing, crushing, grinding, weighing, loading) was conducted by the author.

Previously unpublished analyses by Dr. Gerald M. Ross (formerly of the GSC) from strata of the OFP and WSG have been incorporated into this study and will be included in subsequent publications. These include 39 whole-rock geochemical analyses; 39 total organic carbon; 181 total organic carbon (TOC) analyses; 29 carbon isotopic analyses from organic residue; and 97 oxygen and carbon isotopic analyses from carbonate. These unpublished analyses from the various stratal units are noted in the text and also compiled in the appendices at the end of this thesis.

Chapters 2, 3, 4 and 5 have been written by the author with text editing by Dr. Bill Arnott. From the IGCP512 memoir chapter presented in Appendix A, general information and sections on the Vreeland Formation and OFP were written by the author. All material regarding the Toby Formation was written by Dr. Emmanuelle Arnaud, University of Guelph based on her research work. Co-authorship of Dr. R. W. (Bill) C. Arnott and Dr. Gerald M. Ross reflects the ideas and contributions from their experience working in the WSG. The memoir chapter manuscript has been improved from the comments of two reviewers, Dr. Paul K. Link, Idaho State University and Dr. Brian Kendall, Arizona State University. All graphic images were drafted by the author except where indicated by the original publication. Many of the regional maps have been re-drawn or modified by the author from the original provided by Dr. Gerald M. Ross. A hand-drawn version of Figure 3 in Appendix A was provided by Dr. Emmanuelle Arnaud and drafted by the author.

The following people were instrumental in the completion of the work presented in this thesis. Field assistance was provided by Andres Altosaar in 2004 and Chelsea Hermus in 2004 – 2005. At the University of Ottawa, George Mrazek prepared both thin and polished sections and Ron Hartree assisted in x-ray diffraction and fluorescence analyses. From the G. G. Hatch Stable Isotope Laboratories (University of Ottawa) Paul Middlestead, Wendy Abdi, Patricia Wickham and Gilles St-Jean provided guidance and assisted in analyses of total organic carbon as well as carbon, oxygen and sulfur isotopes. At Carleton University, Peter Jones provided guidance for microprobe analyses of carbonates. Samples for ICP-MS analyses were sent to the University of Saskatchewan, where the work was done by Jianzhong Fan.

Research and Collection Permits to study outcrops and collect samples were provided by Parks Canada (Jasper and Lake Louise National Parks) and B.C. Parks (Mount Robson). Park Wardens Hal and Jim provided shotgun-escorts into grizzly-occupied territories. Glen Stanley allowed use of the Eagle Valley Ski Hut in the

Cariboo Mountains and Resorts of the Canadian Rockies provided access to the Temple Fire Road for areas located on the Lake Louise Ski Resort. Yellowhead Helicopters (Valemount, B.C.) and Canadian Mountain Holidays (Bugaboo Lodge, B.C.) provided safe and efficient helicopter support to remote field areas.

The exceptional exposure of the WSG in the southern Canadian Cordillera makes it one of the premier outcrop analogues in the world for understanding current offshore, deep-water petroleum exploration, development and production. This thesis forms part of a larger research initiative, the Windermere Consortium project initiated in 2001 by Dr. R. W. (Bill) C. Arnott of the University of Ottawa and Dr. Gerald M. Ross (formerly of the GSC) and is funded jointly by the Natural Sciences and Engineering Research Council of Canada (NSERC) and its industry partners during the period of this thesis (Anadarko Petroleum, Canadian Natural Resources Ltd., Devon Canada Ltd., Encana Corp., Husky Energy Corp., Nexen Inc. and Shell Exploration and Production). Additional funding to MDS was provided by the University of Ottawa Ph.D. scholarship, an Ontario Graduate Scholarship (OGS), a R. Dana Russell Memorial American Association of Petroleum Geologists (AAPG) Grant-in-aid, an unnamed AAPG Grant-in-aid, a Canadian Society of Petroleum Geologists (CSPG) Regional Graduate Scholarship, and travel grants from the Geological Society of America (GSA), Canadian Federation of Earth Scientists (CFES) and University of Ottawa (2).

CHAPTER 2: The Old Fort Point Formation: proposed stratigraphic formalization of a distinctive marker horizon and its three constituent members, Neoproterozoic Windermere Supergroup, southern Canadian Cordillera.

2.1 INTRODUCTION

The Old Fort Point Formation (OFP) is a key marker horizon within the Neoproterozoic Windermere Supergroup (WSG), a thick succession of sedimentary rocks of predominantly deep-water character. It consists of three distinctive, siliciclastic and carbonate stratigraphic units, which are locally exposed over an area of 35,000 km² of Alberta and British Columbia, western Canada. These units and their stratigraphic relationship are unique when compared to both fine- and coarse-grained facies in much of the rest of the WSG in the southern Canadian Cordillera. Depending on the author and location of research, these strata were referred to by a variety of names including: basal Hector Formation, Mount Temple and Taylor Lake Members, Old Fort Point Formation, “the Marker” in the Kaza Group, Middle Miette Marker, Baird Brook Division, Comedy Creek unit, upper and lower Markers. This led to the development of an informal stratigraphic framework for each site with proposed basin-wide correlations. As expected, this has created a rather complex and cumbersome stratigraphic nomenclature, commonly of only local applicability.

This marker is arguably the most important stratigraphic unit in the WSG of the southern Canadian Cordillera and we propose that this lithostratigraphic unit be formally termed the Old Fort Point Formation and that use of other informal names be discontinued. We also propose three new lithostratigraphic members for the OFP: Temple Lake Member (lower), Geikie Siding Member (middle) and Whitehorn

Mountain Member (upper). The formal recognition of the OFP and its three constituent members in accordance with the North American Stratigraphic Code (NASCN, 2005) will begin the process of clarifying the complex stratigraphic nomenclature currently found in the literature. It is considered appropriate to introduce this nomenclature now, as a century of fragmented research on this unit has been conducted since it was first described by C. D. Walcott in 1910.

2.2 REGIONAL GEOLOGICAL SETTING

In the southern Canadian Cordillera, the Neoproterozoic WSG is a thick (~9 km), continental margin sedimentary succession exposed in a series of thrust panels in the Main Ranges of the western fold-and-thrust belt and the Omineca belt (Fig. 2.1). In this region, it is composed primarily of deep-marine siliciclastic sandstone and mudstone with subordinate carbonate and mafic volcanic rocks. The WSG generally is interpreted to have accumulated in two stages: the first stage was relatively synchronous with rifting during the break-up of the supercontinent Rodinia and the second stage during thermal relaxation with related stretching and subsidence (Stewart, 1972; Ross, 1991; Ross et al., 1995; Dalrymple and Narbonne, 1996). A key element of the post-rift phase is the widespread depositional setting of the Windermere turbidite system, on a scale comparable to many moderate-sized modern turbidite fans (e.g. Barnes and Normark, 1985). Within the stratal monotony of the turbidite system is the distinctive OFP, the lowest regional marker and timeline that has aided regional correlations across the southern Canadian Cordillera (e.g. Ross and Murphy 1988). The OFP is recognized by its distinctive colours and lithologies, and is sandwiched within a thick succession of WSG coarse- and fine-grained turbidites. More complete reviews of the WSG geological background, including tectonic models and the stratigraphic framework have been published elsewhere (e.g. Ross et al., 1989, 1995; Ross, 1991; Colpron et al., 2002; Ross and Arnott, 2007).

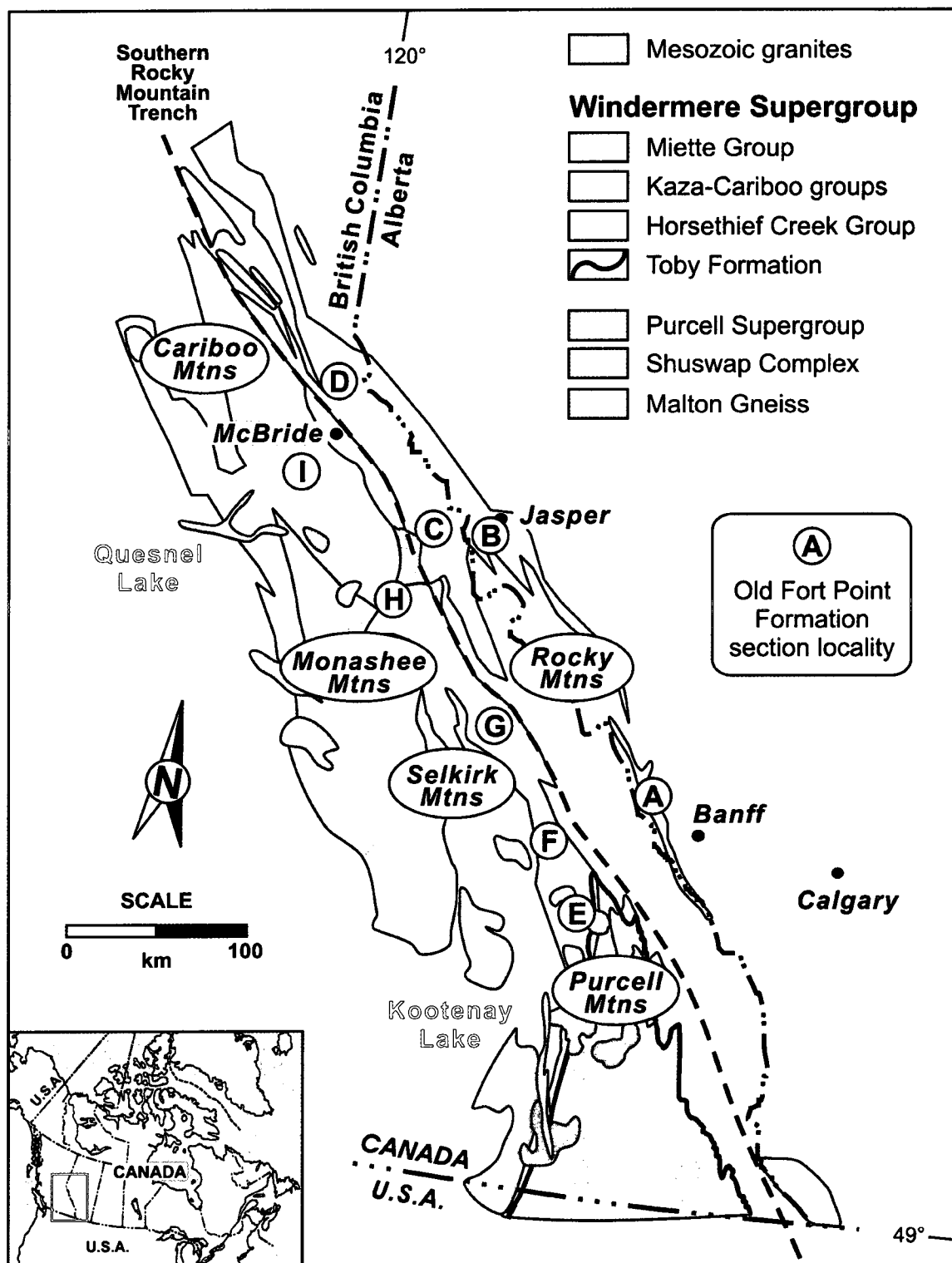


Figure 2.1: Simplified geological map of the WSG, southern Canadian Cordillera showing prominent outcrop localities of the OFP and correlatives (modified from Ross and Murphy, 1988). (Localities: A - Lake Louise; B - Jasper National Park; C - Mount Robson Provincial Park; D - McKale River; E - Frances Creek; F - Dogtooth Range; G - Monashee Mtns.; H - Selkirk Mtns.; I - Cariboo Mtns.).

2.3 STRATIGRAPHIC CORRELATIONS

Regional and local stratigraphic correlations within the WSG have proven a challenge because of: the lack of biostratigraphic control in these Precambrian sedimentary rocks; the deep-marine depositional environment producing lithologically similar, regionally extensive coarse-grained siliciclastic facies; general absence of chemical sedimentary markers; structural complexity related to the Cordilleran orogen; and the overall paucity of suitable material within the succession for conventional radiometric isotopic dating (Ross et al., 1989, 1995). These uncertainties have resulted in a complex and commonly confusing stratigraphic nomenclature for not only strata of the OFP, but the entire WSG (Fig. 2.2 and references in caption). However, this does not imply that previous authors were unaware of the potential regional correlations or significant marker horizons. Many early authors proposed regional or local correlations (e.g. Walker, 1926; Gussow, 1957; Reesor, 1957; Aitken, 1969), but because of the lack of detailed sedimentologic work or regional stratigraphic control, site-specific names were maintained in most cases (e.g. Evans, 1933; Mountjoy, 1962) until more robust correlations could be made.

2.4 HISTORICAL BACKGROUND

The first report of lithologies consistent with the OFP was by Walcott (1910) from his work in the Lake Louise area (Fig. 2.1: A). Walcott (1910) identified two Precambrian units, the Corral Creek (lower conglomerate-sandstone) and Hector (upper slate) formations that were unlike the overlying, cliff-forming quartz arenites of the Cambrian. The division of these two formations over the study area was made possible by a distinctive purple/green slate, limestone and limestone-bearing conglomerate unit that marked the base of the Hector Formation (Walcott, 1910).

COLUMBIA MOUNTAINS				ROCKY MOUNTAINS			
CARIBOO MOUNTAINS ¹	SELKIRK MOUNTAINS ²	PURCELL MOUNTAINS ³	SELWYN AND MAIN RANGES ⁴	JASPER ⁵	LAKE LOUISE ⁶		
Yankee Belle Fm.	Horsechief Group	Horsechief Group	Miette Group	Miette Group	Miette Group		
Cunningham Fm.							
Isaac Formation							
Kaza Group	Upper	Upper Pelite Unit	Upper Clastic Div.	Upper Miette (East Twin Fm.)	Upper Wynd Formation		
	'Marker'	Central Clastic Unit	Carbonate Div.	Middle Miette (McKale Fm.)	Lower Wynd Formation		
	Middle	Comedy Ck. Unit	Slate Division	MMM/OFP	Old Fort Point Fm.		
Lower	Basal Pelite Division	Lower Grit Division	Middle Miette (McKale Fm.)	Meadow Creek Formation			
Middle Marble Unit	Mid-Marble Unit	Basal Pelite Division & Carbonate Unit	Lower Miette (Cushing Ck. Fm.)				
Semipelite Amphibolite Unit	Semipelite Amphibolite Unit	Irene Formation					
Lower Pelite Unit	Pelite Unit	Toby Formation					

Figure 2.2: Stratigraphic nomenclature of the WSG, southern Canadian Cordillera. Sources of information include: 1) Campbell et al. (1973), Ferguson (1994), Ross and Ferguson (2003a, 2003b); 2) Grasby and Brown, 1993; 3) Kubli (1990), Kubli and Mountjoy (1992, 1994), Warren (1996, 1997); 4) McDonough (1989, 1994), McMechan and Hein (1989); 5) Charlesworth and Remington (1961), Charlesworth et al. (1967); 6) Walcott (1910), Gussow (1956, 1957), Aitken (1969).

These distinctive lithofacies were recognized at a number of locations in the Lake Louise area, but were not recognized as a separate, new formation. He also interpreted the Precambrian-Cambrian contact as an angular unconformity, but incorrectly placed it at the base of immature conglomerates, shown later to be Neoproterozoic in age (Aitken, 1969).

Gussow (1956, 1957) was the next to conduct work on Precambrian rocks in the Lake Louise area. He simplified the stratigraphy to the Hector Formation (Gussow, 1957), but then subdivided it into four informal members: 1) basal Corral Creek Member (coarse-grained Corral Creek Formation of Walcott, 1910); 2) Taylor Lake Member (purple argillites or shales); 3) Mount Temple Member (rhythmic bedded limestones); and 4) an unnamed upper member. He was the first to recognize (or at least document) the significance of the Mount Temple member as a marker horizon in the Lake Louise area and assign stratigraphic names to OFP lithologies (Taylor Lake and Mount Temple members), but these were not properly defined, being published in a conference fieldtrip guidebook (Gussow, 1957).

During the first half of the 20th century, additional reconnaissance mapping was carried out in a number of other regions in the southern Canadian Cordillera of Alberta and British Columbia. Walcott (1913) extended his work further north into the Mount Robson area of British Columbia and defined the Precambrian Miette Formation (now Miette Group) from that area. Subsequently, Allan et al. (1932) followed this up with a study of the rocks in the Jasper Park area and described units lithologically similar to the OFP, but incorrectly placed them in overlying Jasper series, according to Charlesworth et al. (1961). Further south, in the Purcell Mountains, Walker (1926) defined the Windermere Series, now Windermere Supergroup, and divided it up into the Toby Formation, comprising coarse conglomerate and diamictite, and the Horsethief Formation, made up of sandstone and fine-grained slate (subsequently changed by Evans (1933) to the Horsethief Creek Formation). Both authors mention purple slates lithologically consistent with the OFP (Walker, 1926: p. 14; Evans, 1933: p. 117), but no specific sub-divisions or

discussion of its stratigraphic significance were noted. Both Walker (1926) and Evans (1933) suggested correlation of the Horsethief Creek Formation within the Purcell Mountains, with the Hector and Corral Creek formations in the Lake Louise area. Later work of Reesor (1957) took it yet another step by correlating strata of the Horsethief Creek series (later renamed to Horsethief Creek Group), Hector and Corral Creek formations with those of the Miette Formation in the Mount Robson area.

Henry Charlesworth and graduate students from the University of Alberta carried out the first detailed structural and stratigraphic mapping of the Precambrian Miette Group within Jasper National Park (Fig. 2.1: B) (Charlesworth et al., 1967). The name Old Fort Point Formation was first informally defined in a fieldtrip guidebook (Charlesworth and Remington, 1960) to describe a unit consisting of phyllite, limestone, limestone breccia and conglomerate that were easily distinguishable from other Miette Formation (Walcott, 1913) stratigraphic units. The name “Old Fort Point” comes from a prominent local landmark south of the Jasper townsite where accessible exposures of the unit are located (Fig. 2.3B). Evans (1961) mapped the OFP at the Old Fort Point landmark and divided it into four informal members each with a type section at this location. Based on lithological similarities, it was recognized that the Miette Formation (later changed to Miette Group) was correlative with the Corral Creek and Hector formations, and that the basal part of the Hector Formation (Walcott, 1910) was potentially correlative with the OFP (Evans, 1961; Charlesworth et al., 1961). Weiner (1966) followed-up on this work with a more regional structural study within Jasper National Park, which included mapping and correlating the OFP using the previously defined units of Evans (1961). Compilation and formal definition of the OFP, including proposed regional correlations between Jasper, Lake Louise and southern British Columbia, were first published in Charlesworth et al. (1967). Aitken (1969) was the first to unequivocally correlate the OFP of the Jasper area (Charlesworth et al. 1967) with Walcott’s distinctive basal unit of the Hector

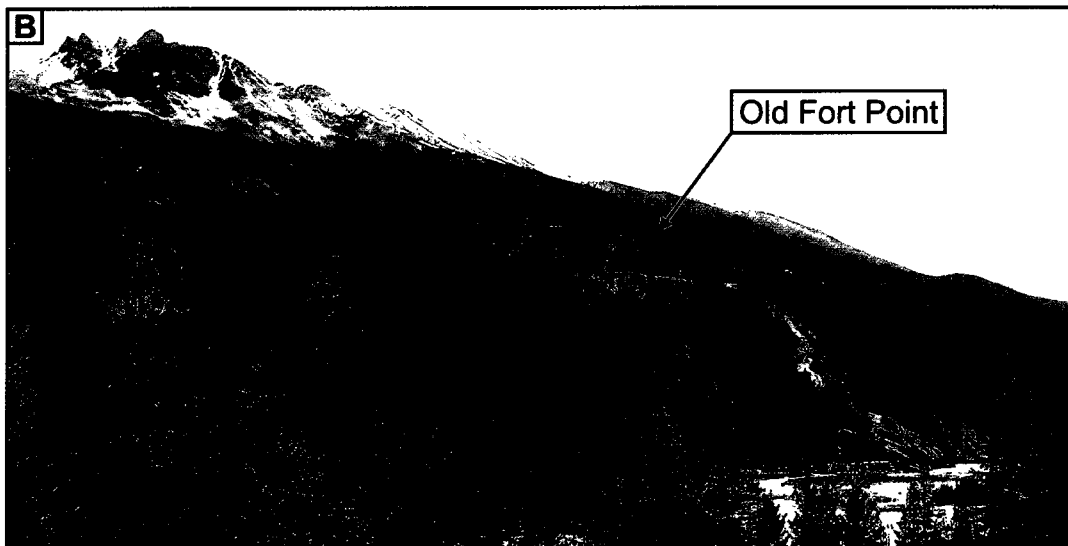
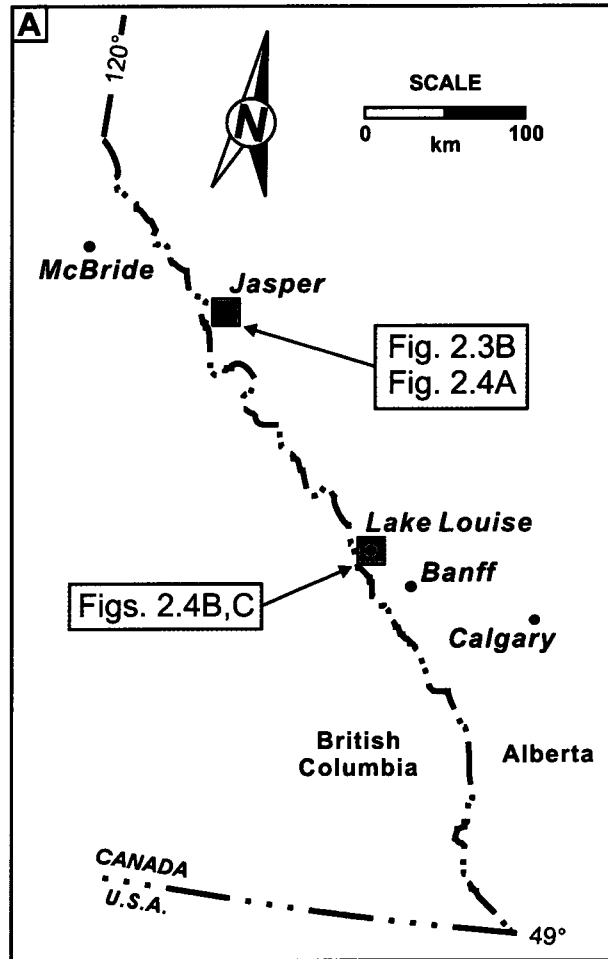


Figure 2.3: A) Location map of key stratigraphic sections. B) OFP Type locality, Old Fort Point Landmark, Jasper National Park.

Formation in the Lake Louise area. He also repositioned the location of the Precambrian-Cambrian contact stratigraphically higher than that of Walcott (1910) and recognized that the prominent “angular” nature of Walcott’s contact was in fact a significant Precambrian erosion surface. Aitken (1969) recognized a major (angular) unconformity at the base of the Cambrian and was the first to document the magnitude of erosion along this regional surface.

Subsequent regional mapping in the Cariboo Mountains (Campbell et al., 1973), Purcell Mountains (Reesor, 1973) and Rocky Mountains (Mountjoy, 1962, 1971; Mountjoy and Price, 1980; Price et al., 1980a, 1980b) focused on the general stratigraphic and structural context in these areas rather than any one specific formation. No detailed documentation of the OFP was recorded, however similar to the early reconnaissance mapping, lithologies consistent with the OFP were noted in the Purcell Mountains (Reesor, 1973; p. 29, 31-32) and the Rocky Mountains (Mountjoy, 1962; p. 5). A geological map (1:50,000-scale) of the Lake Louise area (Price et al., 1980a) also shows a “position of change in facies (approximate)” between the Corral Creek and Hector formations of the Miette Group based on the work of Walcott (1910) and Aitken (1969), and represents the stratigraphic position of the OFP.

The recognition of a consistent, probably correlative, fine-grained triad of lithologies (siltstone, limestone-siltstone, organic-rich mudstone) that cropped out across the southern Canadian Cordillera was noted by a number of workers in the early 1980s:

- 1) P.S. Simony and graduate students from the University of Calgary (Calgary, Alberta): Monashee and Cariboo Mountains (Pell, 1984; Pell and Simony, 1981, 1982, 1984, 1987) (Fig. 2.1: H); Cushing Creek and McKale River areas, Rocky Mountains (Carey, 1984; Carey and Simony, 1985 (Fig. 2.1: D), Mount Robson Provincial Park area and Selwyn Range, Rocky Mountains (McDonough and Simony, 1988; McDonough, 1989) (Fig. 2.1: C), and

- Dogtooth Range, Purcell Mountains (Kubli, 1986, 1990; Kubli and Simony, 1992, 1994) (Fig. 2.1: F).
- 2) E.W. Mountjoy and graduate students from McGill University (Montréal, Québec): Park and Selwyn Ranges, Rocky Mountains (Forest, 1985; Klein and Mountjoy, 1988; Deschesne, 1990a; Deschesne and Mountjoy, 1990; Mountjoy and Grasby, 1990; Grasby, 1991) (Fig. 2.1: C), and Jasper National Park, Rocky Mountains (Deschesne, 1989, 1990b) (Fig. 2.1: B).
 - 3) Others projects include D.C. Murphy from Carleton University (Ottawa, Ontario), Cariboo Mountains (Murphy and Rees, 1983; Murphy, 1986, 1987) (Fig. 2.1: H), S.E. Grasby, Selkirk Mountains (Grasby and Brown, 1993) (Fig. 2.1: G) and M.J. Warren from Queen's University (Kingston, Ontario), Purcell Mountains (Warren, 1996, 1997) (Fig. 2.1: E).

These projects were focused primarily on unraveling the structural complexity in their respective areas which resulted in a number of location-specific, informal names for the OFP including: Old Fort Point Formation, Jasper National Park (e.g. Deschesne, 1989; 1990a) and Selwyn Range (McDonough, 1989; Deschesne, 1990b); Kaza Group "Marker", Cariboo Mountains (Murphy, 1987; Ross and Thomson, 1990); Baird Brook Division, Dogtooth Range (Kubli, 1990; Kubli and Simony, 1992, 1994) Comedy Creek unit, Selkirk Mountains (Grasby and Brown, 1993); and upper and lower Markers, Purcell Mountains (Warren, 1996, 1997).

At the same time, mapping by G. M. Ross from the Geological Survey of Canada (GSC) examined the Windermere succession from a sedimentological perspective and recognized the stratigraphic significance of this distinctive marker horizon in the Cariboo Mountains and correlated it with other regions in the southern Canadian Cordillera (Ross and Murphy, 1988). Although the name "Old Fort Point Formation" was utilized in subsequent maps and publications from the Selwyn Range (McDonough, 1994), Cariboo Mountains (Ross et al., 1995; Ross, 2000; Ross and Ferguson, 2003a, 2003b) and Jasper National Park (Kendall et al., 2004),

alternative names can still be found in the literature (e.g. Kubli and Simony, 1992, 1994; Grasby and Brown, 1993; Warren, 1996, 1997).

2.5 PROPOSED FORMAL DEFINITION OF THE OLD FORT POINT FORMATION AND ITS THREE MEMBERS

2.5.1 Justification for name: Old Fort Point Formation

The OFP is a unique lithostratigraphic unit in the WSG and has been recognized by many authors in many different areas of the southern Canadian Cordillera. This has led to a proliferation of informal names for the succession and its correlative stratal units (e.g. Aitken, 1969; Ross and Murphy, 1988; McDonough, 1989; Kubli 1990; Ross and Ferguson, 2003a, 2003b). It has been known for some time that it comprises three distinctive members that have a consistent stratal relationship, are correlatable and mappable on a regional scale, and can be easily distinguished from encompassing WSG strata. Despite these characteristics, no previous attempt has been made to formalize the nomenclature for this important basin-wide unit beyond the boundaries of a local study (e.g. Gussow, 1957; Charlesworth et al., 1967; Kubli, 1990; Grasby and Brown, 1993). Given the significance of the unit, it is important to properly formalize the stratigraphic nomenclature of OFP across the southern Canadian Cordillera and propose that use of other informal, generally site-specific designations be discontinued.

Although Walcott (1910) was the first to describe lithologies within the OFP, they were included in the basal portion of the Hector Formation and not specified as a separate unit. Gussow (1957) was the first to assign names to OFP lithologies (Taylor Lake and Mount Temple members), but these were not properly defined and were published in a conference fieldtrip guidebook. The name “Old Fort Point Formation” was the first informal (Charlesworth and Remington, 1960; Evans, 1961; Weiner, 1966) and formal (Charlesworth et al., 1967) designation for this recognizable geological unit. Unfortunately, there are two important stratigraphic

problems with these earlier works. Firstly, the type locality is not representative of the full OFP succession. Here, only strata of the upper member are present, and the more regionally extensive lower two members and their recognizable stratal stacking pattern that permits basin-wide correlation is not exposed (e.g. Ross and Murphy, 1988). Secondly, in some cases correlation of OFP strata within the Jasper area were incorrect (e.g. limestone-siltstone rhythmite of the lower Temple Lake Member correlated with limestone-clast breccia of the Whitehorn Mountain Member).

Despite these two issues, we propose that the name “Old Fort Point Formation” be retained and simply undergo a revision in definition to receive proper designation as outlined by the recently amended stratigraphic code (NACSN, 2005). The name “Old Fort Point Formation” is well established and has already been used by a number of authors in mapping and publications (e.g. McDonough, 1994; Ross et al., 1995; Ross and Ferguson, 2003a; Smith et al., 2005, 2007a, 2007b). Formal abandonment and renaming the formation would run contrary to the concept of this paper, which is to simplify the stratigraphy and avoid confusion for potential new researchers and readers. The name “Old Fort Point Formation” is the preferred name because it has historical priority and is more widely used than any of the many location-specific names. Based on previous studies and more recent detailed work, we also propose three new lithostratigraphic members for the OFP, which stratigraphically upward are: Temple Lake Member (TLM), Geikie Siding Member (GSM) and Whitehorn Mountain Member (WMM). These names are based on geographical locations where well-exposed, representative sections can be easily observed and for the most part do not duplicate names already in the literature (Table 1; Figs. 2.3 and 2.4).

Lct.	Regional Area	Section Name	Easting	Northing	Section Description
<u>Alberta</u>					
A	Lake Louise	Temple Lake	557379	5690015	<i>Unit Stratotype:</i> Temple Lake Member
		Upper Boomerang	559666	5702403	<i>Unit Stratotype:</i> Whitehorn Mountain Member
B	Jasper National Park	Old Fort Point Landmark	428577	5858240	<i>Type Locality:</i> Old Fort Point Formation
		Geikie Siding	412974	5858644	<i>Principal Reference Section:</i> Old Fort Point Formation <i>Unit Stratotype:</i> Geikie Siding Member
<u>British Columbia</u>					
C	Mount Robson Provincial Park	Vista Glacier	400911	5847859	Reference Section
D	McKale River	McKale River	692091	5929423	Reference Section
E	Purcell Mountains	Frances Creek	525658	5613170	Reference Section
I	Cariboo Mountains	Eagle Valley	678846	5887412	Reference Section

Notes: Location letters refer to Figure 2.1. UTM coordinates in grid system NAD27.
Locations A, B, C, E and F are in Zone 11; locations D and I are in Zone 10.

Table 2.1: Section locations of the Old Fort Point Formation and its three members.

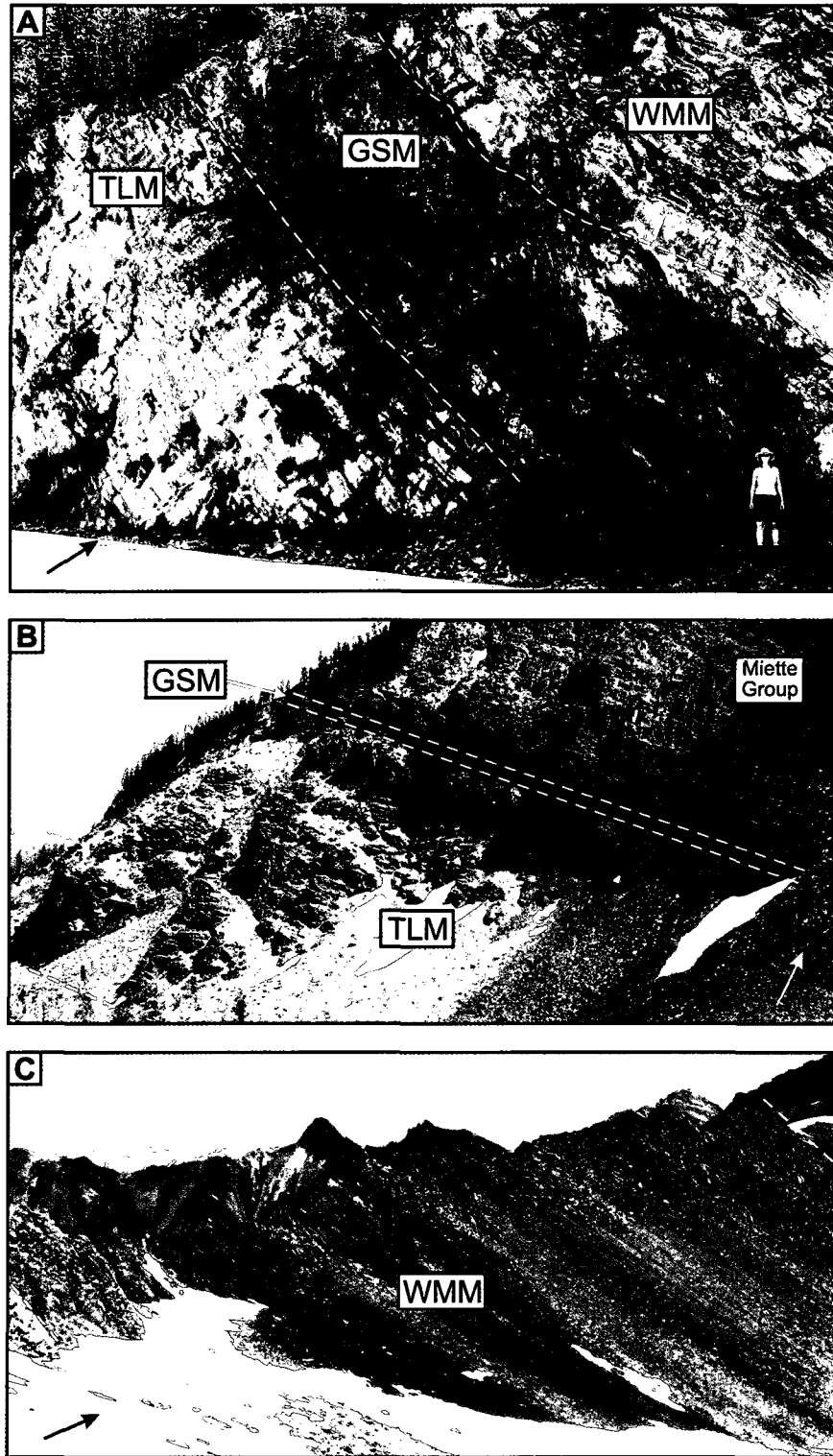


Figure 2.4: A) OFP principal reference section and GSM unit stratotype, Geikie Siding outcrop, Jasper National Park. B) TLM unit stratotype, near Temple Lake, Lake Louise. Note WMM is thinly (<0.5 m) developed here and difficult to distinguish from underlying GSM or overlying fine-grained Miette Group. C) WMM unit stratotype, "Upper Boomerang (#64) Ski Run, Lake Louise Ski Resort.

2.5.2 Designation of category and rank of units, selection and derivation of name, specification of principal reference section and stratotypes

2.5.2.1 Old Fort Point Formation

The Old Fort Point Formation is proposed to define the three-fold lithological unit that is unique to the stratigraphic succession of the Neoproterozoic WSG, southern Canadian Cordillera. The OFP possesses distinctive lithological characteristics, is sufficiently thick to be mapped on a regional scale, and represents a distinctive stratigraphic horizon within Windermere strata (e.g. Price et al., 1980a, 1980b; McDonough, 1994; Kubli, 1990; Ross and Ferguson, 2003a, 2003b, 2003c). The combination of these features warrants its formal definition as a formation in the WSG. The type locality for the OFP is a prominent landmark (Fig 2.3B) located <1 km southeast of Jasper, Alberta where strata of the OFP crop out (Charlesworth and Remington, 1960; Charlesworth et al., 1967).

The new principal reference section of the OFP, however is proposed to be the Geikie Siding roadcut outcrop located along Highway 16, approximately 15 km west of Jasper, Alberta (UTM NAD27: 412974E 5858644N) (Table 1; Fig. 2.4A). The selection of this site as the principal reference section is based on a number of factors: it is well exposed, easily accessible, close to the previously defined type locality (Charlesworth and Remington, 1960; Charlesworth et al., 1967), the recent Re-Os isochron age (607.8 ± 4.7 Ma) is from this locality (Kendall et al., 2004), and representative strata of all three members crop out. Despite its suitability as a principal reference section, there are two drawbacks for its selection. The first is that the roadcut is in the core of the Meadow Creek Anticlinorium and neither the top nor bottom contact of the OFP are exposed (although the base is exposed nearby in the same structure and described by Charlesworth et al., 1961, 1967; Weiner, 1966). The second issue is that the outcrop does not illustrate basin-floor facies (especially the WMM) of the OFP that are further west in the Cariboo Mountains, British Columbia. To illustrate the lithological variability within the OFP, especially in the WMM, a number of supplementary reference sections representing

deposition on different parts of a basin-slope to basin-floor transect are also designated (Table 1). Simplified descriptions and a composite OFP stratigraphic section are supplied in Fig. 2.5 with more detailed sedimentologic and stratigraphic description and interpretation in the companion paper (Chapter 3). Similar to the OFP, type sections of its three component members were selected based on the criteria of good exposure, representative lithological sections and ease of access. Their assigned names, for the most part, do not duplicate pre-existing names in the literature.

2.5.2.2 Temple Lake Member

The Temple Lake Member (TLM) is introduced to describe the variably coloured (purple, green, red-brown, grey) fine-grained, siltstone to mudstone, rare sandstone and rhythmic limestone-siltstone couplets of the lower OFP. The name of the member comes from an exceptional exposure near Temple Lake on the northeastern slope of Mount Temple, Lake Louise area where the unit stratotype is designated (Table 1; Fig. 2.4B). The type section for the TLM is specified as: UTM, NAD27: 557379E 5690015N; approximately 0.5 km east of Temple Lake, on the northeastern slope of Mount Temple, 6 km south from the village of Lake Louise, Alberta. The outcrop is accessed from Moraine Lake Road where 5 km along, a poorly defined trail leads to Temple Lake approximately 1.5 km west.

2.5.2.3 Geikie Siding Member

The Geikie Siding Member (GSM) is introduced to describe the light grey to dark grey, fine-grained mudstone (shale and pelite) unit with rare beds of dark-grey limestone and fine-grained sandstone of the middle OFP. The name of the member comes from the railway marker Geikie Siding, located along Highway 16, approximately 15 km west Jasper, located near the roadcut where the unit stratotype crops out (Table 1; Fig. 2.4A). The type section for the GSM is specified as: UTM, NAD27: 412974E 5858644N; located along Highway 16, between Clairvaux

and Meadow creeks, approximately 15 km west from the townsite of Jasper, Alberta. The roadcut is on the south side of the highway, which also is the proposed new principal reference section for the OFP.

2.5.2.4 Whitehorn Mountain Member

The Whitehorn Mountain Member (WMM) is introduced to describe lithologically diverse strata in the upper part of the OFP. It is composed of diamictite, breccia to conglomerate, sandstone, quartz arenite, calcareous arenite, arenaceous limestone, limestone and mudstone to siltstone. The name of the member comes from Whitehorn Mountain on the Lake Louise Ski Resort. Approximately 0.5 km downslope from the peak on the “Upper Boomerang” Ski Run (#64), the type section is located and specified as: UTM, NAD27: 559666E 5702403N (Table 1; Fig. 2.4C). The narrow, cliff-face outcrop can be accessed in two ways from the base of the Lake Louise Ski Resort. The first is by taking the gondola half-way up the front face (south slope) to the Whitehorn Day Lodge followed by a strenuous 2.5 km hike to the top of Whitehorn Mountain. The second is a ~4 km drive along the Temple Fire Road (access use permit required) to the Temple Day Lodge and then a ~3.5 km hike through the back bowl area. To demonstrate the range of lithological heterogeneity (basin-slope to basin-floor depositional environments) for the WMM, a composite-stratotype consisting of a type section and a suite of supplementary reference sections is proposed. Supplementary reference sections for the WMM include: McKale River area, ~20 km north of the town of McBride, British Columbia; Eagle Valley, ~24 km southwest of McBride, British Columbia; and Frances Creek area, ~30 km west of Brisco, British Columbia. Specific UTM locations are presented in Table 1.

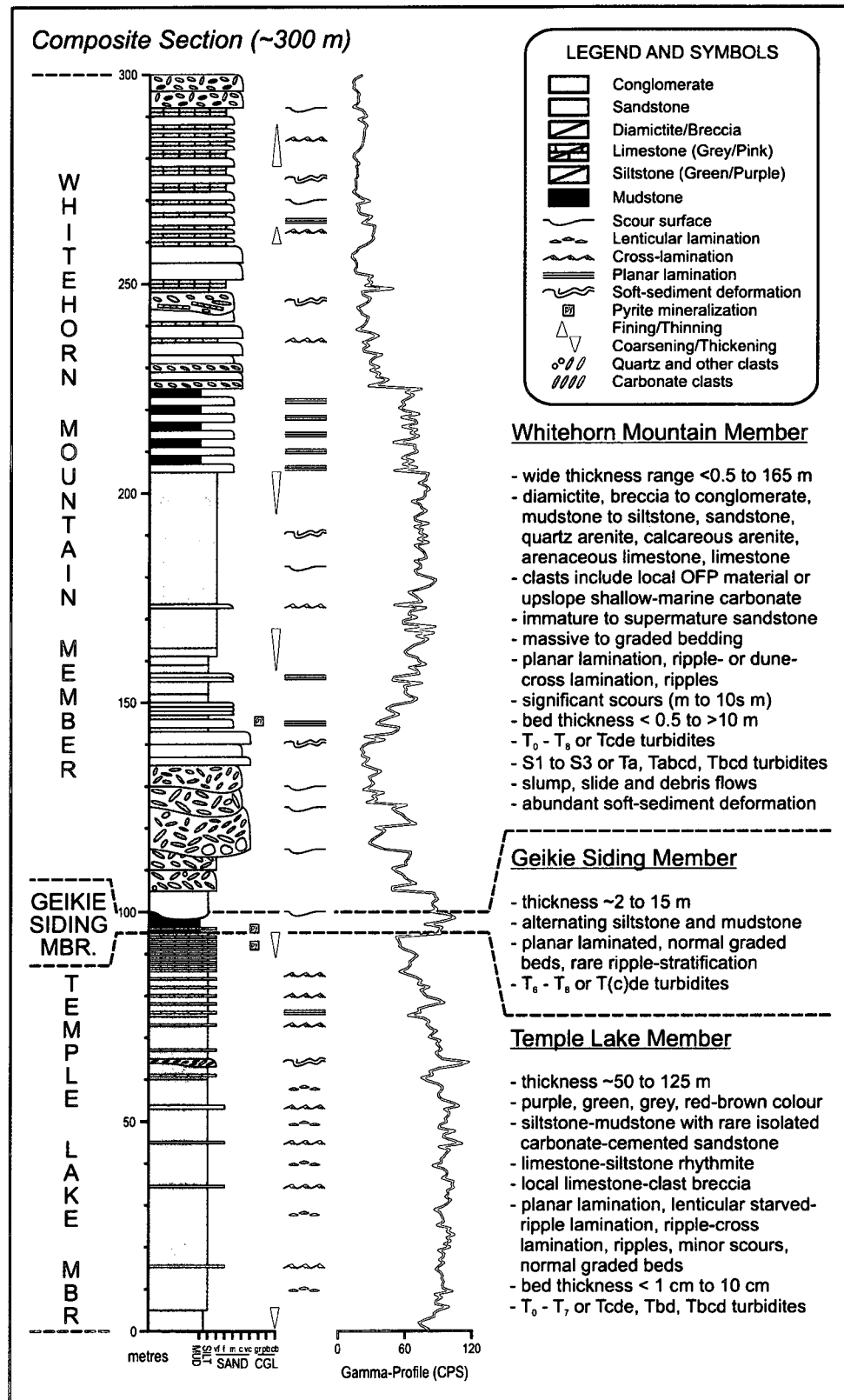


Figure 2.5: Schematic stratigraphic section of the OFF and its three members illustrating main lithofacies and sedimentary features present.

2.5.3 Description of lithologic units

2.5.3.1 *Old Fort Point Formation*

The OFP comprises three distinctive lithological members that have a consistent stratigraphic relationship and are correlatable over 35,000 km² of Alberta and British Columbia, western Canada. These stratal units and their relationship are unique when compared to other basin-slope and basin-floor facies typical of the WSG, southern Canadian Cordillera. The three members that can be recognized are: the lower Temple Lake Member, the middle Geikie Siding Member, and the upper Whitehorn Mountain Member. Complete facies descriptions and detailed stratigraphic logs of the OFP and its members are presented in the complementary paper (Chapter 3) with only a general summary provided below and a composite stratigraphic section (Fig. 2.5).

2.5.3.2 *Temple Lake Member*

The TLM is fairly consistent in thickness (usually 50 to 125 m) and consists primarily of fine-grained siltstone to mudstone with isolated, carbonate-cemented sandstone beds that grade upward into rhythmic limestone-siltstone couplets. A distinctive feature is its variably coloured nature (e.g. purple, green, red-brown) that differentiates the TLM from the generally grey-coloured, fine-grained units of the WSG. Sedimentary structures include: planar lamination, lenticular starved-ripple lamination, ripple cross-lamination, minor scours and normal graded beds. Bed thickness typically ranges from <1 cm to 10 cm, and depending on grain size, beds are interpreted as either T₀ to T₇ (Stow and Shanmugam, 1980) or T_{cde}, T_{bd} or T_{bcd} (Bouma, 1962) turbidites. Subordinate lithofacies in the TLM include uncommon limestone-clast breccia horizons interpreted as slump, slide or debris flow deposits (e.g. Lake Louise area) and at one locality (Frances Creek, Fig. 2.1: E), fine- to medium-grained thick-bedded massive sandstone interpreted to be T_a turbidites (Bouma, 1962). Sedimentologic and stratigraphic features of this member are fairly consistent despite its widespread basin-slope to basin-floor deposition.

The primary regional difference is a change in colour along a slope to basin-floor transect, including: purple to green, green to red-brown, and green to grey. Other minor differences include thinner, less frequent limestone beds in basinal facies (Cariboo Mountains, Fig. 1: H) and thicker, more frequent sandstone beds at some localities (e.g. Purcell Mountains, Fig. 2.1: E).

2.5.3.2 Geikie Siding Member

The GSM is a dark-grey coloured, organic-rich mudstone-pelite that usually is 2 to 15 m thick. Where discernible, strata are laminated with alternating siltstone and mudstone layers that are subtly normal graded implying traction and suspension deposition from dilute sediment-gravity flows (T_6 to T_8 or T_{de}). Isolated, thin-bedded, dark-grey, massive or parallel planar laminated limestone and very-fine, ripple cross-stratified (T_c) sandstone are rarely present. Regionally, the GSM is lithologically uniform across the Windermere basin, and is usually considered the fine-grained mudstone-pelite cap in the lithologic triad of the OFP (Ross and Murphy, 1988; Kendall et al., 2004). Although the fine-grained and fissile character of this unit typically results in poor or covered exposures, notable exceptions are the type section roadcut near Jasper, Alberta and fresh periglacial exposures in the Cariboo Mountains, British Columbia.

2.5.3.3 Whitehorn Mountain Member

Lithologically, the WMM is the most complex of the members of the OFP. Unlike the TLM and GSM, it consists of a diverse assemblage of lithofacies, which commonly are location-specific (Fig. 2.5). Moreover, sections interpreted to have deposited on the paleo-slope or proximal basin-floor tend to be variable in their thickness (<0.5 to 165 m) even over relatively short distances, and contrast the more uniform character of distal basin-floor deposits. Although the lithofacies are diverse within the WMM, they mainly differ from lithofacies consistent with the encompassing WSG strata (e.g. immature arkose turbidites) and can be identified in

outcrop. Lithofacies include diamictite, breccia to conglomerate, mudstone to siltstone, sandstone, quartz arenite, calcareous arenite, arenaceous limestone and limestone. Diamictite and breccia to conglomerate, which are interpreted to be debris flow deposits, are characterized by massive beds with sharp, usually erosional basal contacts and a matrix composed of mudstone to siltstone or well-sorted, coarse-grained quartz-sandstone. Bed thickness (<0.5 to >10 m) and clast-size (cm to m) are variable with clasts composed of material eroded locally from the OFP, or carbonates eroded from a shallow-marine platform and remobilized into deep-water. Mudstone-siltstone (Fig. 4A) consists of medium-laminated turbidites (T₀ to T₈ or T_{cde}) with structures that include parallel-planar lamination, micro-scours, subtle normal grading, single chlorite flakes and rare scours. These strata are up to ~100 m thick and comprise a monotonous fine-grained succession interrupted rarely by interbeds of diamictite, breccia to conglomerate or sandstone. Sandstone shows a variety of textures (fine to very coarse-grained, poor- to well-sorted) and maturity (immature to supermature), but sedimentary structures are fairly uniform with turbidite beds either massive or weakly graded (T_a), planar stratified (T_b), dune (T_c) or ripple cross-stratified (T_c). The well-sorted, mature quartz arenites are interbedded with dark, organic-rich limestone beds. These two end-member lithologies commonly exhibit a range of compositions (e.g. calcareous arenites or arenaceous limestones). Soft-sediment deformation features are common in both fine- and coarse-grained facies, including load structures, convolute or contorted bedding and ductile folding.

2.5.4 Definition of boundaries

Stratigraphically, the OFP is a distinctive, generally fine-grained marker unit that breaks up a monotonous pile of immature, fine- and coarse-grained siliciclastic strata, irrespective of position within the Windermere paleo-basin. The nomenclature of the strata that the OFP divides varies depending on geographic location (Figs. 2.1 and 2.2.): east of the Rocky Mountain Trench, in the Rocky

Mountain Main Ranges and Selwyn Range, Middle Miette Group; west of the Rocky Mountain Trench in the Purcell and Monashee Mountains, the Lower Grit and Upper Grit Divisions of the Horsethief Creek Group; and west of the Rocky Mountain Trench, Cariboo Mountains, the Middle and Upper Kaza Groups. In many sections, contacts between the OFP and the enveloping WSG strata are sharp and easily recognized where there is a significant change in grain size (e.g. fine-grained OFP strata bounded above and below by the coarse “grit” units) or mineralogical composition (e.g. WMM quartz arenite overlain by WSG immature arkose). Although the distinctive colour change in the basal TLM provides an easily recognizable contact with the underlying WSG, these fine-grained facies contacts are usually gradational in nature, but over an interval of less than 0.5 m thick.

The contact between the TLM and the GSM is consistently gradational, and in most outcrops is a recognizable transition zone <0.5 to 2 m thick. The transition is marked by upward-fining, a decrease in limestone bed frequency, and geochemical changes (e.g. Ross et al., 1995; Chapter 4). The basal contact between the WMM and the underlying units is usually sharp and locally can be deeply scoured, removing part, and in some places all of the older GSM and TLM. In sections where the GSM and TLM are completely eroded, the WMM overlies directly strata of the underlying WSG. Where the WMM is thin (<0.5 m), fine-grained and overlain directly by mudstones of the WSG, contacts between the GSM – WMM – WSG are extremely difficult to recognize in outcrop and may require the use of other techniques (e.g. gamma ray or geochemistry) to identify its location (Chapter 4).

2.5.5 Dimensions and regional correlations

The OFP is a recognizable, widespread unit that is locally exposed over an area of 35,000 km² of the southern Canadian Cordillera (Fig. 2.1). Thickness ranges from approximately 50 to 450 m, with most sections between 60 to 125 m. The isopach of the TLM (50 to 125 m) and GSM (2 to 15 m) are fairly consistent across

the Windermere basin, except for the anomalously thick section at Frances Creek (see Chapter 3 for discussion). In contrast, the WMM thickness is highly variable and ranges from <0.5 to ~165 m.

Although early correlations of the OFP were based primarily on its distinctive purple and green colours (Gussow, 1957; Charlesworth et al., 1967; Aitken, 1969), the recognition of the lithological triad of the siltstones, limestone-siltstone rhythmites (TLM) and mudstone-pelite (GSM) and their consistent stratigraphic position sandwiched between two thick coarse-grained WSG units, in regional mapping facilitated its widespread correlation throughout Alberta and British Columbia (e.g. Pell and Simony, 1987; Ross and Murphy, 1988; McDonough, 1989; Kubli, 1990; Ross et al., 1995; Ross and Ferguson, 2003a). Sections interpreted as located on the paleo-slope or proximal basin tend to display more variability whereas distal basin outcrops (Cariboo Mountains) tend to be more constant in thickness and easier to distinguish on a regional mapping scale.

2.5.6 Geological Age

Unlike most strata from the ca. 750 to 569 Ma WSG, the minimum timing of deposition for the OFP is constrained by a precise Re-Os isochron age of 607.8 ± 4.7 Ma (MSWD = 1.2) from organic-rich mudstone from the GSM type section along Highway 16, approximately 15 km from Jasper, Alberta (Kendall et al., 2004; Fig. 2.4A). From the same samples a similar, but an imprecise 634 ± 57 Ma (MSWD = 65) using the conventional inverse aqua regia digestion method was obtained (Kendall et al., 2004). Both ages are consistent within the poorly resolved WSG where only maximum and minimum limits on the deposition have been obtained. A local maximum deposition age of $736 +23/-17$ Ma (U-Pb zircon) was obtained from orthogneisses of the Malton Gneiss Complex (McDonough and Parrish, 1991) and corresponds well with the range of ~740 Ma to 728 Ma from other basement rocks that the WSG overlies unconformably (Ross et al., 1995; Colpron et al., 2002). Rift-related mafic metavolcanic rocks in northeastern Washington, interpreted to be

Toby Formation correlatives were imprecisely dated at 762 ± 44 Ma from a Sm-Nd isochron (Devlin et al., 1988). More recent work on similar rift-related volcanic rocks in northern British Columbia and Idaho has produced precise U-Pb zircon ages ranging from ca. 709 to 684 Ma (Ferri et al., 1999; Lund et al., 2003; Fanning and Link, 2004), but they are much younger than local WSG estimates and differ from each other by ~ 25 Myr. The minimum timing of deposition is constrained by a U-Pb zircon age of 569.6 ± 5.3 Ma from synrift felsic volcanic rocks of the Hamill Group that unconformably overlie the WSG (Colpron et al., 2002).

2.6 DEPOSITIONAL MODEL

Sedimentary rocks of the OFP were deposited in environments that range from basin-slope to basin-floor (upper bathyal to upper abyssal plain). Fine-grained, mostly turbiditic strata of the lower (TLM) and middle (GSM) members are regionally uniform in thickness and lithofacies, have gradational contacts and imply synchronous, basin-wide deep-marine sedimentation. They are interpreted to be related to a eustatic rise that caused an overall shutdown of coarse, immature siliciclastic sediment supply to the basin (Ross and Murphy, 1988; Chapter 3). The eustatic rise and related transgression is attributed to the melting of a continental glaciation event, with the increase in nutrient supply leading to an increase in organic productivity and possible seawater stratification that facilitated the development of episodic bottom-water anoxia (Ross and Murphy, 1988; Chapters 3 and 4). The upper member (WMM), on the other hand, is locally variable in thickness, which in large part is related to deep incision along its basal contact. Subsequent deposition was controlled potentially by a combination of paleogeographic location, topography along the basin-floor, structural activity and/or relative sea-level change. Deposition of the WMM is interpreted to have coincided with an abrupt fall in relative sea-level caused, at least in part, by uplift, that temporarily interrupted the eustatic rise related to melting of continental ice

sheets (Chapter 3). In slope settings, the sediment transport pathways are controlled by the location of submarine canyons or a combination of canyons, syn-sedimentary growth faults and paleo-seafloor topography. A more complete description and interpretation of the OFP and its three members is found in the companion paper (Chapter 3).

2.7 CONCLUSIONS

The stratigraphic nomenclature for strata of the deep-marine WSG in the southern Canadian Cordillera is complex and may be confusing or even disheartening to researchers unfamiliar with the region. The OFP is a lithologically unique unit that forms an important stratigraphic marker horizon in the WSG, and is mappable and correlatable on a regional scale in the southern Canadian Cordillera. The purpose of proposing the formalization of the stratigraphic nomenclature of the OFP and its three distinctive members in accordance with the North American Stratigraphic Code (NASCN, 2005) is an attempt to provide a simple and consistent stratigraphic framework for part of the WSG in the southern Canadian Cordillera. Proper formalization of the name Old Fort Point Formation and elimination of other informal designations (e.g. basal part of the Hector Formation, Taylor Lake and Mount Temple members, “the Marker”, Baird Brook Division, Comedy Creek unit) eliminates ambiguity for a unit previously interpreted by many authors to be regionally correlatable (e.g. Aitken, 1969; Ross and Murphy, 1988; McDonough, 1989; Kubli, 1990; Ross et al., 1995; Ross and Ferguson, 2003a) and therein provides a vital stratigraphic aid in unraveling the stratigraphic complexities of the Neoproterozoic in western North America.

CHAPTER 3: Transgression, anoxia, submarine canyon incision and highstand sand deposition along an ancient continental margin: the deep-marine Old Fort Point Formation (Ediacaran), southern Canadian Cordillera.

3.1 INTRODUCTION

The Neoproterozoic Windermere Supergroup (WSG) of the southern Canadian Cordillera is a thick (~9 km) stratigraphic succession, composed mostly of deep-marine, siliciclastic sedimentary rocks deposited in upper bathyal to upper abyssal plain water depths along the ancient western margin of Laurentia. Strata of WSG are extensively exposed within thrust sheets of the eastern Cordilleran orogen, and cover an area of approximately 35,000 km². The recognition of a number of regionally persistent lithostratigraphic marker units has been useful in establishing an internal stratigraphic framework by representing key time-significant surfaces in the fossil-poor, Neoproterozoic WSG (e.g. Ross et al., 1995; Ross and Arnett, 2007). The interpretation that these units are relatively isochronous permits the local to regional patterns and characteristics of sediment deposition to be reconstructed. The Old Fort Point Formation (OFP) is the lowermost of these stratigraphic markers. Although named from exposures at a prominent local landmark south of Jasper, Alberta (Charlesworth et al., 1967) these distinctive, mappable strata have been recognized throughout the southern Canadian Cordillera by previous workers for 100 years (e.g. Walcott, 1910; Gussow, 1957; Charlesworth et al., 1967; Aitken, 1969; McDonough, 1988; Ross and Murphy, 1988; Kubli, 1990; Ross et al., 1995; Warren, 1997). The OFP is easily differentiated based on its strikingly different lithological characteristics compared to the fine- and coarse-grained arkose turbidites (“grits”) that typify much of the rest of the deep-marine basinal WSG.

Although the importance of the OFP as a synchronous regional marker has been known for some time, neither its lithological characteristics nor lithostratigraphic significance have been investigated in a detailed, systematic, regional study. The purpose of this paper is to present, for the first time, a detailed sedimentological analysis and sequence stratigraphic depositional model of the OFP. A conservative palinspastic restoration, correcting for the effects of tectonic shortening (~30%) suggests that the WSG turbidite system may have originally occupied an area of ~80,000 km² (Ross, 2000; Ross and Arnott, 2007), and hence comparable in scale to modern turbidite systems like the Amazon and Mississippi submarine fans (e.g. Barnes and Normark, 1985). Thus, the areally expansive preservation of the OFP offers the rare opportunity to identify basin-wide changes in the WSG depositional system on a scale comparable to that of 2D and 3D seismic studies.

3.2 REGIONAL GEOLOGICAL SETTING

The Neoproterozoic WSG is impressive in its widespread distribution across western North America (Fig. 3.1). Strata crop out discontinuously in northwestern Mexico and throughout the western United States and form a fairly continuous outcrop belt in southwestern Canada that extends northwards to the Yukon-Alaska border region; a total distance of more than 4000 km (e.g. Ross et al. 1989; Link et al., 1993). In the southern Canadian Cordillera, the WSG is a thick unconformity-bounded succession (~9 km) consisting primarily of deep-marine meta-sedimentary rocks exposed over an area of 35,000 km² (Fig. 3.2 and Fig. 3.3).

Although there is a paucity of high-precision geochronological information for WSG in the southern Canadian Cordillera, high-precision radiometric ages of underlying and overlying igneous rocks constrain broadly the timing of deposition between ca. 740-728 Ma to 569 Ma (e.g. Ross et al., 1995; Colpron et al., 2002; Ross and Arnott, 2007). The WSG unconformably overlies the Malton Gneiss Complex

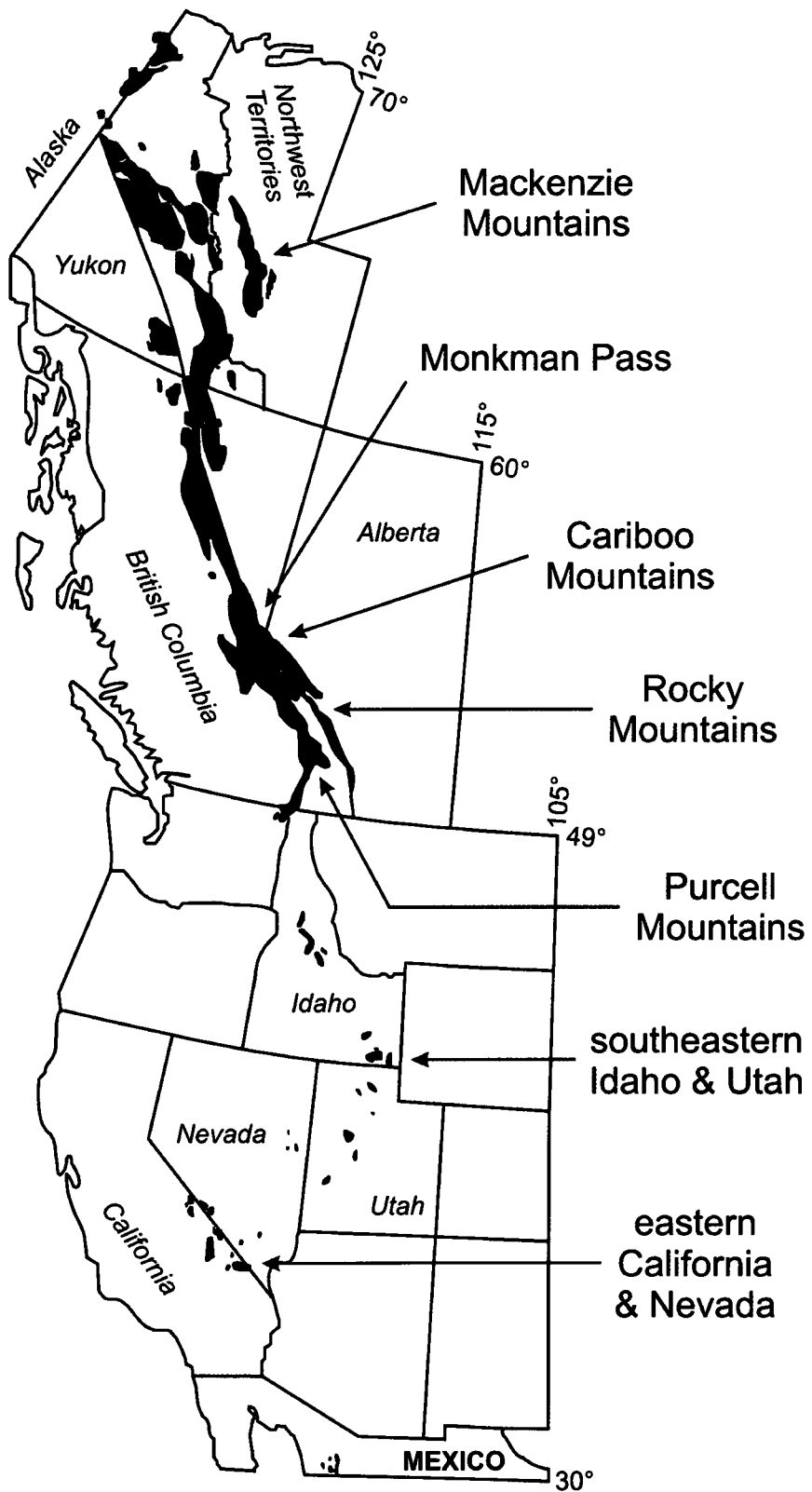


Figure 3.1: Distribution of WSG strata in western North America (modified from Ross 1991).

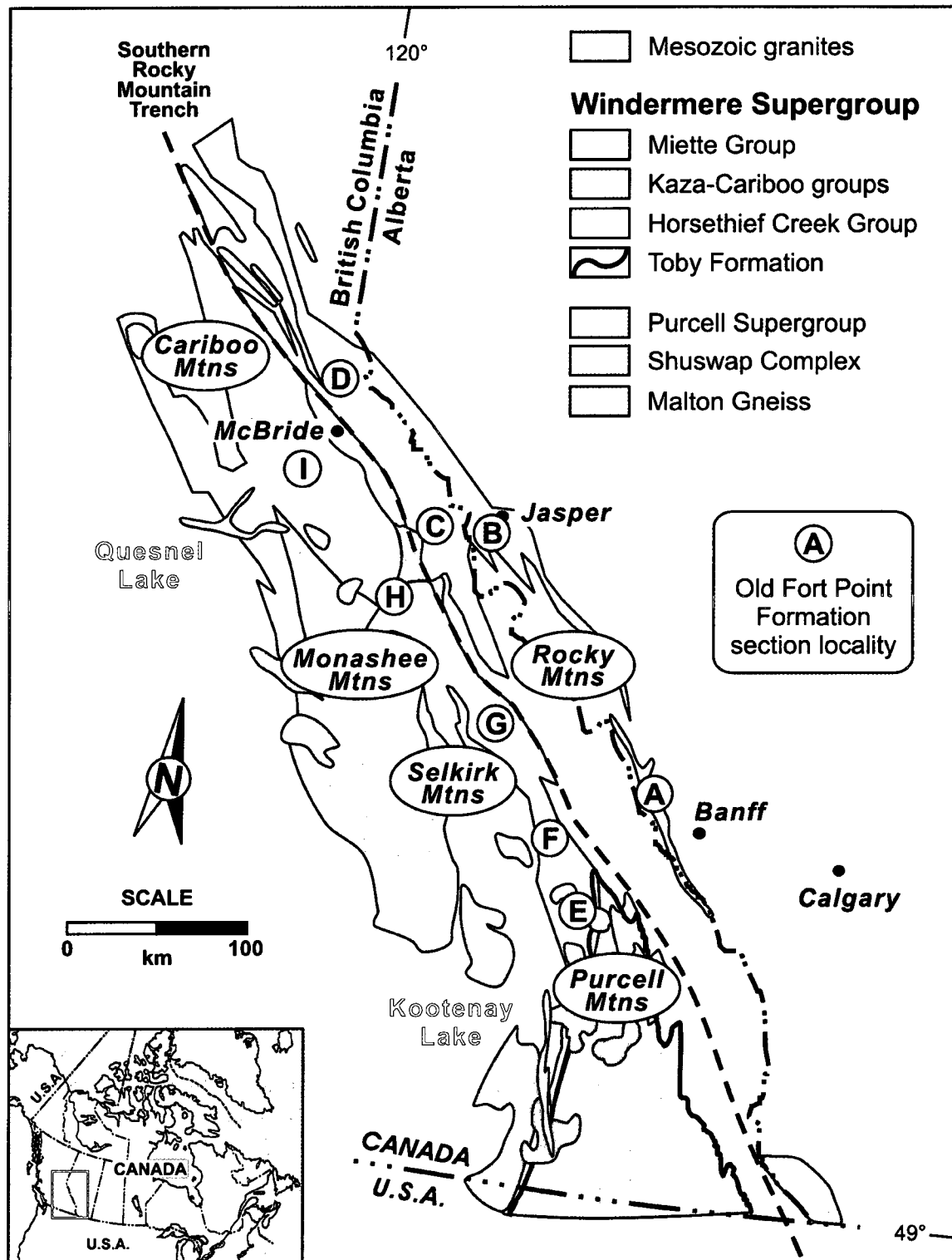


Figure 3.2: Simplified geological map of the WSG, southern Canadian Cordillera showing prominent outcrop localities of the OFP (modified from Ross and Murphy, 1988). (Localities: A - Lake Louise; B - Jasper National Park; C - Mount Robson Provincial Park; D - McKale River; E - Frances Creek; F - Dogtooth Range; G - Monashee Mountains; H - Selkirk Mountains; I - Cariboo Mountains)

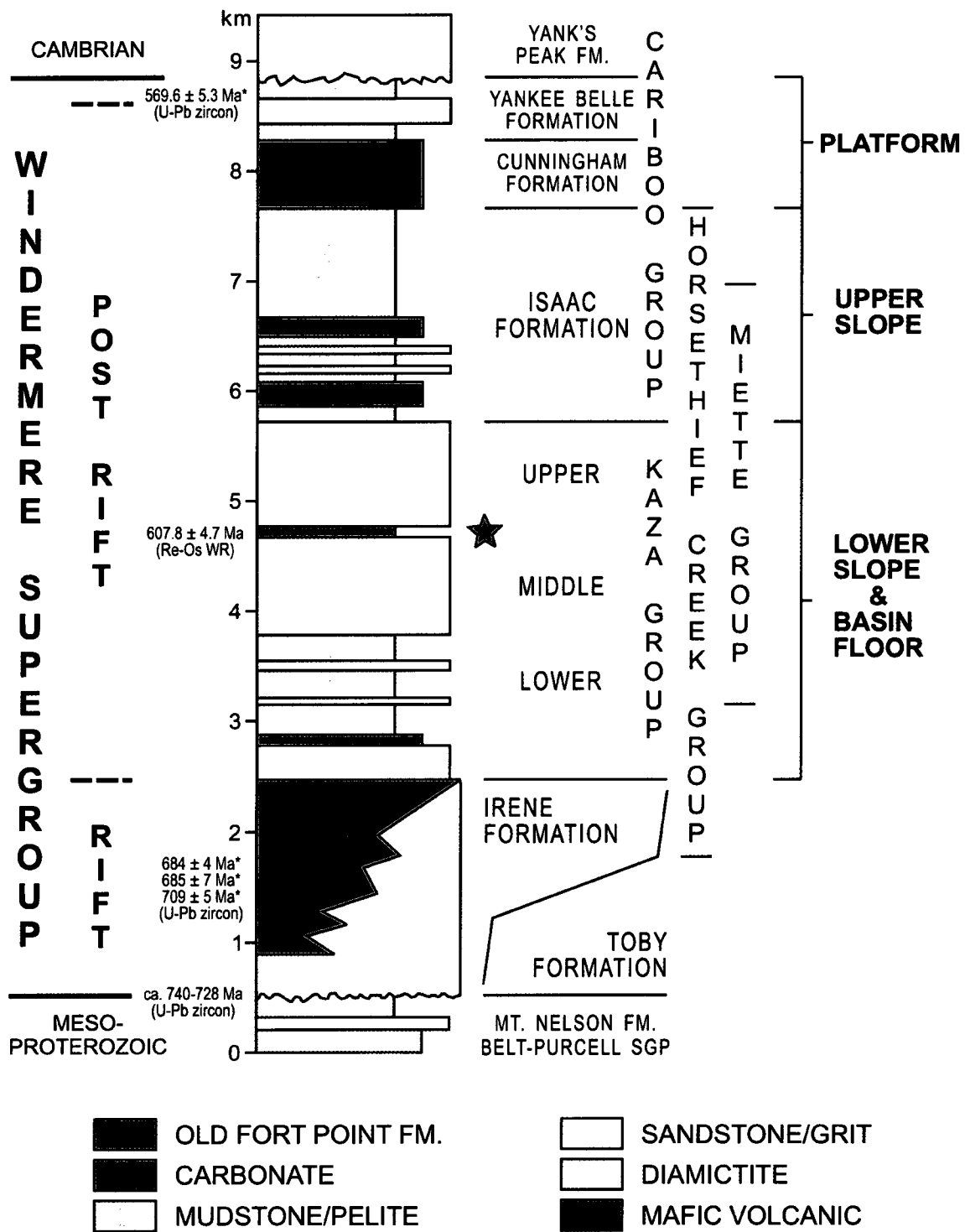


Figure 3.3: Stratigraphic column for the WSG from the Cariboo-Purcell-Rocky Mountains in the southern Canadian Cordillera (modified from Ross et al. 1995). Rift and post-rift strata, paleogeographic environment and relative stratigraphic position of the OFP are shown. Ages shown in stratigraphic order are from McDonough and Parrish (1991), Lund et al. (2003), Kendall et al. (2004) and Colpron et al. (2002). Asterisk indicates the age is from correlative strata to the column.

which is constrained by a U-Pb zircon date of $736 \pm 23/-17$ Ma (McDonough and Parrish, 1991). This local maximum depositional age corresponds well with U-Pb zircon dates of 740 ± 36 Ma (Parrish and Scamell 1988) and $728 \pm 8/-7$ Ma (Evenchick et al. 1984) obtained from other WSG basement rocks in the Canadian Cordillera. The minimum timing of deposition is well-constrained from a U-Pb zircon age of 569.6 ± 5.3 Ma from synrift felsic volcanic rocks of the Hamill Group that unconformably overlie the WSG (Colpron et al., 2002) (Fig 3.3).

The WSG is interpreted to have accumulated in two phases: a rift phase during the break-up of the supercontinent Rodinia and subsequent post-rift thermal relaxation phase (Stewart, 1972; Ross, 1991). At the base of the WSG, the Toby Formation unconformably overlies the Mount Nelson Formation of the Purcell Supergroup (Aalto, 1971; Root, 1987) (Fig. 3.3). It consists mainly of diamictite and is associated with volcanic rocks of the Irene Formation. These basal units of the WSG are variable in thickness, limited in their areal extent and largely restricted to the Purcell Mountains region (Fig. 3.2). Deposition of these units is interpreted to have been controlled by syn-sedimentary extensional faulting during the active rift phase (Aalto, 1971; Root, 1987; Warren, 1997). No direct geochronological control is currently available to constrain the timing of the rift event in the southern Canadian Cordillera. However, potential rift-related volcanic correlatives of the Irene Formation have been dated elsewhere. These include: a U-Pb zircon age of $688.9 \pm 9.5/-6.2$ Ma from the Gataga Volcanics, northern British Columbia (Ferri et al. 1999); an imprecise Sm-Nd isochron age of 762 ± 44 Ma from the Huckleberry Formation in northeastern Washington (Devlin et al. 1988); and three SHRIMP U-Pb zircon ages from volcanic rocks in Idaho, which are 684 ± 4 Ma and 685 ± 7 Ma from the two different members of the Edwardsburg Formation (Lund et al., 2003), and 709 ± 5 Ma from the Scout Mountain Member, Pocatello Formation (Fanning and Link 2004).

The tectonic setting of the Windermere basin during deposition of the post-rift strata is currently a source of some debate. In the southern Canadian Cordillera,

the Horsethief Creek Group (Purcell Mountains), Kaza and Cariboo groups (Cariboo Mountains) and Miette Group (Rocky Mountains) all refer to parts of the same ~5 km thick sedimentary succession that consists mainly of basin-slope and basin-floor strata (e.g. Ross et al. 1989; 1995; Ross and Arnott, 2007) (Fig. 3.3). One model proposes that these units accumulated in an elongate, northwest-flowing turbidite system on a continental passive margin with a substantial open ocean (Ross 1991; Ross et al. 1995; Dalrymple and Narbonne 1996). The other model postulates a ~2500 km intracontinental rift and restricted ocean basin for the southern WSG, which opened to the north and was post-dated by a major late Neoproterozoic-early Cambrian rift event that culminated in the inception of the proto-Pacific Ocean (Colpron et al. 2002). Irrespective of tectonic setting, the WSG represents one of the world's most expansive ancient laboratories of deep-marine sedimentary rocks.

Lithologically, strata of the WSG are dominated by coarse-grained arkosic sandstone and granule conglomerate intercalated with mudstone-dominated intervals and minor carbonate (e.g. Ross et al., 1989; 1995; Ross and Arnott, 2007). The Vreeland Formation of the Misinchinka Group in north-central British Columbia, however, is an exception, being composed mainly of diamictite units of interpreted glacial origin that pass laterally into typical turbidites of the WSG, both westward and southward (McMechan, 1987; McMechan and Thompson 1995a; McMechan, 2000). Within the Windermere basin, the overall monotony of immature, feldspar-rich turbidites of the Horsethief Creek, Miette and Kaza groups is interrupted by the predominantly fine-grained, regionally widespread Old Fort Point Formation (OFP) (e.g. Ross and Murphy, 1988) (Fig. 3.3). The OFP ranges from 60 to 450 m in thickness and consists of a distinctive tripartite stratigraphic framework, which in ascending order is: 1) Temple Lake Member consisting of basal siltstone grading upward into limestone-siltstone rhythmite; 2) Geikie Siding Member, an organic-rich mudstone; and 3) Whitehorn Mountain Member, a heterolithic unit of diamictite, breccia to conglomerate, sandstone, siltstone-

mudstone and limestone (Chapter 2). The minimum timing of deposition for the OFP is constrained from a Re-Os isochron age of 607.8 ± 4.7 Ma from organic-rich mudstone of the Geikie Siding Member in the Jasper area, Alberta (Kendall et al. 2004) placing it in the newly defined Ediacaran Period (Knoll et al., 2004, 2006). The OFP is interpreted to be a regionally extensive deep-marine post-glacial deposit temporally linked with the glacial Vreeland Formation (e.g. Ross et al., 1995), although nowhere is the OFP observed to be in contact with diamictite of the Vreeland Formation. The OFP is also thought to correlate to carbonate strata overlying glacial diamictite in the Mackenzie Mountains (Aitken, 1991a, b; Ross et al., 1995; James et al., 2001).

The OFP is overlain by coarse-grained, feldspar-rich basin-slope to basin-floor turbidite deposition, suggesting a return to the more typical sedimentation patterns and mineralogical compositions of the WSG. These deposits form a kilometre-scale upward-shoaling trend that culminates in mudstone-dominated units interpreted as upper slope deposits and shelf platform carbonates, and is interpreted to represent the long-term westward progradation of the continental margin of Laurentia as the rate of thermal subsidence decreased (e.g. Ross et al. 1989; Ross et al., 1995; Ross and Arnott, 2007) (Fig. 3.3).

Approximate water depths for deposition of the basin-slope to basin-floor WSG are interpreted to range from upper bathyal (~500 m) to upper abyssal plain (~3000 m) settings. This interpretation is based on two main observations: 1) preservation of turbidite sedimentary structures that show no evidence for re-working by storms which would imply deposition above storm wave base (~300 m); and 2) an uninterrupted, ~3 km upward-shoaling stratigraphic succession from basin-floor to basin-slope to platform sedimentary deposits suggestive of progressive filling of accommodation as the rate of sedimentation gradually outpaces the rate of thermal subsidence along the continental passive margin. This water depth range (500 to 3000 m) for deposition of the WSG (including OFP) and

overall succession thickness are consistent with other modern, deep-water passive margin analogues (e.g. Damuth and Flood, 1985).

A locally subtle, but significant regional unconformity marks the end of WSG deposition and the beginning of a latest Neoproterozoic to Cambrian rift-drift succession with the clastic and volcanic sedimentary rocks of the upper Cariboo, Hamill and Gog groups. Regional uplift associated with this rift-event has resulted in significant sub-Cambrian erosion in the southern Canadian Cordillera, which perhaps is responsible for the lack of preserved shallow-water WSG strata in the eastern outcrops (Ross and Murphy, 1988; Ross et al., 1995). More complete reviews of the WSG geological background, including tectonic models and the stratigraphic framework have been published elsewhere (e.g. Ross et al., 1989, 1995; Ross, 1991; Ross and Arnott, 2007).

3.3 STUDY AREA AND METHODS

In this study, strata of the OFP were examined in six separate regions in the southern Canadian Cordillera of Alberta and British Columbia (Fig. 3.2). The selection of these localities was based on previous geological mapping and research over the past 100 years (e.g. Walcott, 1910; Charlesworth et al., 1967; Aitken, 1969; Ross and Murphy, 1988; McDonough, 1989; Kubli, 1990; Ross et al., 1995; Warren, 1997; Ross and Ferguson, 2003a, 2003b) that noted factors critical to a detailed sedimentological and stratigraphic analysis such as: low metamorphic grade and relatively simple structure enabling observation of well preserved primary sedimentary structures and textures; stratigraphic continuity of the OFP and stratigraphic context with encompassing WSG; and exceptional quality of exposure from roadcuts, cliff-forming faces or periglacial zones with little or no cover or alteration. Although the lateral continuity of individual outcrops is limited (<0.5 km), the OFP can be correlated on a regional-scale from mapping of other nearby high-quality outcrops (e.g. 1 to 10 km distance separation) (e.g. Price et al. 1980a,

Kubli 1990; McDonough 1994; Ross and Ferguson 2003a, 2003b). The specific study areas (Locations A to E, I) are listed in Table 3.1 with individual section localities (names and UTM coordinates) indicated on the simplified geological map of the southern Canadian Cordillera in Fig. 3.2. Three additional areas where the OFP crops out, but were not visited as part of this study, are also indicated (Locations F to H).

Data presented in this paper were collected from nine vertical stratigraphic sections measured at cm-scale detail, ranging in thickness from approximately 25 to 500 m. Additional data were collected from 8 complementary sections measured at dm-scale and stratigraphic information gleaned from previous studies. Detailed bed-by-bed observations of physical sedimentary structures, lithofacies, bed thickness and stratigraphic characteristics were made for the OFP and encompassing WSG strata (Appendix D). Outcrop gamma-radiation measurements were collected using a handheld spectrometer from each section using a 0.75 cm interval between measurements with five readings (10 second averages) collected at each station (Appendix E). The highest and lowest outlier values were dropped with the calculated average from the remaining three values used to generate a continuous vertical profile. Representative samples were collected from each lithofacies and a total of 155 petrographic thin sections analyzed for mineralogy, grain size and textural attributes (Appendix F). It should be noted that although the rocks of the OFP have experienced varying degrees of low-grade metamorphism, primary sedimentary structures and textures are well preserved in sections studied for this study and thus, sedimentary terms will be used in this paper (e.g. mudstone instead of pelite). Terminology for stratification of fine-grained sedimentary rocks follows that of Potter et al. (1980).

Lct.	Regional Area	Section	Code	Easting	Northing
<u>Alberta</u>					
A	Lake Louise area	Temple Lake	LL1	557379	5690015
		Railway/Bath Creek	LL2	551641	5701337
		Redoubt SW Spur	LL3	562261	5700626
		Upper Boomerang	LL4	559666	5702403
		Wolverine Bowl	LL5	563943	5698491
		Taylor Lake	LL6	563860	5682541
		Icefields Parkway	LL7	549902	5709796
		Arnica Lake	LL8	570447	5674427
B	Jasper National Park	Geikie Siding	JP1	412974	5858644
		Athabasca River	JP2	428416	5857171
		OFP Landmark	JP3	428577	5858240
		Marmot Ski Road	JP4	430208	5848258
<u>British Columbia</u>					
C	Mount Robson Provincial Park	Vista Glacier	MR1	400911	5847859
		The Comb	MR2	374335	5861575
D	McKale River area	McKale River	MK1	692091	5929423
E	Purcell Mountains	Frances Creek	PM1	525658	5613170
I	Cariboo Mountains	Eagle Valley	CM1	678846	5887412
		Mount Quanstrom	CM2	693512	5867836

Notes: Location letters refer to Figure 2.2. UTM coordinates in grid system NAD27.
Locations A, B, C, E and F are in Zone 11; locations E and I are in Zone 10.

Table 3.1: Locations of Old Fort Point Formation stratigraphic sections.

3.4 OLD FORT POINT FORMATION

The Old Fort Point Formation comprises three distinctive units: Temple Lake Member (TLM); Geikie Siding Member (GSM); and Whitehorn Mountain Member (WMM) (Chapter 2). Proposed formalization of the OFP and its three members in accordance with the North American Stratigraphic Code (NASCN, 2005) is presented in Chapter 2. Detailed OFP lithofacies descriptions are supplied in this paper for the first time (as opposed to local descriptions in previously unpublished theses) in order to provide pertinent stratigraphic detail that will complement the stratigraphic formalization (Chapter 2). Individual lithofacies and lithofacies associations are generally specific to one of the three members and are presented in that manner. A summary of lithofacies characteristics are presented in Table 3.2.

3.5 TEMPLE LAKE MEMBER

The basal Temple Lake Member (TLM) is the most lithologically distinctive unit in the OFP and consists mostly of variably coloured fine-grained facies and rhythmically bedded limestone-siltstone couplets. Although the distinctive colour change in the TLM forms an easily recognized contact with the underlying WSG, these fine-grained facies contacts are usually gradational in nature, but over an interval of less than 0.5 m thick. Its basal contact is also marked by sharp upward-fining, where TLM siltstone directly overlies coarse-grained, immature arkose (grits) of the WSG; or conversely, a slight upward-coarsening where siltstone-dominated TLM strata overlie mudstone-rich, fine-grained facies of the WSG. The upper contact of the TLM and overlying Geikie Siding Member (GSM) is usually gradational, and in most outcrops is a discernible transition zone varying in thickness from <0.5 to 2 m. The transition is marked by upward-fining, a decrease in limestone bed frequency, and a number of measurable geochemical changes (e.g. increase in total organic carbon and molybdenum content) (Chapter 4).

Lithofacies	Lithology	Bed Thickness	Sedimentary Textures & Structures	Division	Depositional Processes
<u>Temple Lake Member (TLM)</u>					
TLM-1 Siltstone	siltstone, mudstone, very fine sandstone	thin to medium laminated (<0.1 to 0.3 cm)	poorly-sorted, immature, thin to medium bedded units (5 - 50 cm), lenticular, wispy, discontinuous or planar lamination, starved ripples, 3D ripple formsets, ripple-cross-lamination, micro-scours, normal grading, rare discoid structures	T ₀ - T ₇ T(c)de	Minor tractional deposition with suspension fallout from dilute turbidity flows
TLM-2 Stratified sandstone	lower medium to very fine sandstone, siltstone	very thin to medium bedded (1 to 12 cm; ave: 4 cm)	poorly-sorted, immature, planar lamination, 3D ripple formsets, cross-stratification, scours, normal grading, lenticular bed geometry, carbonate-cemented	Tbed Tbd Tcd	Low-concentration turbidity flows with tractional deposition followed by suspension fallout
TLM-3 Interbedded limestone-siltstone	lower fine sandstone to siltstone	very thin to medium bedded couplets (1 to 84 cm) (ave: 3 to 8 cm)	moderately-sorted, immature, lenticular, wispy, discontinuous and planar lamination, 3D ripple formsets, cross-lamination, scours, normal grading, lenticular bed geometry, minor loading features	Tbcd Tbd	Low-concentration turbidity flows with tractional deposition followed by suspension fallout
TLM-4 Breccia	mudstone-siltstone matrix	medium to thick bedded (0.13 to 1 m)	poorly-sorted, immature, matrix- to clast-supported, TLM lithofacies clasts, minor clast imbrication or chaotic texture, ductile clast deformation, pygmatical folded clasts, cohesive stratigraphic blocks, basal scour or glide plane, lenticular bed geometry	Mass Slump, Slide or Flow	Slump or slide processes with en masse freezing; intraformational slope collapse, disaggregation and muddy debris flow
TLM-5 Massive sandstone	fine- to medium sandstone	medium to very thick bedded (0.1 to 1.7 m)	poorly-sorted, immature, massive, basal scour surface, amalgamated beds	Ta, (Tad) S3	Rapid suspension fallout deposition by high-concentration turbidity flow
<u>Geikie Siding Member (GSM)</u>					
GSM-1 Mudstone	mudstone, siltstone, rare limestone or very fine sandstone	thin laminated to very thin bedded (<0.1 to 3 cm)	poorly-sorted, immature, planar lamination, subtle normal grading, organic-rich, lenticular bed geometry for limestone or sandstone beds, rare cross-lamination	T ₃ - T _{6,7} , P Tde (Tbcd)	Minor traction deposition with suspension fallout from dilute turbidity flows, organic-rich hemipelagic and pelagic suspension fallout
GSM-2 Breccia	mudstone matrix	very thick bedded (2.4 m)	poorly-sorted, immature, matrix- to clast-supported, limestone clasts of GSM-1 roughly parallel to bedding	Mass Flow	Intraformational slope collapse, disaggregation and muddy debris flow

Table 3.2: Lithofacies description of the Old Fort Point Formation.

Lithofacies	Lithology	Bed Thickness	Sedimentary Textures & Structures	Division	Depositional Processes
Whitehorn Mountain Member (WMM)					
WMM-1 Diamictite-breccia	mudstone to siltstone matrix	medium to very thick bedded (0.1 to 2.12 m, >6 m)	poorly-sorted, immature, matrix- to clast-supported, massive matrix, basal scour, undulatory tops, elongated clasts of OFP facies up to 1 m in length, chaotic to imbricated texture, lenticular bed geometry, amalgamated beds	Mass Flow	Intraformational slope collapse, disaggregation and muddy debris flow
WMM-2 Laminated mudstone	mudstone, siltstone, very fine sandstone	thin laminated to very thin bedded (<0.1 to 2 cm)	poorly-sorted, immature, planar and discontinuous lamination, micro-scours and scours, normal grading, rare ripples or cross-lamination, rare parting lineation, normal grading, soft-sediment deformation features	T ₀ - T ₅ Td (Tcde)	Minor tractional deposition with suspension fallout from dilute energy turbidity flows
WMM-3 Sandstone	conglomerate to fine sandstone	very thin to very thick bedded (0.01 to 2.20 m)	moderately to poorly-sorted, submature, planar and cross-lamination, scours, undulatory contacts, lenticular bed geometry, carbonate-cemented, rare limestone lenses, load and de-watering structures; massive, basal pebble lag or carbonate clasts	Tb, Tbd Tbcd Ta, Ta(bcd) S2 - S3	Low- to moderate-concentration turbidity flows with tractional deposition; Rapid suspension fallout deposition by high-concentration turbidity flows
WMM-4 Quartz arenite	conglomerate to medium sandstone	medium to very thick bedded (0.1 to 2.4 m)	well-sorted, mature, massive, planar or cross-lamination, normal grading, rare basal reverse grading, basal scour, basal rip-up clasts, load and de-watering structures, amalgamated beds, sheet-like geometry	Ta, Tad Ta(bcd) S2 - S3	Rapid suspension fallout deposition by high-concentration turbidity flows
WMM-5 Calcareous arenite to arenaceous limestone	coarse to fine sandstone, limestone	very thin to thick bedded (2 to 46 cm)	well-sorted, mature, planar or cross-lamination, normal grading, micro-scours, slump and load structures, undulatory contacts, consistent metre-scale thinning upward's trends	Tb, Tbc, Tbcd Tbd	High to low-concentration turbidity flows with tractional deposition followed by suspension fallout
WMM-6 Limestone	limestone	very thin to medium bedded (1 to 20 cm)	moderately-sorted, mature, planar and discontinuous lamination, cone 'n' cone structures, micro-scours, organic-rich, pyrite-rich	P T(d)e	Hemipelagic and pelagic suspension fallout; minor traction deposition
WMM-7 Organic-rich mudstone	mudstone - siltstone	medium laminated (0.1 to 0.5 cm)	poorly-sorted, immature, planar lamination, pyrite-rich laminations, organic-rich	P T(d)e	Organic-rich hemipelagic and pelagic suspension fallout
WMM-8 Breccia-conglomerate	granule conglomerate to coarse sandstone matrix	medium to very thick bedded (0.12 to >10 m)	poorly-sorted, mature, matrix- to clast-supported, sharp basal scour or rare glide plane, rounded and elongated clasts from cm-scale to >3 m, diverse range of intrabasinal clasts with TLM, WMM and non-OFP lithologies, lenticular bed geometry, chaotic to imbricated texture, rare reverse grading	R1 - R3 S1 - S3 Mass Slump, Slide or Flow	Traction, traction carpet and rapid suspension fallout deposition by high-concentration turbidity flows; Slump or slide and/or sandy debris flow

Table 3.2 (cont.): Lithofacies description of the Old Fort Point Formation.

The TLM is fairly consistent in lithology and thickness, which in most places ranges from either 50 to 65 m or 100 to 125 m, although reported values have a wider range (~20 - 200 m) (e.g. McDonough, 1989; Kubli, 1990; Warren, 1997). Stratigraphically upward, the TLM exhibits an increase in carbonate content (limestone beds) and also shows a slight overall coarsening from siltstone-dominated at the base to very-fine sandstone near the gradational upper contact with the GSM. The wide range of colours include purple (greyish purple, pale purple, very dusky purple, greyish purple-red), green (pale green, greenish grey, greyish green, light to dark greenish grey), pink (greyish pink to white), yellow (yellowish white to white-grey, moderate yellow-brown) and brown (moderate reddish brown to moderate brown, brownish-grey) (Munsell Colour Chart). Siliciclastic portions of the TLM are dominated by poorly sorted, immature siltstone with colour a direct reflection of its accessory mineral content (e.g. purple from hematite, green from chlorite, brown from iron-rich dolomite). Mineralogically, the TLM is characterized by angular to sub-rounded, silt-sized quartz (~15 to 30%) and mainly altered plagioclase (~1 to 10%) in a matrix of recrystallized muscovite-chlorite (~50 to 65%). Other minerals include detrital muscovite or chlorite (not associated with regional metamorphism), which are present as elongate crystals up to 200 μm in length. The TLM also has a relatively high-proportion of accessory minerals (~1 to >5%) that are disseminated within the matrix or form discrete laminae. These minerals include: apatite, hematite, ilmenite, monazite, pyrite, rutile, titanite, tourmaline and zircon. Hematite is mainly within purple-coloured units as either sub-rounded detrital grains, disseminated specks (<2 μm) within the siltstone to mudstone matrix, or as irregular filamentous shapes parallel to bedding that may be >300 μm in length. Pyrite is absent in the purple-coloured units, but is common in green-coloured varieties. The TLM is also variably cemented by secondary iron-rich dolomite or iron-rich calcite with the degree of cementation directly related to detrital grain-size.

3.5.1 Lithofacies description

3.5.1.1 Siltstone (TLM-1)

TLM-1 consists predominantly of poorly sorted siltstone-mudstone and very-fine sandstone that form a wide range of very thin to thick bedded units (5 to 50 cm), with most being medium-bedded (10 to 30 cm) (Fig. 3.4A to F). Internally, strata are thin- to medium-laminated (<0.1 to 0.2 cm), although this can be difficult to determine depending on the quality of outcrop. Commonly in purple-coloured siltstone units, a green-coloured band is observed at, or near the base of each lamina. Sedimentary structures include a wide range of small-scale tractional features including: lenticular, wispy, discontinuous, planar lamination; starved ripple form-sets and ripple cross-lamination; micro-scours; and normal grading. At one locality (LL8) this facies also possesses some curious discoid structures at the base of the section (Fig. 3.4G, H). Discovered by Allan (1913) and later described by Gussow (1973) who attributed them to *Chuaria circularis* (Walcott, 1899). The discoid structures are ~3 mm in size, lentil-shaped with either hypo- or epirelief, have concentric wrinkles and a 5-point star-like figure inside the concentric pattern (Hofmann, 1972; Gussow, 1973; this study). The specimens are physically similar to the Neoproterozoic disc-like body fossils attributed to *Beltanelliformis brunssae* by McIlroy et al. (2005) but are unlike other examples of *Beltanelliformis brunssae* reported from the Mackenzie Mountains (Narbonne and Hofmann, 1987). Although the structures do not appear to be a physical sedimentary feature, they lack any carbonaceous material that would strengthen a biogenic origin and certainly require further detailed examination.

3.5.1.2 Stratified sandstone (TLM-2)

TLM-2 consists of poorly sorted, immature lower fine- to very fine-grained sandstone with intercalated siltstone (Fig. 3.5A to F). Bed thickness ranges from very thin- to medium-bedded (1 to 12 cm) with rare thick-beds (~50 cm). Typically it is about 4 cm and shows little regional variation. Sedimentary structures include

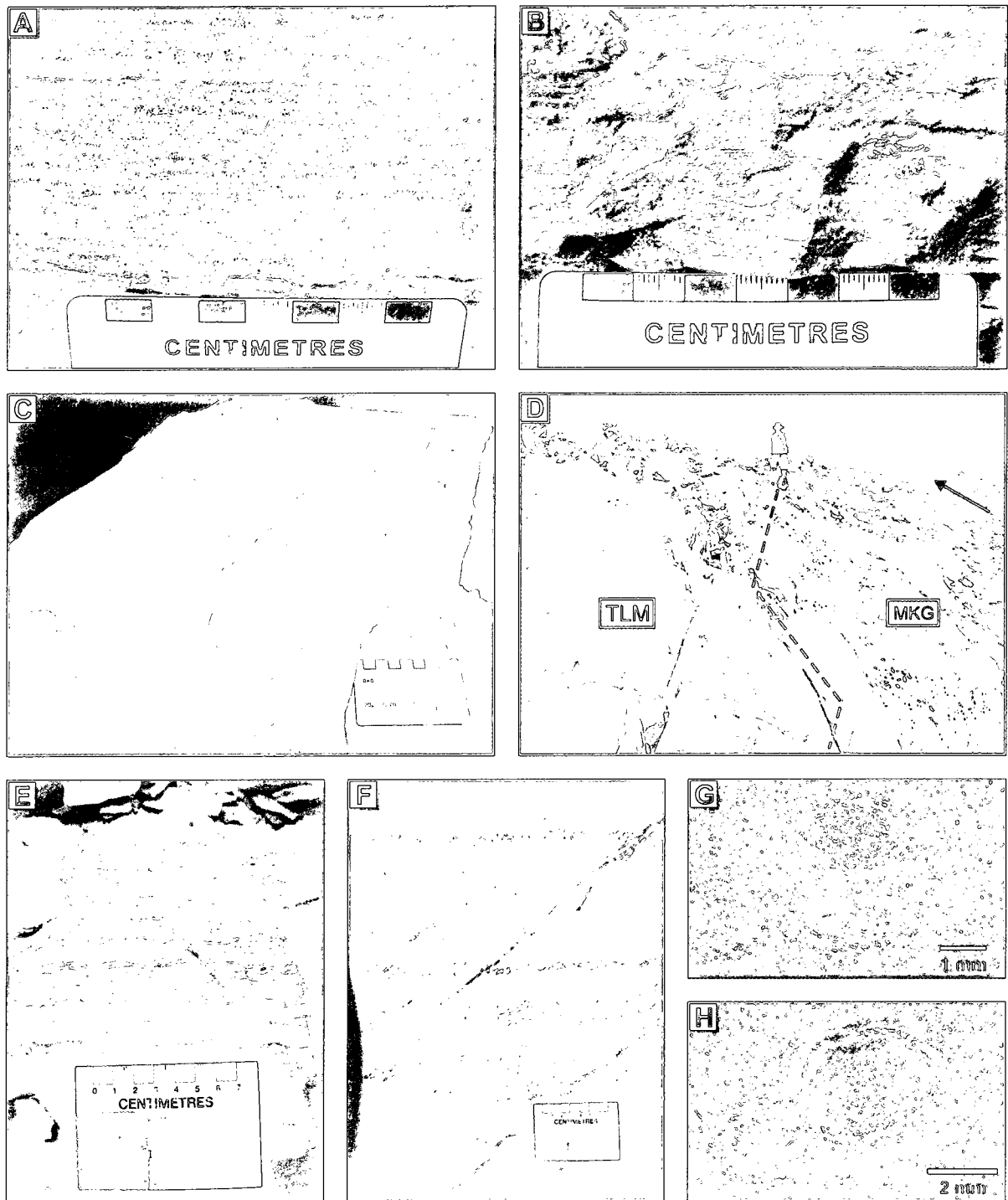


Figure 3.4: A) to F) Representative lithofacies photos of variably-coloured TLM-1 siltstone. A) JP1: T₄ to T₆ turbidites. B) LL5: T₀ to T₆ turbidites. C) MR1: T₃ to T₆ turbidites. D) CM1: Contact between mud-rich Middle Kaza Group (MKG) and silt-rich, carbonate-cemented TLM. Arrow indicates upward stratigraphic direction. E) LL5: T₀ to T₆ turbidites. F) CM1: T₃ to T₆ turbidites. G) - H) LL8: Discoid structures with concentric wrinkles of possible biological origin. G) Example of epirelief with 5-point star-like figure. H) Example of hyporelief.

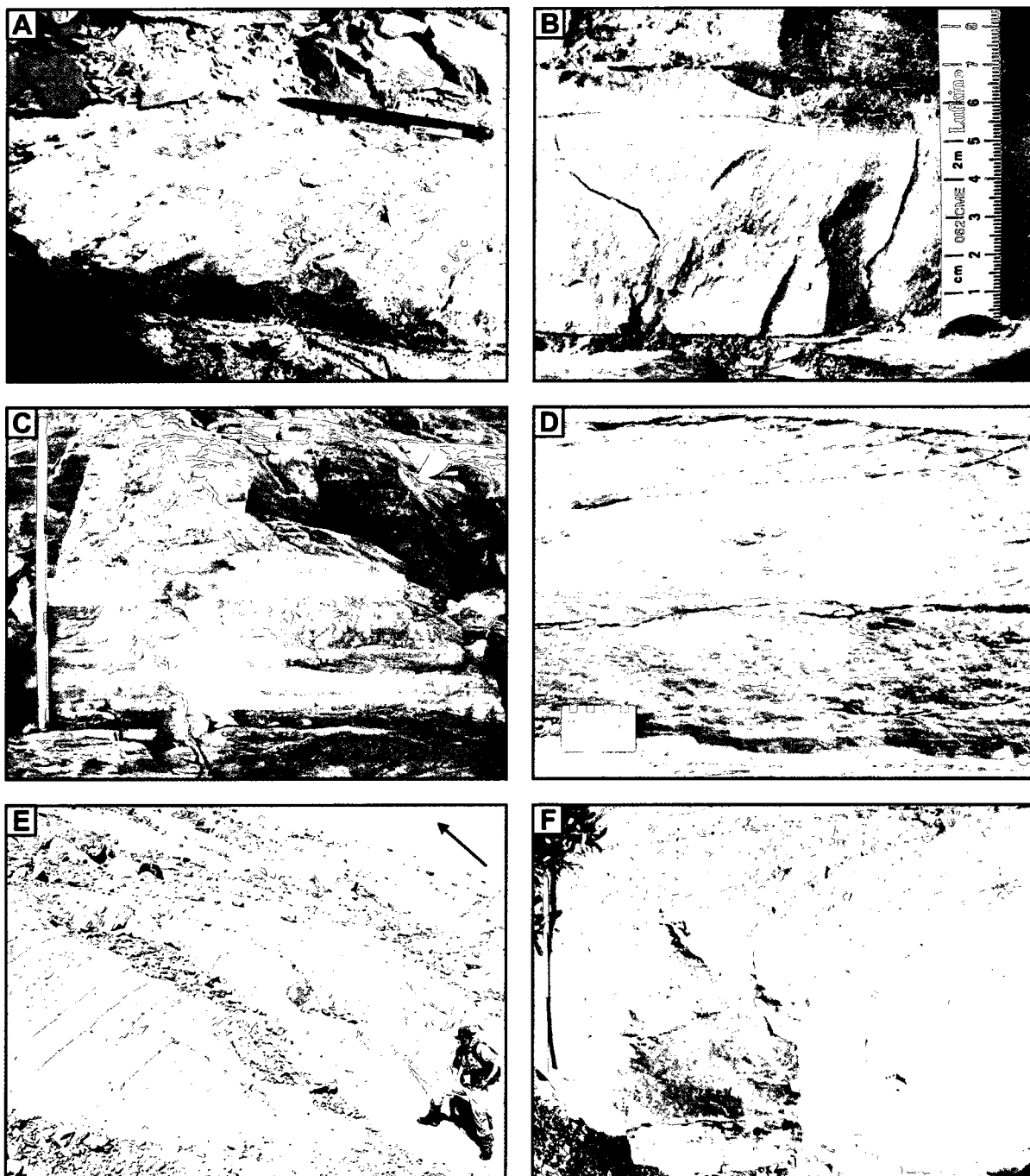


Figure 3.5: A) to F) Representative lithofacies photos of TLM-2 stratified sandstone. A) LL5: Tbc turbidite with 3D ripple-top. Pencil is ~15 cm long and is pointed in the direction of flow. B) JP1: Planar laminated Tb turbidite. C) MR: Interstratified TLM-2 Tb turbidites and TLM-1 siltstone. Ruler is 50 cm. D) PM1: Ripple-stratified Tc bed and planar laminated Tb turbidite. E) CM1: Laterally-extensive, repetitive T(b)cd basinal turbidites. Arrow indicates upward stratigraphic direction. F) CM1: Two, stacked Tbc turbidites. Ruler is 50 cm.

planar or small-scale (ripple) cross-lamination, 3D ripple form-sets and rare medium-scale (dune) cross-bedding. Other structures include normal grading, scours and locally, beds with a lenticular geometry. Paleocurrents ($n = 26$) measured from 3D current-ripples generally indicate flow varying from the southwest to northwest (Appendix G).

3.5.1.3 Interbedded limestone and siltstone (TLM-3)

TLM-3 consists of impure limestone to limestone interbedded with poorly sorted immature siltstone to very fine sandstone (Fig. 3.6A to G). In outcrop, this is the most striking facies of the OFP based on its rhythmic alternation of carbonate and siliciclastic strata and its variable colour that commonly changes gradationally-upward from purple to green. In sections where there is a colour alternation and/or transition from purple to green (e.g. LL or JP), the limestone beds change from a greyish pink or moderate red colour to a grey or greyish-white. Although TLM-3 limestone beds range from 1 to 10 cm thick, they show a consistent average of 2 to 3 cm ($n > 1000$) across the basin, irrespective of location. Rare isolated medium beds (10 to 30 cm) are observed in some sections, or are more common at certain locations (e.g. MR2). The overall rhythmic couplets range in thickness from very thin- to thick-bedded (1 to >50 cm), which mostly is related to the thickness of the siltstone component. Sedimentary structures in both carbonate and siliciclastic strata include planar lamination, ripple cross-lamination, 3D ripple form-sets, scours, normal grading and possible load features. Some beds are characterized by a lenticular geometry in outcrop. Paleocurrents ($n = 10$) measured from 3D current-ripples consistently indicate flow toward the southwest (Appendix G).

Stratigraphically upward, the limestone becomes more pure as the detrital siliciclastic content decreases from approximately 40% to <5%. Petrographically, the limestone consists of microsparite (5 to 20 μm) to sparite (20 to 60 μm) that becomes more recrystallized as metamorphic grade increases towards the west. At locations of lowest metamorphic grade, SEM backscatter images show that the microspar

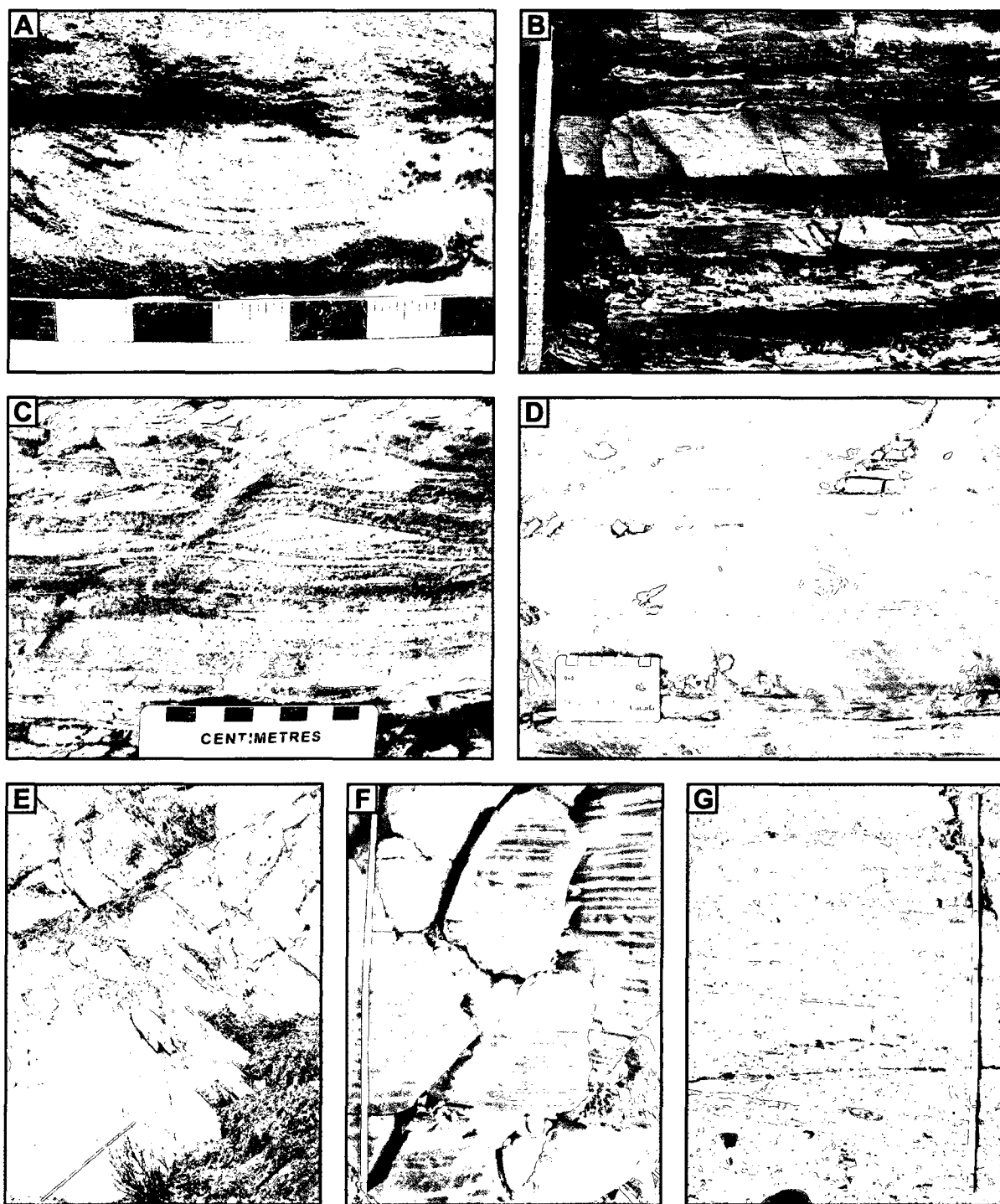


Figure 3.6: A) to G) Representative lithofacies photos of TLM-3 interbedded limestone and siltstone. A) LL1: T_c limestone turbidite showing ripple trough. B) LL1: T_{bc} limestone turbidites interbedded with siltstone. Ruler is ~35 cm. C) LL5: T_{de} limestone turbidite overlain by T(a)bcd very-fine grained sandstone turbidite. D) PM1: T_{bc} limestone turbidites interbedded with siltstone. E) JP1: TLM-3 purple to green colour transition. Note colour change is not parallel to bedding. Arrow indicates upward stratigraphic direction. Ruler is 100 cm. F) MR1: T_{bc} limestone (grey) turbidites interbedded with siltstone (red-brown). Ruler is 100 cm. G) CM1: T_{bc} limestone turbidites interbedded with siltstone. Ruler is 100 cm.

calcite forms inclusion-rich, irregular rounded shapes with no distinctive crystal boundaries, which then is enveloped by a secondary poikilotopic microspar to spar calcite cement (Chapter 5). Detrital material consists of silt to very fine-sand quartz, plagioclase, micas and accessory heavy minerals. Fine-grained siliciclastic beds are consistently carbonate-cemented. In the lower part of this lithofacies, the limestone bed consistently forms the basal part and the siltstone the upper part of the couplet. Although uncommon, a number of sections (e.g. LL1, LL5) show a reversal up-section where the very-fine sandstone to siltstone forms the base of the couplet. At these locations, there is an upward-coarsening (siltstone to very-fine sandstone) of the TLM, however, identifying the precise stratigraphic position of the reversal is difficult.

3.5.1.4 Breccia (TLM-4)

TLM-4 is a clast- or matrix-supported breccia with a massive mudstone to siltstone matrix and clasts derived from strata of the TLM (TLM-1 to TLM-3) (Fig. 3.7A to F). The facies is mostly as isolated medium to thick beds (12 to 55 cm), although rare thin (~1 cm) or very thick examples (up to 1 m) are also observed. Beds have a sharp, commonly scoured basal surface and are laterally discontinuous, with many exhibiting a lenticular geometry. Limestone clasts from TLM-3 are generally elongate and exhibit a chaotic or only weakly developed fabric. Some clasts also exhibit ductile (ptygmatic folds) or brittle (broken-up) syn-sedimentary deformation features. Breccia units can be separated into two types: clast-supported breccia that consist of small to large blocks of coherent strata with ductile deformation features and a non-erosive, loaded, basal surface; or clast- or matrix-supported (TLM-1 and TLM-2 clasts) breccia with erosive basal scours that commonly grade laterally into TLM-1 or TLM-3 beds. Strata of TLM-4 are thickest and most abundant in the Lake Louise sections (LL1, LL5). Although less abundant and thinner, these strata are also at Jasper and Mount Robson, but are apparently absent in all other areas (e.g. PM1, CM1).

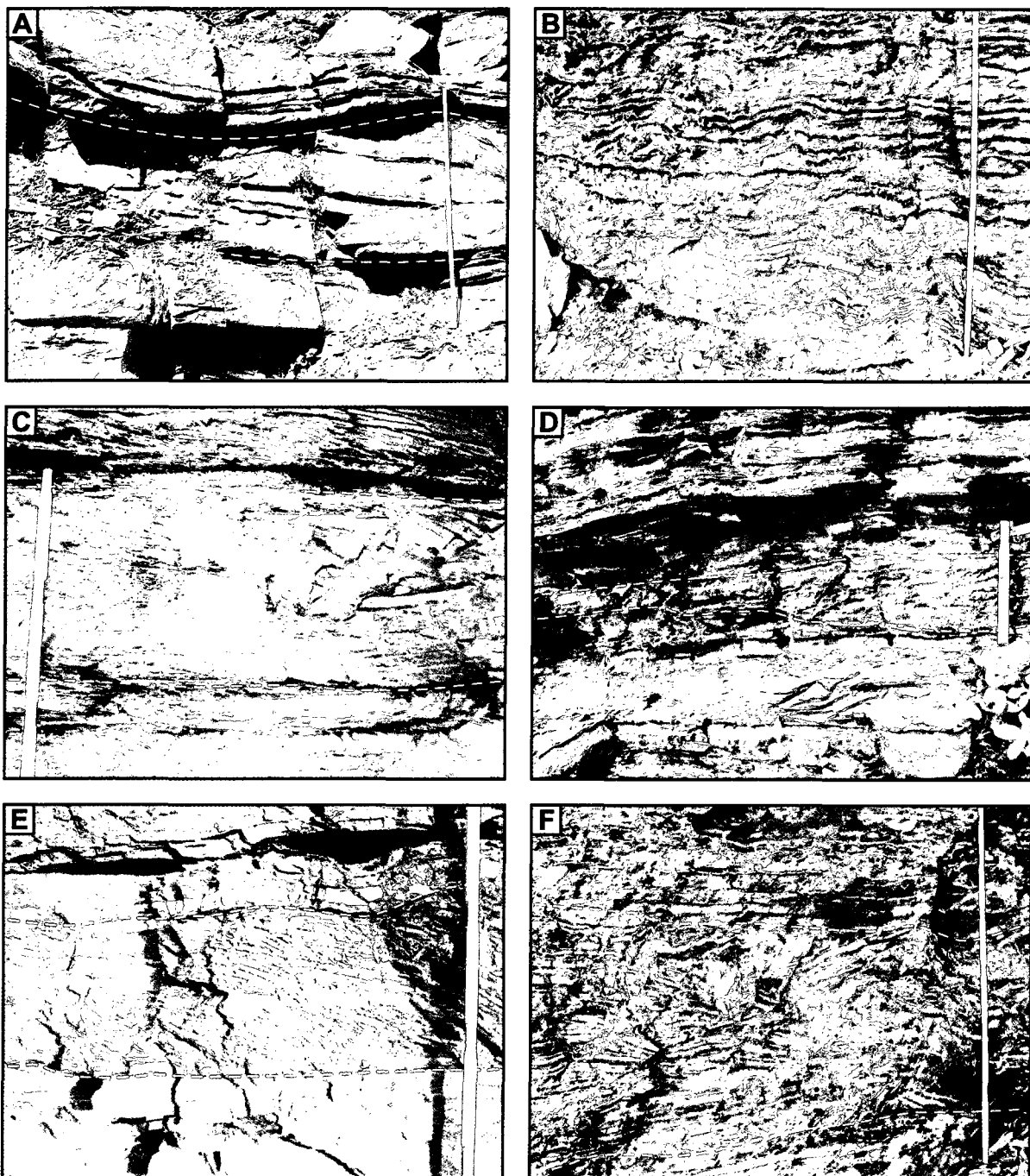


Figure 3.7: A) to F) Representative lithofacies photos of TLM-4 breccia. A) LL5: basal slump or slide scar surfaces in TLM-1 siltstone. Ruler is 100 cm. B) LL5: large, deformed slide block of TLM-3 in strata of TLM-1 and TLM-2. Ruler is 100 cm. C) LL1: ptygmatically-deformed limestone clasts. Ruler is ~50 cm. D) LL1: lenticular bed geometry which grades laterally into a TLM-3 limestone bed. Ruler is 20 cm. E) LL5: poorly-developed imbrication in debris flow deposit. Ruler is ~50 cm. F) LL5: debris flow deposit in TLM-3 strata. Ruler is 100 cm.

3.5.1.5 Massive sandstone (TLM-5)

TLM-5 consists of thin- to very thick-bedded (0.08 to 1.70 m) fine- to medium-grained sandstone. Beds are massive with scour bases and locally are amalgamated. This facies was observed only at one location (PM1) and beds thicken-upward (0.08 to 0.25 m, 0.25 to 0.50 m, 0.35 to 1.70 m) over an interval approximately 75 m thick.

3.5.2 Lithofacies associations and interpretations

3.5.2.1 Siltstone association

The siltstone-dominated lithofacies association of TLM-1 + TLM-2 + TLM-4 ± TLM-5 is interpreted as regionally line-sourced, siliciclastic basin-slope to basin-floor deposits. Although TLM-1 and TLM-2 are composed mostly of fine-grained sedimentary rocks, the two lithofacies consistently exhibit bedload transport features indicating the importance of traction transport during deposition. In many cases, the quality of the outcrop or level of metamorphism obscures these features, but on fresh or cut surfaces, structures are obvious. TLM-1 siltstone to mudstone beds are characterized by the T₀ to T₇ turbidite sequence as described by Stow and Shanmugam (1980). In sections of the TLM, incomplete sequences are observed, commonly with base-cut-out units (Stow et al. 1984; Stow and Piper 1984). Preferential weathering tends to accentuate the alternating units of T₄₋₅ (discontinuous siltstone laminae in mudstone) and T₆₋₇ (graded mudstone with siltstone lenses) enabling their identification. They deposit from minor traction with subsequent suspension fallout from low energy, waning turbidity currents. The wispy, lenticular or discontinuous lamination combined with isolated/fading ripple stratification is indicative of sediment starvation. Although not as commonly recognized in the ancient rock record as the Bouma (1962) turbidite sequence, these fine-grained turbidites have been documented in many other mid- to lower- slope environments (e.g. Reading and Walker 1966; Pickering 1982; Stow and Piper, 1984 and references therein; Coniglio and James, 1990; Oaie, 1998). Isolated TLM-2 very-

fine sandstone beds are present within TLM-1 siltstone strata and form classic Tbc(d) turbidites (Bouma, 1962) deposited from low-concentration turbidity currents. Strata of the TLM are distinctively more siltstone-rich than the underlying WSG mudstone-rich units suggesting a shift occurred in erosional and transport processes in the upslope hinterland. The relatively high abundance of detrital micas and heavy accessory minerals (e.g. Fe- and Ti-oxides) in the TLM is explained by the lack of significant seafloor reworking with turbidites sourced directly from physically weathered debris that underwent a low intensity of continental chemical weathering.

At Lake Louise and Jasper (also Dogtooth Range, Kubli, 1990) the TLM is a distinctive purple colour from the presence of secondary diagenetic hematite. The non-detrital hematite in the siltstone is interpreted to be the result of the voluminous input of oxygen-rich, surface water by turbidity currents and its reaction with reduced iron forming a paleo-oxidation zone in the shallow subsurface (e.g. Wilson et al., 1985; Thomson et al., 1987; Buckley and Cranston, 1988). The thin green zone (~1 cm) at or near the base of most laminae is a paleo-reduction zone, and is interpreted to mark the ferric-ferrous iron boundary (Lyle, 1983). This part of the relict turbidite bed is not in communication with the oxygen front diffusing downward from the sediment-water interface. The relatively thicker oxidized purple-coloured layer in the upper part of the bed suggests that the influx of sediment and oxygen-rich waters (and downward migrating oxygen front) occurred relatively quickly and provided insufficient time between turbidity current events for background reducing conditions to become re-established in the shallow substrate (e.g. Buckley and Cranston, 1988). It is important to note that although the process is similar to turbidites described by previous authors (e.g. Wilson et al., 1985; Thomson et al., 1987; Buckley and Cranston, 1988), the paleo-oxidation fronts in the TLM do not appear to be controlled solely by the amount of organic matter available for the downward migrating oxygen front. Rather, this reflects the voluminous influx of oxygen-rich surface water mixing and reacting with reduced

iron in the seawater (upwelled?) and production of diagenetic hematite. The filamentous morphology of the hematite also suggests the influence of bacterial processes (e.g. Juniper and Fouquet, 1988; Kennedy et al., 2004). This process might also explain the lack of organic carbon in the enigmatic discoid structures (Hofmann, 1972; Gussow, 1973) observed in the purple siltstone of TLM-1, because the organic material would have been completely oxidized during bacterially mediated diagenetic reactions. Other reduction zones in the purple siltstone units are green-coloured diagenetic haloes that likely nucleated around remnant organic material or are the result of secondary alteration along fracture planes by (Mesozoic) metamorphic fluids.

Sedimentary structures in the lower part of the TLM consistently indicate that the dominant depositional process of this fine-grained material was turbidity currents, and not other processes like bottom-currents (contour currents) or suspension settling from sediment lofting. The TLM does not exhibit features common to contourites such as inversely graded sequences (cm-scale), sediment of local and exotic origin, nor paleocurrents oriented consistently parallel to the paleo-slope (e.g. Stow and Piper, 1984). Furthermore, the lack of continuous mudstone-rich parallel laminae, rhythmic couplets of sandstone-siltstone and siltstone-mudstone, or ice-rafted debris (IRD) also suggest that suspension settling from lofted sediment turbidity plumes was of secondary importance as a depositional mechanism (e.g. Ó Cofaigh and Dowdeswell, 2001; Hesse et al., 2004).

Rare TLM-4 breccia beds are interpreted to be mass movement deposits caused by intraformational slope failure related to gravitational instability (e.g. Mulder and Cochonat, 1996). Beds consisting of contorted blocks of TLM strata are interpreted to be slump or slide blocks bounded beneath by its failure plane. A second type of breccia consists of massive mudstone- to siltstone-rich matrix with ptygmatically deformed, and/or imbricated clasts. Clasts were sourced from fragmentation of local TLM-material during collapse. The disorganized, unconsolidated mass of sediment remobilized as a cohesive, muddy sediment

gravity flow (debris flow) with subsequent en-masse freezing slightly farther downslope. The relatively common slump and slide deposits in the TLM at Lake Louise, Jasper and Frances Creek suggest that these areas were located in mid- to lower-slope environments; and that the paleo-slope gradient was relatively steep, on the order of $>1^{\circ}$ to 3° (e.g. Coleman and Prior, 1988; Mulder and Cochonat, 1996). Toward the west, the Mount Robson area is characterized by rare, thin-bedded mass movement deposits and these locations are interpreted to have been at the base of slope and mark the transition to basin-floor environments.

Only at Frances Creek (PM) is there the thick, massive sandstone beds of TLM-5 interbedded with green-coloured siltstone (TLM-1). TLM-5 corresponds to the basal Ta (Bouma, 1962) or S3 (Lowe, 1982) division. Beds of TLM-5 are interpreted to have been deposited rapidly from suspension by high concentration turbidity currents capped by siltstone to mudstone deposits emplaced by the dilute, low-energy tail of the current. At this location, these strata are above the TLM-3 limestone-siltstone rhythmites and result in a thicker (~135 m) TLM section and an atypical upward gradation into the GSM.

In the westernmost sections (e.g. Cariboo Mountains), TLM strata lack slope-type deposits, in particular slump/slide and debris flow deposits and are interpreted to be basin-floor deposits. At these locations, TLM-2 turbidites consistently dominate suggesting that, on average, higher energy sand-dominated flows were capable of greater travel compared to the silt- to mud-dominated flows that deposited strata of TLM-1. TLM-2 forms distinctive repetitive Tbcd turbidites that are persistent laterally for more than 500 m.

3.5.2.2 Rhythmic limestone-siltstone association

In all outcrops, the TLM siltstone association grades upward into the rhythmic limestone-siltstone association of TLM-3 + TLM-4. The interbedded limestone-siltstone strata are interpreted to consist of classical Bouma Tbcd turbidites. In the basal part of this lithofacies, the limestone part of the bed

consistently forms the lower tractional Tbc portion of the turbidite whereas the siltstone forms the low-energy traction and suspension-dominated Td portion. This lithofacies deposited under low- to moderate-concentration turbidity flows, with tractional features suggesting deposition of limestone under relatively high energy, upper-stage plane bed to lower-stage ripple conditions followed by suspension deposition of siliciclastic mudstone and siltstone. In sections LL1 and LL5 the mineralogical units are reversed, with very-fine siliciclastic sandstone to siltstone forming the basal tractional part and limestone the upper suspension fallout deposit. In nearly all sections (exception being PM1), TLM-3 strata then grade upward into GSM-1.

Limestone turbidites become more abundant and increase in calcite content up-section. They are composed of calcite with low trace-element concentrations, which then is enveloped by secondary poikilotopic calcite cement (Chapter 5). The irregular rounded shape and inclusion-rich nature of the early calcite phase combined with the common tractional sedimentary structures implies that these are transported calcite grains from upslope areas and remobilized into the basin by dilute turbidity currents. Cements in the fine-grained siliciclastic strata were primarily derived from re-precipitation of calcite sourced from dissolution of detrital carbonate grains similar to the limestone beds (Chapter 5). Diagenesis resulting in localized dissolution of carbonate silt-mud, remobilization and carbonate re-precipitation most probably accentuated the sharply defined boundaries of the TLM rhythmites (e.g. Hallam, 1986; Coniglio and James, 1990). However, the rhythmite aspect in the silt-dominated TLM is interpreted to reflect a primary depositional pattern with diagenetic enhancement only partly contributing based on the lack of remineralization textures (e.g. concretions, nodules) and lower mudstone content compared to other examples in the literature (e.g. Coniglio and James, 1990). The rhythmites are widespread across the Windermere basin arguing for regionally line-source deposition of the mixed sediments (e.g. Coniglio and Dix, 1992; Coniglio and James, 1990).

In the most proximal sections, the limestone-siltstone rhythmites grade upward from purple-colour (with hematite) to green-colour (with pyrite), implying an overall progressive shift from oxic to reducing conditions. However, this shift is not everywhere bedding parallel (e.g. unlike the gradational contact between TLM-GSM). In some sections (e.g. LL5), purple and green units alternate over a stratigraphic interval before the transition to fully reducing conditions (green colour). In other areas, the transition is at different stratigraphic levels within the rhythmites (e.g. LL1 vs. LL6), or at an oblique angle to bedding (e.g. JP1). This suggests that the redox transition may be influenced by local variations such as paleo-slope inclination, subtle sea-floor topography, relative proportion of oxygen-rich surface water input, or irregularities along the diffusion gradient fronts in the shallow subsurface. In most places the rhythmites of TLM-3 grade rapidly (over a few metres) into mudstone of the GSM.

Similar to the TLM siltstone association, rare TLM-4 breccia beds are locally observed in the rhythmic limestone-siltstone strata. They consist of slump and slide blocks from intraformational slope failure and/or remobilized muddy debris flows (e.g. Mulder and Cochonat, 1996). In one section (LL4) a thick ~ 1 m block of rhythmic limestone-siltstone is within the TLM siliciclastic association, below the initial stratigraphic appearance of the TLM-3 lithofacies. This implies that similar limestone units had deposited upslope (e.g. outer shelf and/or the upper slope) prior to their progradation and deposition in outboard locations.

3.6 GEIKIE SIDING MEMBER

The Geikie Siding Member (GSM) is a homogeneous unit composed mostly of organic-rich mudstone to siltstone that exhibits an overall upward-fining trend. Rare isolated interbeds of dark-grey limestone or very fine sandstone are also observed. In general, the thickness of the GSM varies little, ranging from ~2 to 6 m in most locations, except for the Cariboo Mountains where it is slightly thicker, from

10 to 15 m. A notable exception is at Frances Creek (PM1) where strata of GSM are >200 m thick (see below for discussion). The member is generally grey in colour including medium light grey to medium light blue-grey and dark grey to greyish black with the darker colours indicating higher organic-carbon content. Post-metamorphic, total organic carbon content (TOC) in GSM averages 0.83% with values as high as 1.82% (Chapter 4). The basal contact between the GSM and underlying TLM is gradational with the transition over an interval <0.5 to 2 m thick and marked by a progressive colour change (e.g. green to grey), an overall decrease in carbonate content and increase in organic matter content. Conversely, the upper contact of the GSM with the Whitehorn Mountain Member (WMM) is usually sharp and marked by a distinctive lithofacies change. Where the WMM is fine-grained and thinly developed (<0.5 m) the GSM grades into the WMM, which in turn grades into mudstone of the overlying Windermere Supergroup (WSG). At these locations (e.g. LL1, LL5, MR1), contacts between the GSM-WMM-WSG are extremely difficult to recognize in outcrop and require the use of other techniques such as gamma-ray counts (e.g. shift to lower values) or geochemistry (e.g. decrease in TOC content or molybdenum concentration) to identify its location (Chapter 4). The fine-grained nature of the GSM tends to make it susceptible to surface weathering and also secondary deformation related to Cordilleran orogenesis. As a result, small-scale features are typically difficult to identify except in outcrops polished by recent glacial abrasion (e.g. Eagle Valley, Cariboo Mountains) or in fresh roadcuts (e.g. Geikie Siding).

3.6.1 Lithofacies description

3.6.1.1 Mudstone (GSM-1)

GSM-1 consists of thin- to thick-laminated (0.2 to 1.0 cm) mudstone with alternating siltstone to mudstone (light-coloured) and mudstone-rich (dark coloured) laminae (Fig. 3.8A to D; Fig. 3.9A to F). The unit fines-upward and becomes darker grey in colour reflecting the gradual increase in organic-matter

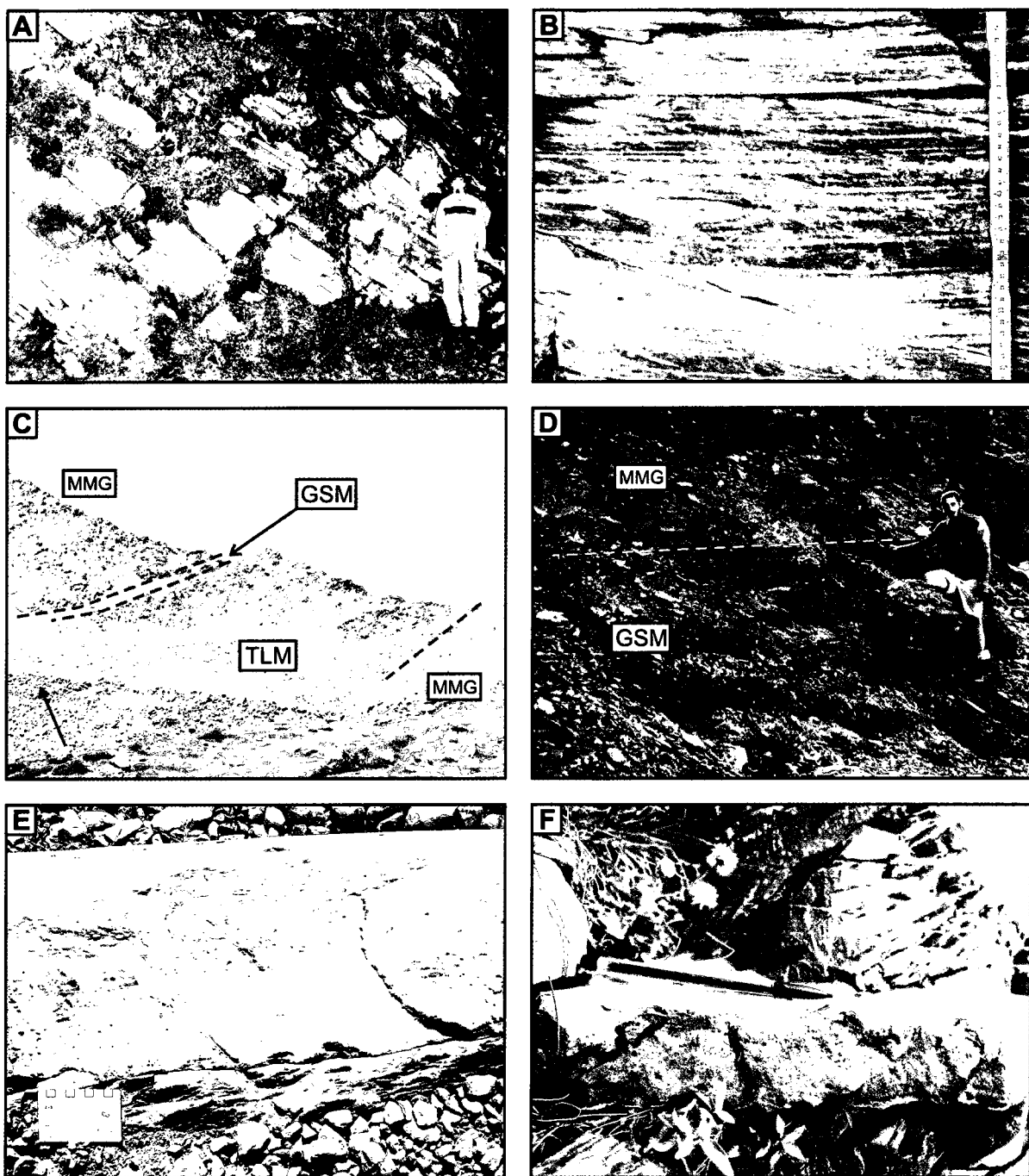


Figure 3.8: A) to F) Representative lithofacies photos of GSM. A) and B) JP1: Interbedded siltstone and organic-rich mudstone. Ruler is ~30 cm. C) MR1: Recessive nature of GSM compared to strata of underlying TLM and mudstone units of the overlying Middle Miette Group (MMG). D) MR1: Contact between mudstone units of the GSM and overlying Middle Miette Group (MMG). GSM is finer-grained and more recessive with the GSM-WMM-MMG contact marked by a decrease in gamma-ray counts, total organic carbon content and selected trace elements (e.g. molybdenum) E) PM1: Carbonate-cemented Tbc turbidite sandstone with basal scour surface. F) PM1: Carbonate-cemented sandstone Tbc turbidite with ripple-top. Pencil is ~15 cm and points in the direction of flow. Arrows indicate upward stratigraphic direction.

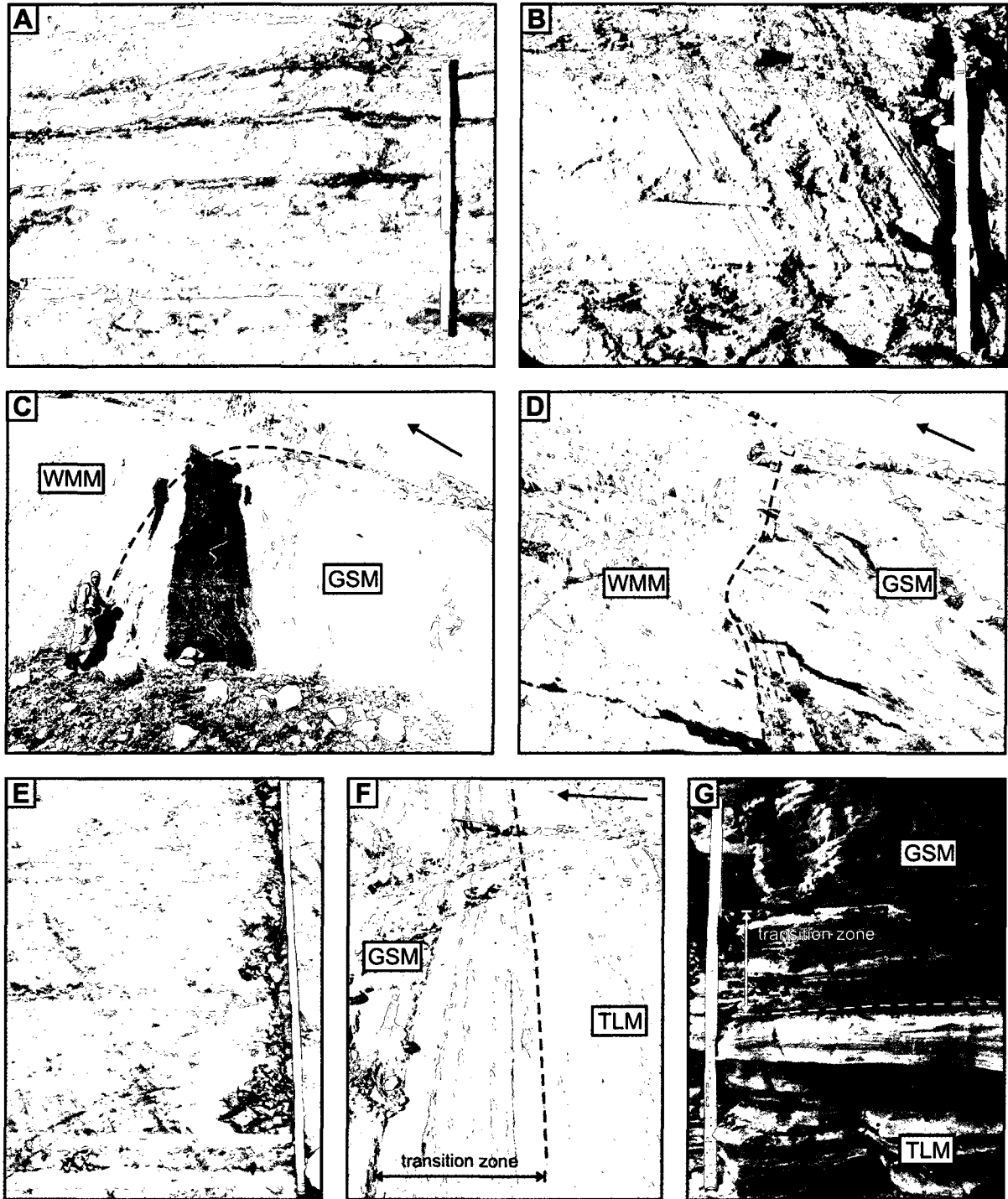


Figure 3.9: A) to G) Representative lithofacies photos of GSM. A) CM1: Mudstone (pelite) interbedded with limestone. Ruler is 50 cm. B) CM1: Mudstone (pelite) with interbedded limestone bed. C) - D) CM1: Sharp contact between GSM and overlying fine-grained carbonate-rich units of WMM. E) CM1: Mudstone (pelite) interbedded with Tbc turbidites of fine-grained sandstone. Ruler is 100 cm. F) CM1: Gradational contact between GSM and underlying TLM. Ruler is 100 cm. G) LL1: Gradational contact between GSM and underlying TLM marked by dark limestone beds. Ruler is 50 cm. Arrows indicate upward stratigraphic direction.

content (Chapter 4). Sedimentary structures are limited to planar lamination, siltstone lenses, normal grading and micro-scours. Silt-sized sediment consists mostly of quartz with trace amounts of plagioclase feldspar, muscovite and accessory heavy minerals. Also present within the GSM are outsized, (100 to 400 μm) single chlorite flakes. Locally, pyrite is common either as disseminated cubes or as distinct laminae. Isolated, very thin to medium beds (1 to 16 cm) of light to dark grey, organic-rich limestone with no apparent tractional features are usually lensoid and commonly more abundant at certain locations (e.g. CM1 and CM2). Rare, very thin to thin beds of very fine sandstone (1 to 5 cm) with small scoured bases are observed and in some cases are planar laminated or ripple cross-stratified. The Frances Creek locality (PM1) is an exception, where sandstone forms common interbeds (Fig. 3.8E, F). Beds range up to 30 cm thick, and commonly have a lenticular geometry. Sedimentary structures include planar lamination, ripple or dune cross-stratification, 3D ripple formsets, scours and load structures. Sandstone beds are easily recognized in the field by their distinctive brown colour caused by pervasive iron-rich dolomite or calcite cement.

3.6.1.2 Breccia (GSM-2)

GSM-2 consists of clast-supported breccia composed of a dark grey mudstone to siltstone matrix and grey limestone or mudstone clasts. It is observed at a single locality (JP1) where it is 2.4 m thick. The clasts consist of either grey to dark grey limestone or mudstone to siltstone. They were derived from underlying lithofacies of GSM-1, and are oriented sub-parallel to the base of the bed. Clasts are elongate, up to 30 cm long, with aspect ratios of 5 to 15.

3.6.2 Lithofacies interpretations and associations

With the exception of two localities (JP1 and PM1), the GSM is regionally consistent in thickness and lithology from basin-slope to basin-floor settings. GSM-1 is thinly laminated indicating slow sedimentation rates and a predominance of

suspension fallout of hemipelagic or pelagic material. This lithofacies becomes more organic-rich upsection suggesting a possible combination of three main factors (e.g. Katz, 2005; Tyson, 2005): 1) elevated organic-matter preservation (e.g. anoxic environments); 2) elevated productivity levels (e.g. upwelling, riverine nutrient input); 3) lowered sedimentation rate (e.g. slow sedimentation rate results in an increase in organic concentration from reduced mineral dilution). Elevated productivity levels during GSM deposition were likely the result of increased nutrient supply to deep-marine environments while the slow rates of sedimentation permitted the concentration and preservation of organic-matter and select redox-sensitive trace-elements (e.g. molybdenum, vanadium), perhaps under low oxygen levels (Chapter 4). The inter-stratification of organic-rich pelagites and organic-poor hemipelagites and/or turbidites suggests the periodic influx of dilute, oxygen-rich sediment gravity flows, and that the Windermere basin was not completely stagnant during deposition of the GSM. Later maturation of the regional organic-rich strata would have formed a high-quality deep-marine source-rock horizon that may have charged parts of the enveloping turbidites of the WSG.

Large, metamorphic chlorite flakes are observed in laminae of the GSM-1 show a foliation that is discordant to the regional metamorphic trend. Chlorite is physically unstable and when present as a detrital mineral is interpreted to reflect provenance from plutonic or low-grade metamorphic rocks characterized by minimal chemical weathering, either because of rapid physical erosion from uplift, or glacial abrasion in a cold-climate environment (e.g. Chamley, 1989). Flakes were subsequently transported (lofted?) from the upslope area (e.g. shelf) into the water column where they then settled to the seafloor.

Although the dominant deposition mechanism for the GSM is suspension settling, it is important to note that tractional sedimentary structures are common. These structures are interpreted to have deposited from dilute, low-energy turbidity currents followed by waning flow that allowed suspension fallout, and are classified as Tde or T₃ to T₇ turbidites. Deposits of higher energy turbidity currents

are usually rare and isolated, except at Frances Creek (PM1), which is composed of common Tbc sandstone turbidites. At this location, the deposition of a comparatively larger volume of sand reflects a higher local sedimentation rate (dilution factor) that prevented the concentration of organic matter and resulted in organic-poor GSM strata an order of magnitude thicker (>200 m).

Similar to TLM-4, the isolated presence (JP1) of GSM-2 breccia is interpreted to be the result of local slope failure caused by gravitational instability. During movement the sediment mass, which consisted of locally derived GSM-material, became sufficiently remoulded and disaggregated that it then evolved into a cohesive debris flow and deposited downslope.

3.7 WHITEHORN MOUNTAIN MEMBER

The Whitehorn Mountain Member (WMM) is the most complex and lithologically diverse of the members of the OFP. Also, it is the most variable in thickness, ranging from <0.5 to 165 m. Unlike the TLM and GSM, the WMM consists of a diverse assemblage of lithofacies that are commonly location specific. The base is usually sharp and locally deeply scoured, especially where it has removed part of the GSM and TLM. In certain places (e.g. Lake Louise, Jasper, McKale River), erosion of the lower two members is areally extensive (10s of km), whereas at other locations, local erosion (10s of m) is more common (e.g. Cariboo Mountains). In places where the GSM and TLM are eroded completely, the WMM overlies directly strata of the underlying WSG. Although sandstone lithofacies of the WMM are coarse-grained, and therefore similar to the overlying arkosic sandstone ("grit") turbidites of the WSG, certain lithofacies are readily distinguished by their mature, well-rounded quartz-rich mineralogy and the contact between the two is usually sharp. Although rare ($n = 4$), paleocurrent indicators (3D current ripples, parting lineation) in the WMM indicate flow principally toward the northwest with one toward the southwest (Appendix G).

3.7.1 Lithofacies description

3.7.1.1 *Diamictite to breccia (WMM-1)*

WMM-1 consists of purple-, green- or grey-coloured, matrix- to clast-supported, diamictite to breccia in a massive, mudstone to siltstone matrix (Fig 3.10A to G). The matrix mineralogy has a composition similar to laminated mudstone of WMM-2. The unit is generally medium- to very thick-bedded (0.1 to 2.12 m) with some exceptionally thick, most likely amalgamated beds (>6 m). The lithofacies is poorly sorted, has a sharp scoured basal contact, undulatory top contact and exhibits a lenticular geometry in outcrop where it grades laterally into WMM-3. This lenticular geometry is also observable at the map-scale where the diamictite to breccia units are laterally discontinuous and pinch-out (Evans, 1962; Charlesworth et al., 1967; Waldron, personal communication, 2006). Clasts are elongate, up to 1 m long and exhibit a wide range of fabrics from chaotic, sub-parallel to bedding and imbricated. This lithofacies is present at, or near the basal WMM contact with clasts derived from local TLM lithofacies, consisting of purple to green siltstone (TLM-1), carbonate-cemented sandstone (TLM-2), or limestone (TLM-3).

3.7.1.2 *Laminated mudstone (WMM-2)*

WMM-2 is poorly sorted, immature mudstone to very fine sandstone with a distinctive “pinstripe” character and general lack of observable sedimentary structures in the field (Fig. 3.11A to D). This lithofacies displays a range of colours including: blue (medium blue-grey), purple (greyish purple to greyish purple-red), green (blue-green, bright green, greenish grey) and grey (medium grey) (Munsell Colour Chart). It is mostly very thin- to thick-laminated (<0.5 to 10 mm) but locally is very thin-bedded (<1 to 2 cm) and shows a subtle upward-coarsening trend in some sections (mudstone to siltstone to siltstone-very fine sandstone). This facies is defined by discontinuous to planar lamination and locally is up to 125 m thick

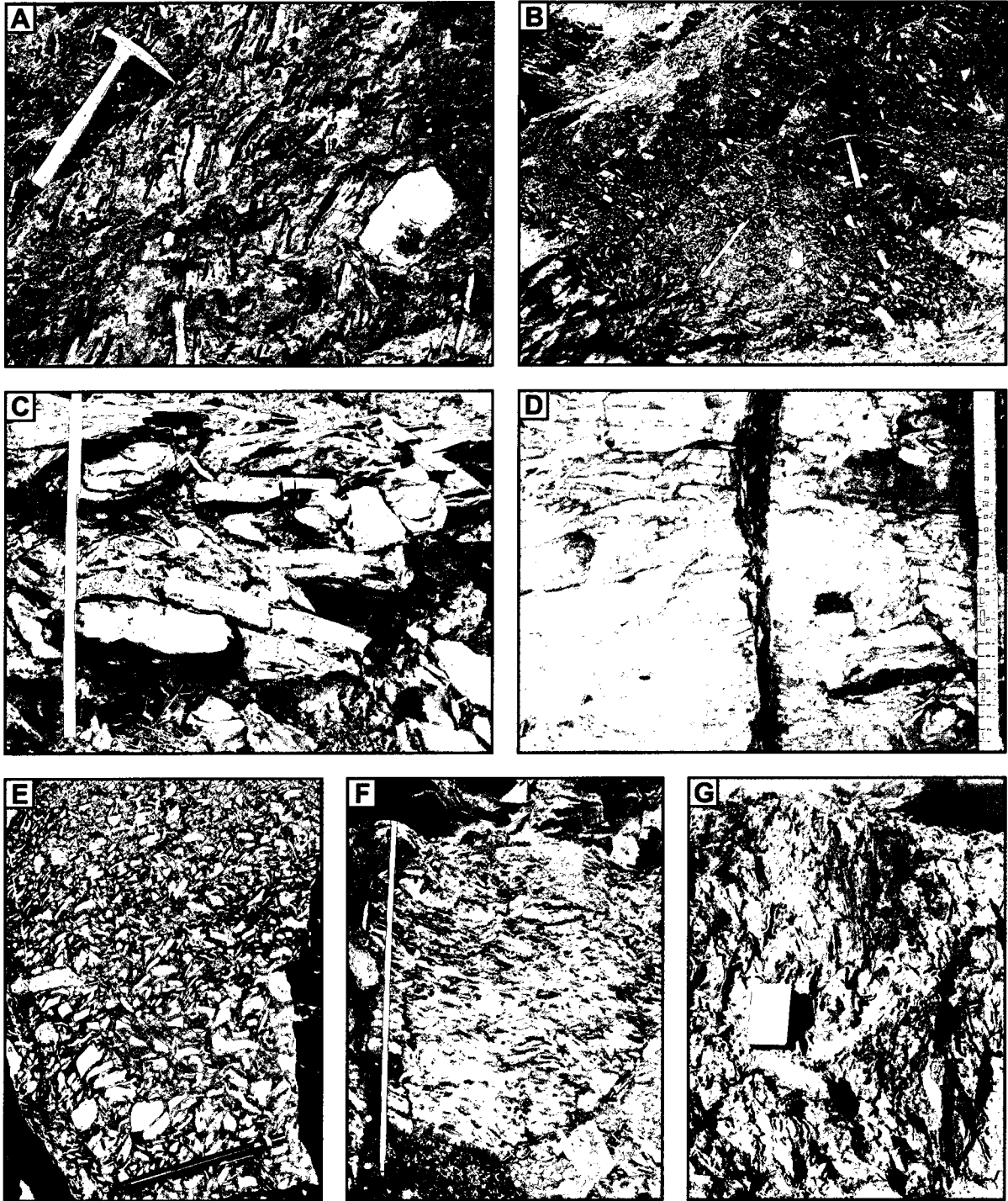


Figure 3.10: A) to G) Representative lithofacies photos of WMM-1 diamictite to breccia. A) LL4: Debris flow dominated by lenticular carbonate clasts. Hammer is ~35 cm. B) LL4: Thick amalgamated beds near base of WMM. Hammer is ~35 cm. C) LL4: Debris flow marking contact between WMM and overlying Hector Formation (Middle Miette Group). Ruler is ~50 cm. D) JP3: Debris flow dominated by grey limestone clasts. Ruler is 100 cm. E) LL4: Block of WMM-1 with cm-sized angular carbonate clasts. Pencil is ~15 cm. F) LL4: Debris flow near top of WMM dominated by grey limestone clasts. Ruler is 100 cm. G) JP3: Debris flow with large, (up to 1 m) elongated carbonate clasts. Fieldbook is ~20 cm. Photos A), B) and E) are courtesy of G. M. Ross.

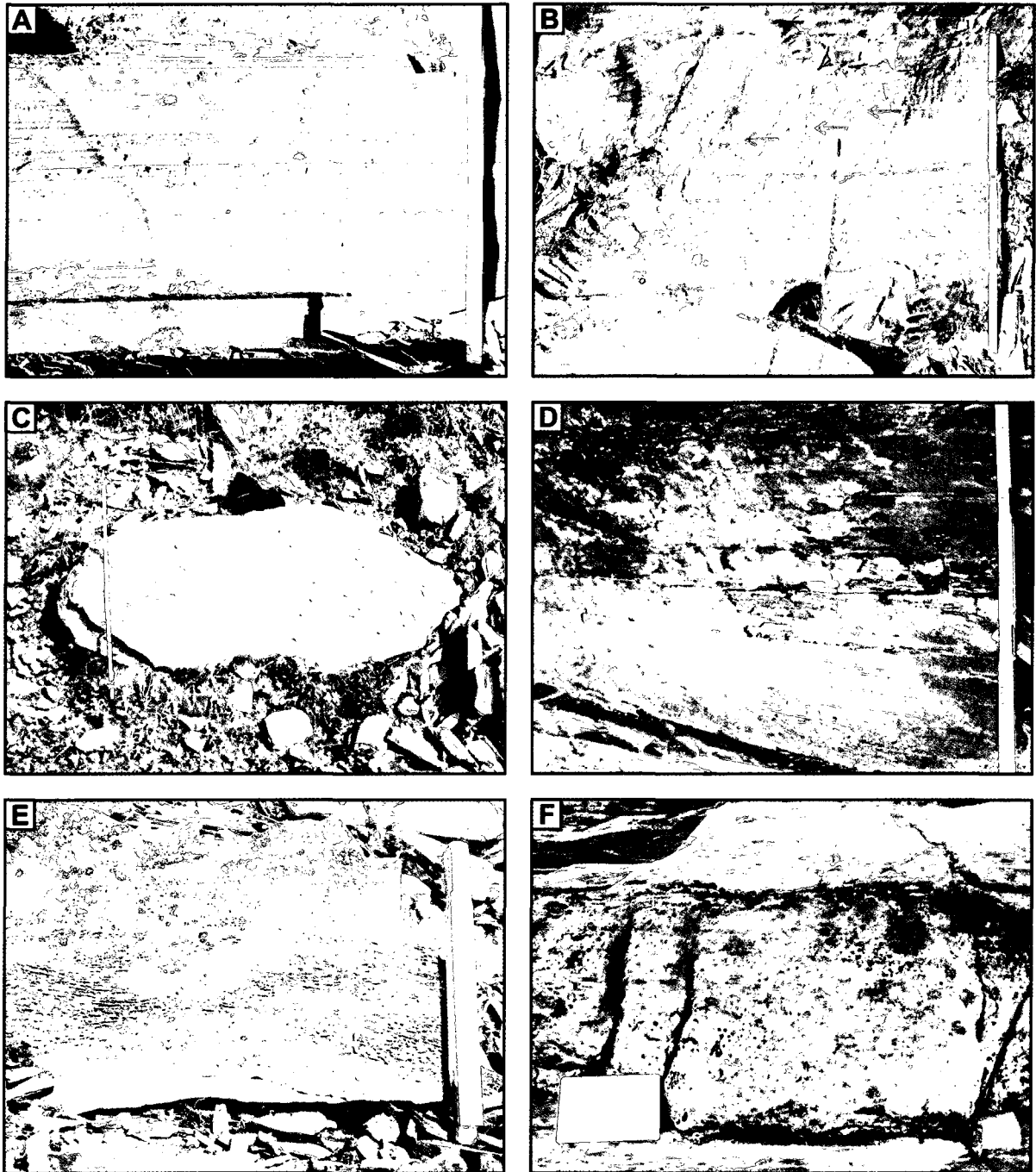


Figure 3.11: A) to D) Representative lithofacies photos of WMM-2 laminated mudstone. Ruler is ~40 cm. A) LL4: T_3 to T_6 turbidites illustrating purple and green redox changes. B) LL4: Repetitive T_3 turbidites with rare example of scour surface. Ruler is 50 cm. C) LL2: overturned slab with current ripple formsets. Ruler is 100 cm. D) JP3: isolated WMM-3 Tbc turbidite in WMM-2 strata. Ruler is ~45 cm. E) to F) Representative lithofacies photos of WMM-3 sandstone. E) LL4: Ripple cross-stratified Tc turbidite. F) PM1: Planar laminated Tb turbidite.

interstratified with other WMM lithofacies. Sedimentary structures, although uncommon, include micro-scours and normal grading with rare ripple-stratification, scours and parting lineation. Soft-sediment deformation features include ductile micro-folding and distorted or convolute lamination (Fig. 3.17A, E). Mineralogically, strata of WMM-2 are similar to TLM-1 and consist of silt-sized quartz (10 to 20%), plagioclase feldspar (1 to 10%) with subordinate (1 to 5%) detrital chlorite, muscovite and heavy accessory minerals (see TLM-1 above for list) in a recrystallized matrix of chlorite-muscovite. Heavy minerals are disseminated within the matrix or form discrete laminae. Detrital chlorite is present either as outsized (>250 µm), large flakes in the matrix similar to GSM-1 or in some siltstone laminae it makes up a significant portion (15 to 30%) of the overall mineralogy. Trace amounts of iron-dolomite cement are also present.

3.7.1.3 Sandstone (WMM-3)

WMM-3 is a poorly to moderately sorted, submature, fine- to very coarse-grained sandstone (rarely conglomerate) classified principally as a feldspathic wacke (Fig. 3.11 E, F). Strata range in thickness from 1 to 95 cm but mostly are thin- to medium-bedded (~ 5 cm). Typically, beds are planar laminated or ripple cross-stratified and carbonate cemented by either iron-rich dolomite or iron-rich calcite and as a consequence is brown-coloured on weathered surfaces. Contacts are either scoured or undulose with uncommon dark limestone lenses present. At the Frances Creek locality (PM1) strata of WMM-3 form a ~20 m thick interval consisting generally of medium to very thick bedded (0.21 to 2.20 m) massive sandstone. Beds are scoured and have local quartz pebbles and/or carbonate rip-up clasts in the lower part of the bed. In places, beds have a lenticular geometry, and laterally grade from strata of WMM-2 (and WMM-8?) into strata of WMM-1. Soft-sediment deformation features are common and include loading and dewatering structures like “wrap-over lamination” in the planar-laminated beds (Fig. 3.17B, F). WMM-3 sandstone is composed primarily of quartz (~25 to 60%) and plagioclase feldspar (2

to 10%) with a relatively high proportion of recrystallized matrix (~10 to 45%) and carbonate cement (10 to 30%).

3.7.1.4 *Quartz arenite (WMM-4)*

WMM-4 consists of well-sorted, well-rounded, mature, medium- to very coarse-grained quartz arenite (rarely conglomerate) (Fig. 3.12A to F). The lithofacies ranges from medium- to very thick-bedded (0.1 to 2.4 m). Beds are laterally extensive, (“sheet-like”), and generally massive with subtle normal grading. Beds show basal scours and are typically amalgamated. Quartz pebble lags, carbonate or mudstone rip-up clasts, rare reverse-grading and patchy iron-rich calcite cement are found locally at the base of beds. Bed tops are locally planar laminated or ripple cross-stratified. Load and de-watering features (e.g. loading) are common between sandstone-sandstone contacts and are usually accentuated by preferential iron-rich calcite cementation (Fig. 3.17C, D, and G).

3.7.1.5 *Calcareous arenite to arenaceous limestone (WMM-5)*

WMM-5 encompasses a wide spectrum of mineralogical compositions between its two end-member kinds: quartz arenite (WMM-4) and limestone (WMM-6) (Fig. 3.13A to G). This lithofacies consists of well-rounded, mature quartz sandstone (coarse- to fine-grained) mixed with recrystallized calcite (30 to 90 µm). Petrographically, these two components comprise over 90% of the rock with trace amounts of plagioclase feldspar, chlorite, muscovite or heavy minerals. Strata are very thin- to thick-bedded (2 to 46 cm) and show tractional sedimentary structures that include: planar lamination, ripple or dune cross-stratification and minor scours. Subtle normal grading, undulatory contacts and rare load or slump features are also observed. WMM-5 strata commonly alternate between a predominance of quartz-sand rich units (quartz arenite and calcareous arenite) and carbonate-rich units (arenaceous limestone and limestone). In most instances, each bed-set exhibits repetitive thinning-upward trends over a thickness range of 1 to 5 m. However, the

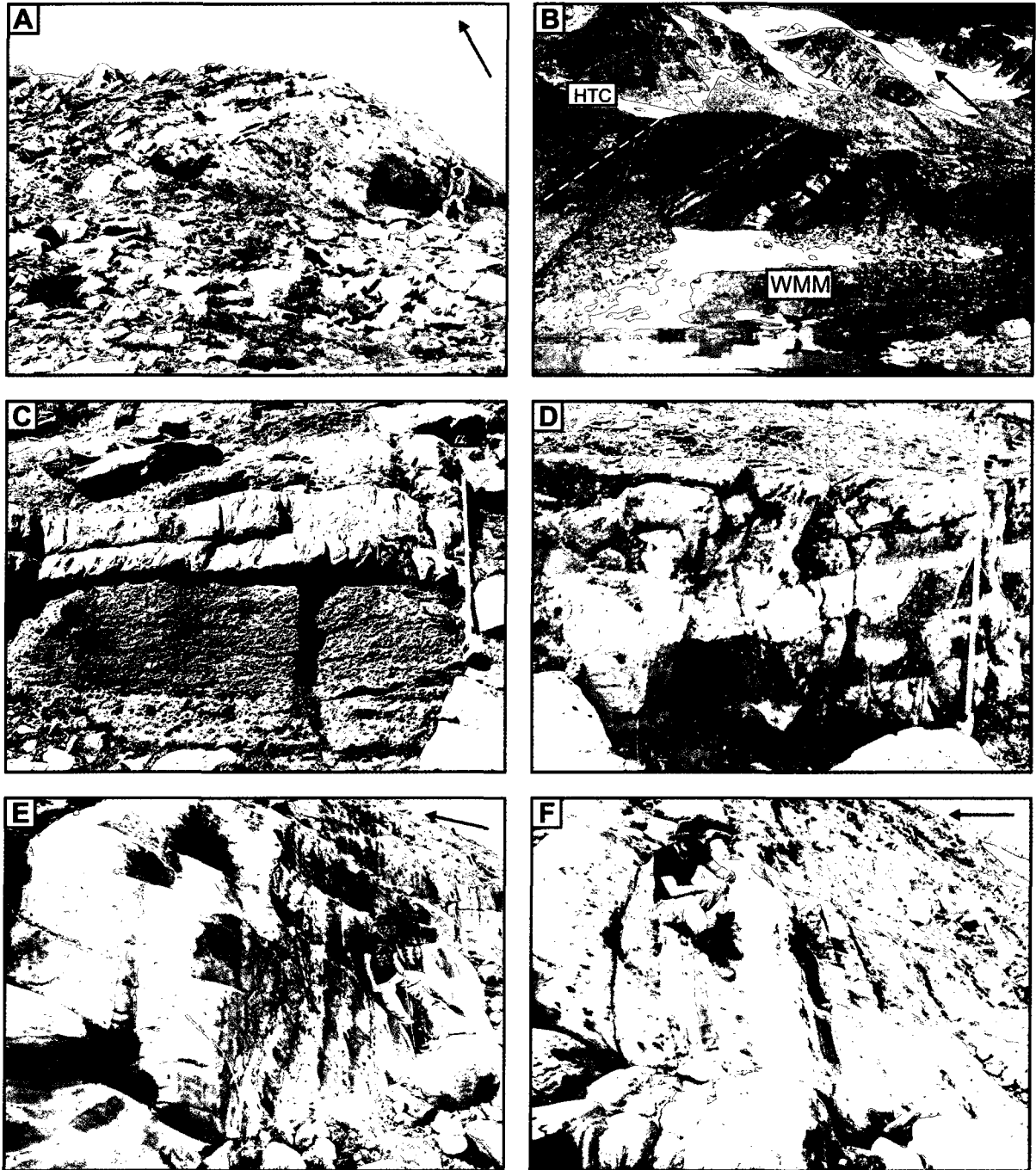


Figure 3.12: A) to F) Representative lithofacies photos of WMM-4 quartz arenite. A) PM1: Thick, amalgamated Ta turbidites interbedded with Tbc turbidites. B) PM1: Two, ~5 m thick WMM-4 Ta turbidites (light-coloured) encompassed by WMM-5 strata (dark-coloured). C) MK1: WMM-4 Ta or S2-S3 turbidite sharply overlying a WMM-8 S1 breccia. Ruler is ~50 cm. D) MK1: Preferential carbonate-cementation within Ta turbidites near contact between WMM and overlying MMG (Middle Miette Group). Ruler is 100 cm. E) – F) CM1: Basinal examples of thick, repeating WMM-4 Ta turbidites. Arrows indicate upward stratigraphic direction.

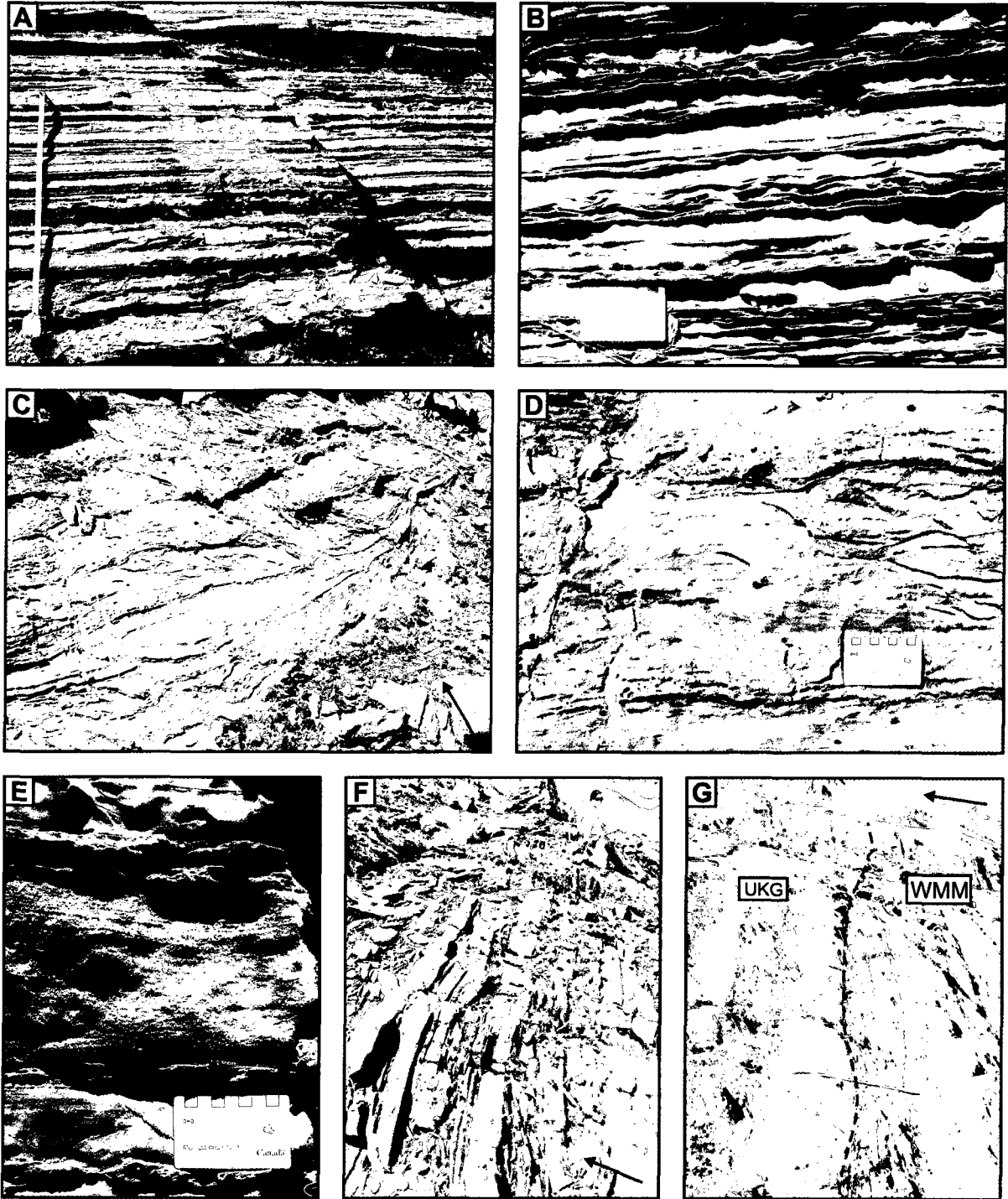


Figure 3.13: A) to G) Representative lithofacies photos WMM-5 (also WMM-4 and WMM-6). A) MK1: Thin calcareous arenite interbedded with planar laminated Tb(c) arenaceous limestone turbidites. Ruler is 50 cm. B) PM1: Thin calcareous arenite interbedded with planar laminated Tb(c) arenaceous limestone turbidites. C) PM1: Onlap of beds, possibly in small-scale erosional feature. Ruler is 50 cm. D) Interbedded Tb(c) turbidites. E) Tb(c) turbidites. F) PM1: T(a)b calcareous arenite turbidites interbedded with planar laminated Tb(c) arenaceous limestone turbidites. G) CM1: Contact between carbonate-rich WMM and generally non-calcareous overlying Upper Kaza Group (UKG). Ruler is 100 cm. Arrows indicate upward stratigraphic direction.

opposite was also observed where coarse-grained, calcareous arenite beds thicken-upward over ~9 m.

3.7.1.6 Limestone (WMM-6)

WMM-6 consists of dark-grey coloured, usually organic-rich limestone that is very thin- to medium-bedded (1 to 20 cm) (Fig. 3.14A to D). Strata are characterized by discontinuous to faint planar laminae with rare micro-scours and disseminated pyrite. It is composed mainly of recrystallized poikilotopic sparry calcite (20 to 60 μm) with minor (5 to 20%) silt-sized quartz, feldspar, mica or heavy minerals. WMM-6 is commonly found as clasts in the breccia to conglomerate beds of WMM-8.

3.7.1.7 Organic-rich mudstone (WMM-7)

WMM-7 mudstone consists of planar, medium-laminated (<0.1 to 0.5 cm) mudstone that forms units 0.13 to 1.60 m thick (Fig. 3.14E, F). Strata of lithofacies WMM-7 are differentiated from WMM-1 laminated mudstone by its higher mudstone content (recrystallized chlorite-muscovite matrix), higher organic-carbon content (average TOC 0.62%), abundant pyrite (disseminated or laminated) and common limestone lenses. In addition, tractional sedimentary structures are absent.

3.7.1.8 Breccia to conglomerate (WMM-8)

WMM-8 consists of poorly sorted, medium- to very thick-bedded breccia to conglomerate in a generally mature coarse-grained sandstone matrix, with rare mudstone- to siltstone-matrix (Fig. 3.15A to F). This lithofacies shows a wide range in bed thickness, matrix grain size, and type of clasts. Beds typically have a lenticular geometry and reverse grading is observed rarely. In a number of sections, it is very thickly bedded (1 to >10 m) with a matrix composed of mineralogically and texturally mature granule conglomerate to very coarse-sandstone. It is characterized by a variety of intrabasinal clast types which range from spherical to

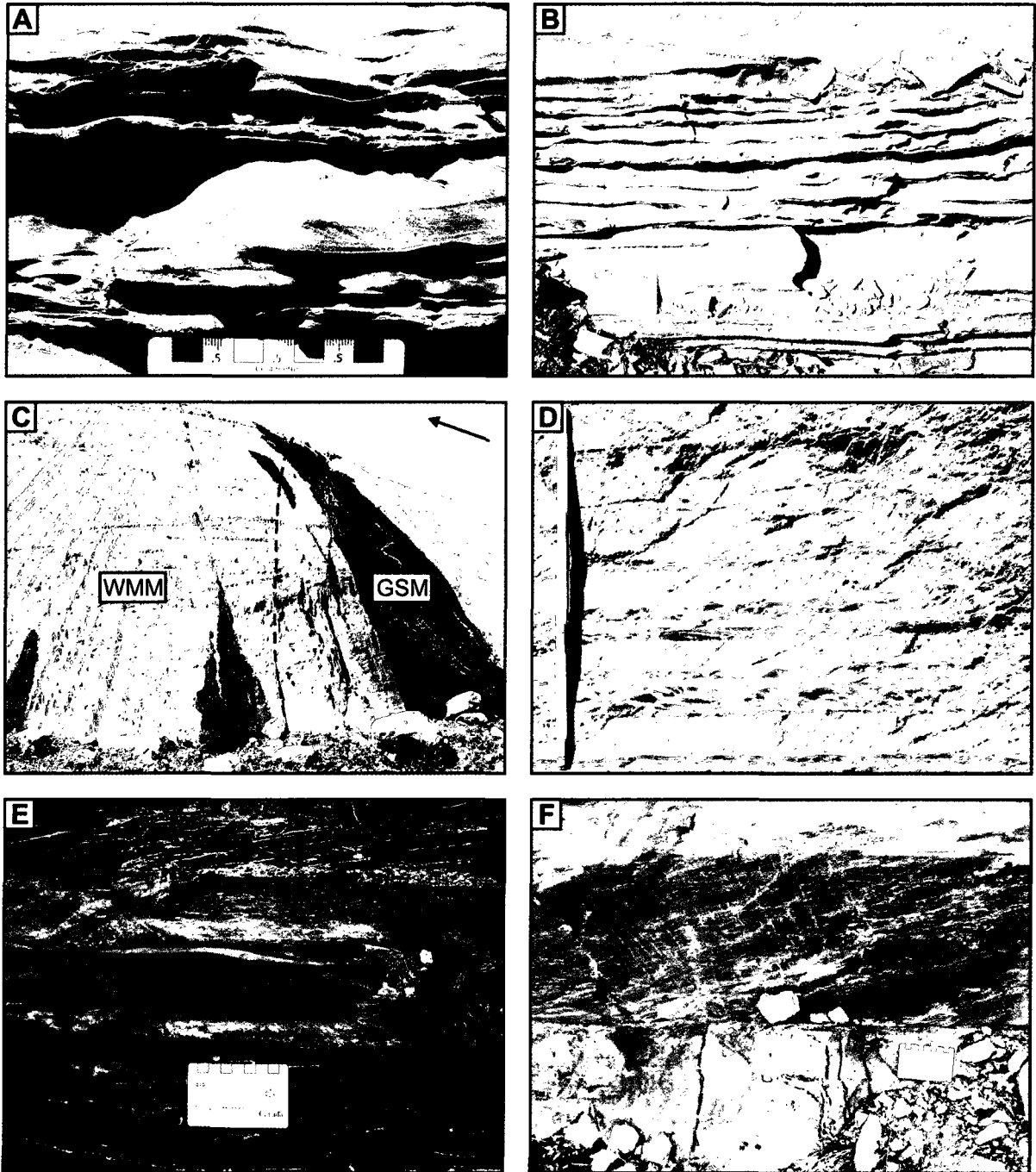


Figure 3.14: A) to D) Representative lithofacies photos of WMM-6 limestone (and WMM-5). A) PM1: Planar-laminated Td limestone turbidite. B) PM1: Example of metre-scale upward thinning of limestone beds. C) CM1: Sharp contact between WMM carbonate-rich strata and underlying GSM organic-rich mudstone (pelite). Arrow indicates upward stratigraphic direction. D) CM1: WMM-6 limestone interbedded with thin Tbc turbidites. Ruler is 50 cm. E) to F) Representative lithofacies photos of WMM-7 organic-rich mudstone (also WMM-5 and WMM-6). E) PM1: WMM-7 mudstone interbedded with WMM-5 calcareous arenite and WMM-6 limestone. F) PM1: WMM-7 mudstone interbedded with WMM-5 Tb turbidites.

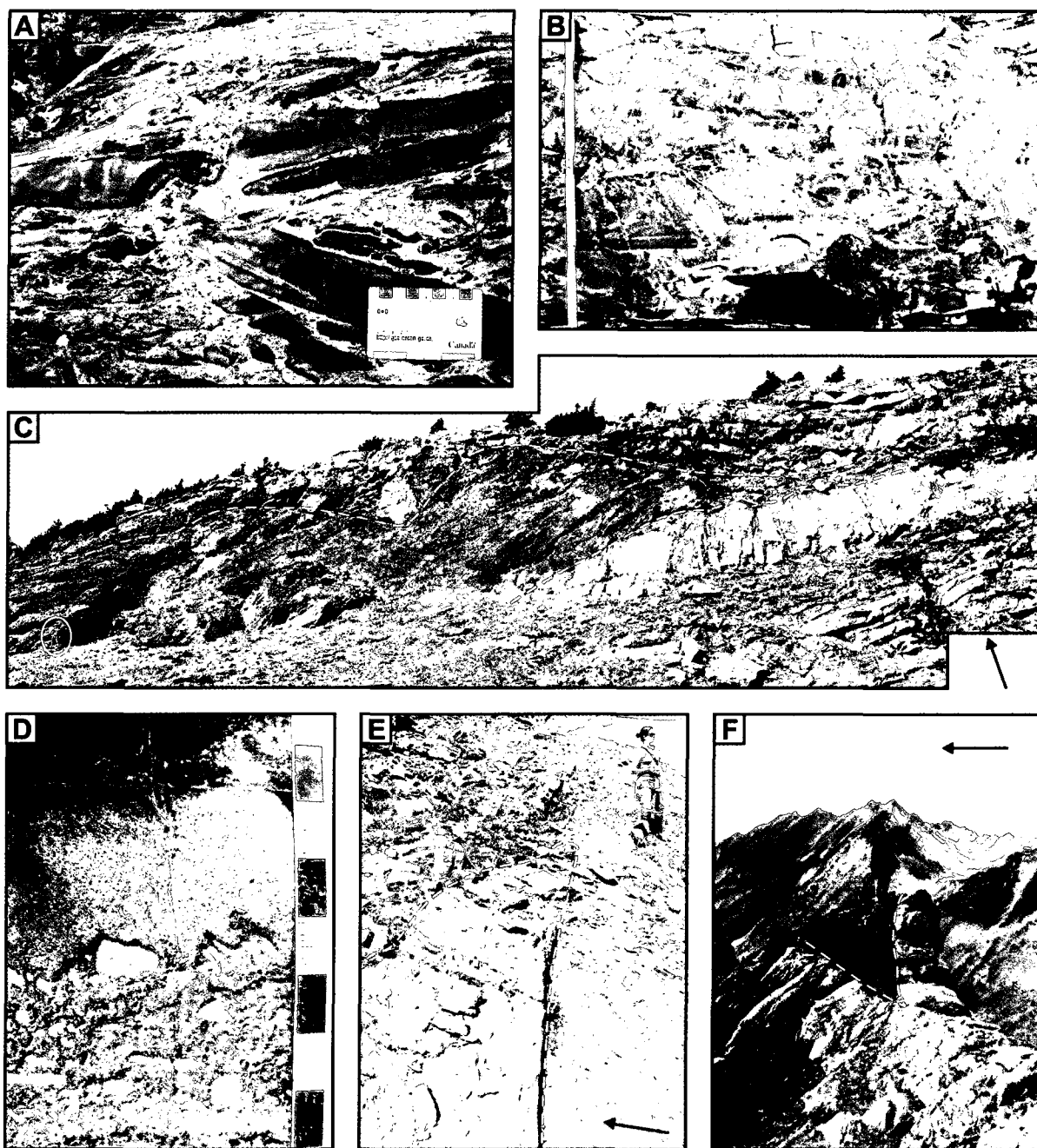


Figure 3.15: A) to F) Representative lithofacies photos of WMM-8 breccia to conglomerate. A) PM1: Debris flow or R1 turbidite with quartz-sand rich matrix and WMM-6 limestone clasts. B) JP1: Debris flow or S1 turbidite with quartz-sand rich matrix and WMM-6 limestone clasts. Ruler is 50 cm. C) MK1: Example of prominent erosional surface associated and overlying WMM-8 debris flow deposits. Irregular top contact of WMM-8 units also created topography for subsequent turbidites. Note person for scale in bottom left corner. D) LL4: WMM-8 S1 breccia overlain directly by WMM-3 Tb turbidite sandstone. D) PM1: Lenticular bed geometry for WMM-8 mass flow. E) and F) MK1: Lenticular bed geometry for WMM-8 mass flow. Arrows indicate upward stratigraphic direction.

elongate shapes up to 3 m long (Fig. 3.16A to F). TLM and WMM lithologies are common, as well as a diversity of upslope carbonates such as: ooid limestone, wave-ripple dolostone, microbial-laminated dolostone, sandy dolostone and bladed-calcite crystal limestone. An isolated siltstone clast containing a lonestone was observed at the Frances Creek locality (PM1). In other instances, WMM-8 ranges from medium to very thick-bedded (0.12 to 0.82 m), characterized by a very coarse- to coarse-grained sandstone matrix and a restricted clast distribution. Clasts in these beds are elongate, ranging from 1 to 10 cm, and are consistently smaller than those in the very thickly bedded WMM-8 described above. Clast types include locally sourced TLM pink limestone (e.g. Lake Louise) or WMM limestone and mudstone (e.g. Jasper, Mount Robson, McKale River), in addition to brown coloured sandy dolostone. These two kinds of breccia to conglomerate typically are near the base of the WMM and overlie a sharp basal contact that scours underlying units.

In areas where strata of WMM-4 to WMM-6 dominate, a third variety of breccia to conglomerate is commonly present. In this case, WMM-8 is clast- or matrix-supported with a medium- to very coarse-grained, well-sorted, quartz sandstone matrix and clasts composed of strata derived from WMM-5, WMM-6 or WMM-7. Strata are present mostly as isolated medium to very thick beds (0.28 to 3.10 m). Beds have sharp, commonly scour-bases and consistently are laterally discontinuous with many exhibiting a lenticular geometry. Clasts are elongate, up to 1 m long with a chaotic or weakly developed fabric. This third variety is further sub-divided into two types based on sedimentary structures: clast-supported breccia with erosive basal scours; and clast-supported breccia containing large coherent blocks of relatively undeformed strata with a flat (non-erosive), but deformed basal surface.

3.7.2 Lithofacies interpretations and associations

The effect of paleogeographic location within the basin on architectural elements of the WMM is readily identifiable. Unlike the regional lithological

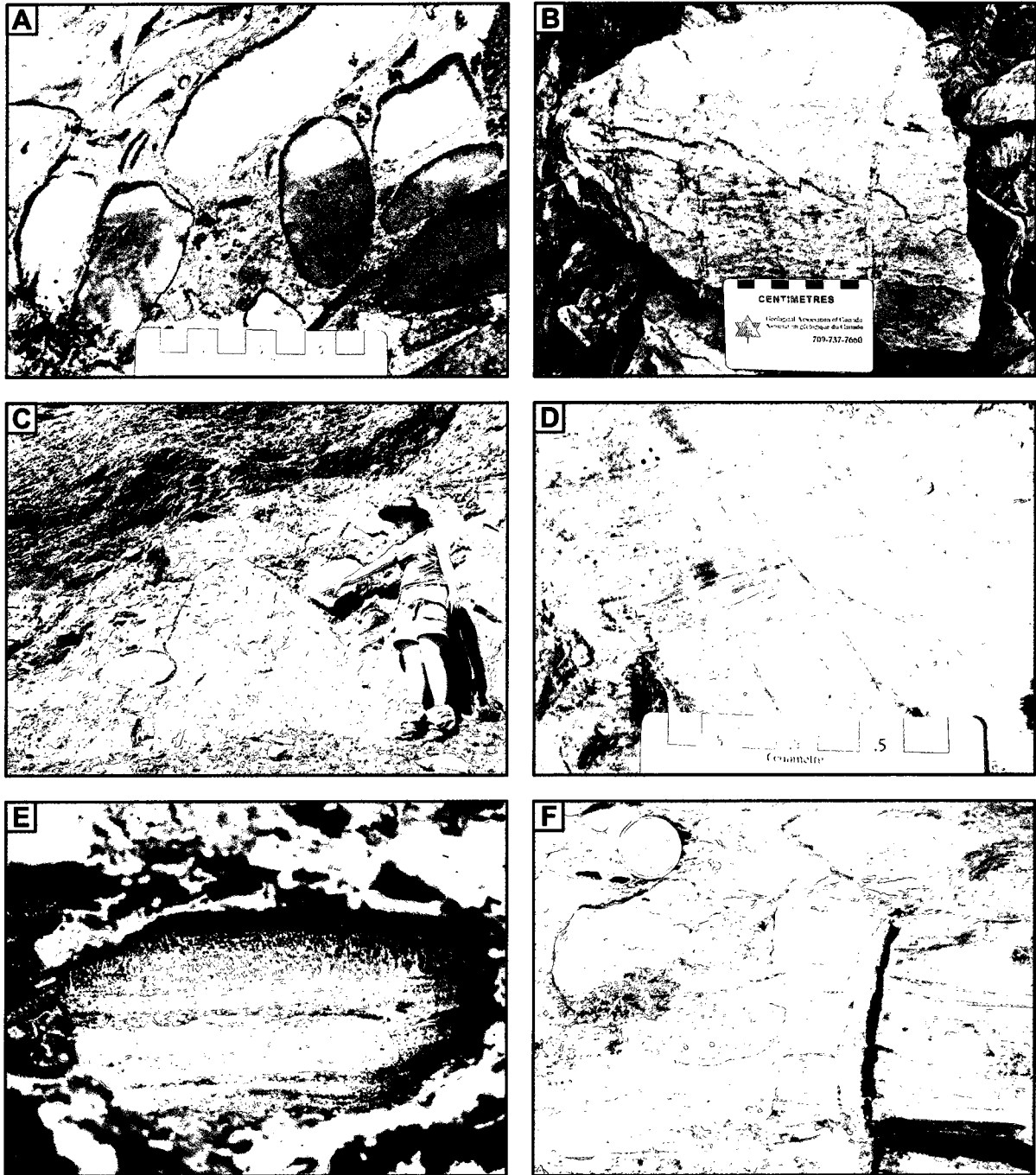


Figure 3.16: A) to F) Representative photos of clast types from WMM-8 breccia to conglomerate. A) MK1: Common, sub-rounded, bimodal clast assemblage of local WMM-6 limestone and brown sandy dolostone from shallower carbonate environments. B) LL4: Dolomitized microbial laminite. C) MK1: Large, metre-sized, diverse assemblage of clasts in basal debris flow. D) MK1: Beige-coloured, wave-ripple cross-stratified dolostone. E) LL2: Limestone clast with bladed-calcite crystals. Pencil tip is ~ 1 cm. F) PM1: Lonestone in a siltstone clast. Penny is ~ 2 cm. Photos E) and F) courtesy of G. M. Ross.

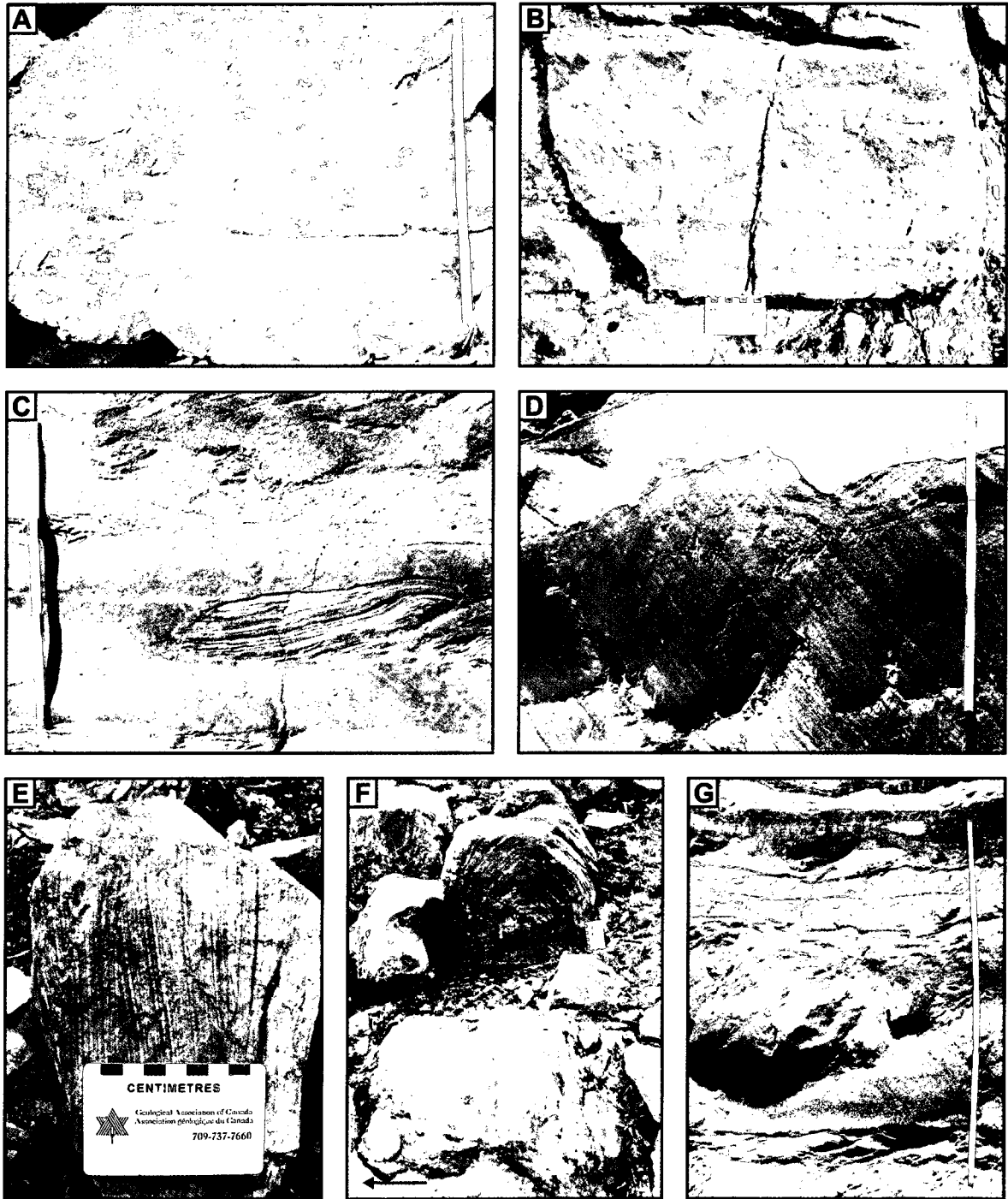
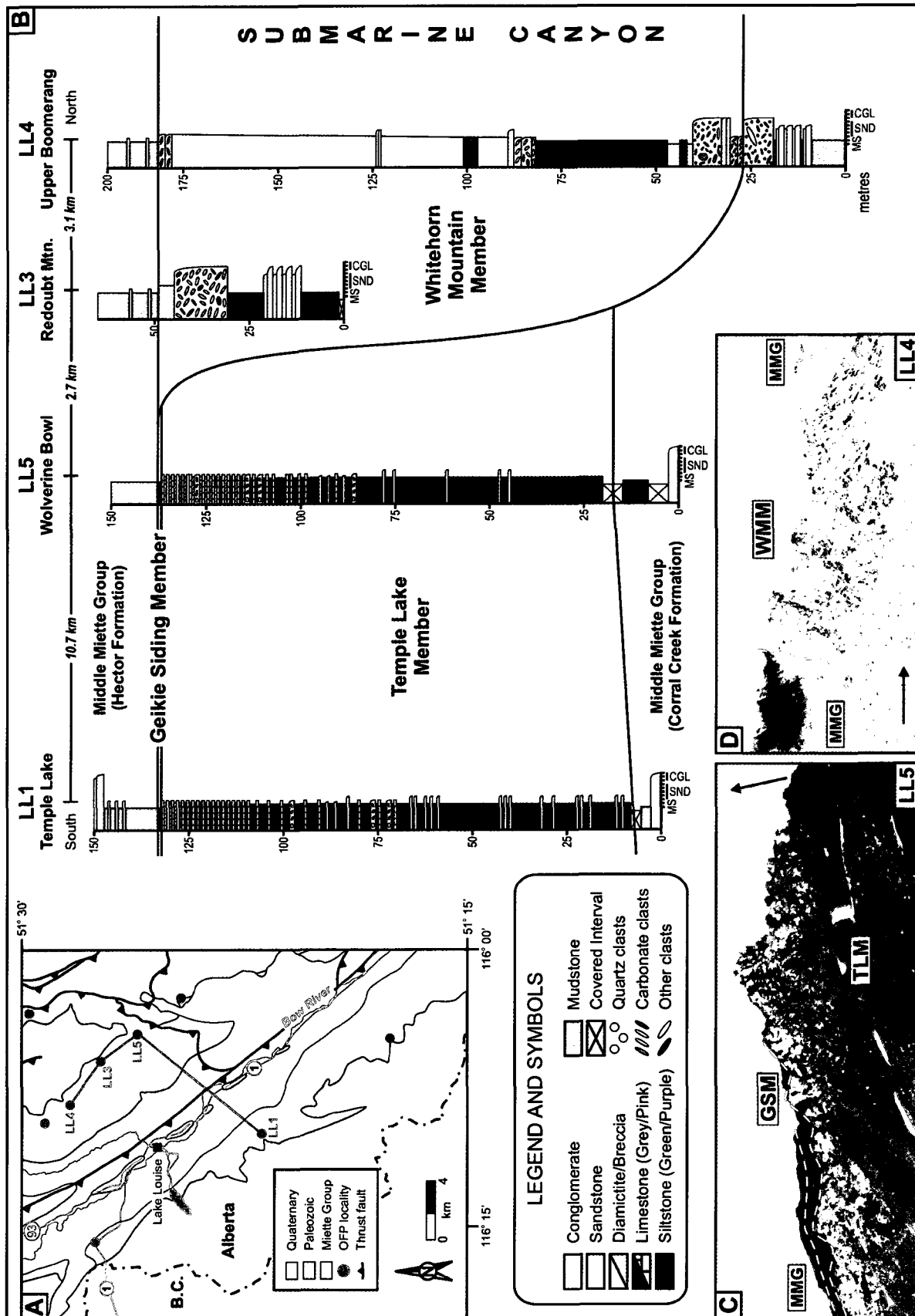


Figure 3.17: A) to G) Representative photos of soft-sediment deformation features observed in WMM strata. A) LL4: Convolute bedding in WMM-2 laminated mudstone. Ruler is 50 cm. B) PM1: Sand-on-sand dewatering structures in WMM-3 sandstone. C) CM1: Basal load structures and "sinking dune" within WMM-4 to WMM-6 strata. Ruler is 50 cm. D) CM1: Sand-on-sand basal load structures in WMM-4 with preferential carbonate-cementation in more stratified turbidite bed. Ruler is 50 cm. E) LL4: Block of WMM-2 laminated mudstone exhibiting soft-sediment folds. F) PM1: "wrap-over lamination" in WMM-3 sandstone which laterally grades into planar-laminated Tb turbidite. Arrow indicates upward stratigraphic direction. G) CM1: Basal load structure within interbedded WMM-4 to WMM-6 strata. Ruler is 100 cm.

uniformity of the lower two members of the OFP, the stratal diversity of the WMM suggests deposition downslope from multiple point-sources along the basin margin. In outcrop exposures interpreted as slope settings (e.g. Lake Louise, Jasper, Mount Robson, McKale River, Frances Creek) the WMM is highly variable in lithology and thickness with significant, laterally extensive erosion of the lower two members (10s of km), sometimes involving their complete removal (>100 m of strata). In the basinal settings (e.g. Cariboo Mountains), erosion is typically more localized and less deeply scoured, and WMM strata tend to be more uniform in thickness and lithology (e.g. Ross and Ferguson, 2003a, 2003b)

At the Lake Louise ski hill area, the base of the WMM has scoured more than 100 m deep over a distance of approximately 3 km (Fig. 3.18). At Wolverine Bowl (LL5), TLM and GSM are well exposed and there is a gradational contact with the overlying WMM, which is <0.5 m thick and overlain by mudstone-dominated, thin-bedded turbidites of the WSG (Hector Formation). At Redoubt Mountain (LL3) and Upper Boomerang (LL4) study locations, however, only the WMM (~150 m) crops out and overlies directly strata of the underlying WSG (Corral Creek Formation). The WMM is then overlain by mudstone-dominated, thin-bedded turbidites of the WSG (Hector Formation) like those observed at Wolverine Bowl. The physiography of the relatively abrupt and drastic thickness change in the WMM in conjunction with the complete removal of the TLM and GSM is interpreted to represent a deeply incised submarine canyon. Submarine canyons are the principal conduit for directing sediment gravity flows down the slope and then out onto the basin-floor (e.g. Shepard and Dill, 1966; Normark and Carlson, 2003), and although common along modern continental margins, are rarely recognized in ancient successions possibly because of limited outcrop exposure (e.g. Von der Borch et al., 1982; Arnott and Hein, 1984; Williams et al., 1998; Anderson et al., 2006). The paleo-canyon wall is not exposed, but rather is inferred between the Wolverine Bowl (LL5) and Redoubt Mountain (LL3) exposures. Coincidentally, approximately 150 m above this inferred OFP canyon, is part of a well-exposed submarine canyon fill (~145 m)

Figure 3.18: A) Simplified geological map of the Lake Louise area, Alberta showing outcrop localities of the OFP and cross-section location. Modified from Price et al. (1980a, b). B) Simplified stratigraphic columns of the OFP in the Lake Louise area illustrating the correlation of the lower two members (TLM + GSM), prominent incision event and deposition of the WMM in a submarine canyon. C) LL5 section (Wolverine Bowl) showing TLM and GSM. D) LL4 section (Upper Boomerang) showing only WMM where the TLM and GSM are completely eroded. Arrows indicate upward stratigraphic direction.



within the Hector Formation of the WSG (Arnott and Hein, 1986). The location of this younger canyon may have exploited a pre-existing topographical depression, or alternatively, may have been tectonically controlled (e.g. long-lived fault margin).

3.7.2.1 Heterolithic association

At Lake Louise, Jasper, Mount Robson and the basal portion of Frances Creek, WMM strata consist predominantly of the heterolithic lithofacies association of WMM-1 + WMM-2 + WMM-3 + WMM-8. This assemblage is subdivided into three types: thick strata associated with complete erosion of the lower two members interpreted to have been deposited in a submarine canyon (e.g. LL2, LL3, LL4, JP3); thick strata associated with no erosion, and fill controlled by a combination of factors (e.g. PM1, see discussion below); and thin strata with no evidence for significant erosion interpreted to have been deposited in a smaller, splay-type feature (e.g. JP1, MR2). Paleogeographically, this lithofacies association is restricted to basin-slope environments.

Diamictite to breccia (WMM-1) is restricted to Lake Louise and Jasper areas, is observed locally above the basal WMM contact and is consistently interstratified with laminated mudstone (WMM-2). Similar to other breccia units of the OFP, this lithofacies is interpreted to represent local mass wasting caused by gravitational instability that led to slope collapse of pre-existing TLM or WMM strata and subsequent remoulding and remobilization downslope as cohesive, muddy debris flows (e.g. Mulder and Cochonat, 1996).

Although laminated mudstone of WMM-2 is similar to TLM-1 in colour, mineralogy and lithological characteristics, a number of important differences are noted: 1) WMM-2 tends to be more consistently planar laminated and lacks the wispy siltstone laminae common to TLM-1; 2) WMM-2 is laterally discontinuous and interbedded with thick, coarser-grained facies (WMM-1, WMM-3, WMM-8) instead of thin sandstone beds like in TLM-2; and 3) WMM-2 does not grade upward into regionally extensive limestone rhythmites of TLM-3. Petrographically,

WMM-2 is also slightly finer-grained than TLM-1, with a consistently lower ratio of silt-sized detritus to recrystallized matrix. These mudstones tend to alternate between purple and green near the base of stratal successions before becoming progressively grey-coloured upsection. Similar to TLM siltstone-rich turbidites previously described, the distinctive colour changes are interpreted to reflect paleo-redox changes in the shallow subsurface (e.g. Buckley and Cranston, 1988) and perhaps mixing of oxygen-rich waters with reduced iron in the ocean.

WMM-2 is characterized by tractional structures interpreted to be part of Td (Tcde) or T₀ to T₅ turbidites that deposit from minor traction with subsequent suspension fallout from dilute turbidity currents. Their purple colour near the base of successions simply illustrates the travel capacity of oxygen-rich turbidity currents within the canyon. Strata of WMM-2 represent low-energy background sedimentation, which periodically was interrupted by deposition of coarse-grained units (WMM-1, WMM-3 or WMM-8). Similar to GSM-1, WMM-2 is characterized by large detrital chlorite flakes interpreted to be the product of rapid physical weathering of upslope material and transport into the basin by either low-energy turbidity currents or suspension settling. Uncommon soft-sediment deformation of the fine-grained laminae suggests slope creep and/or minor instabilities leading to post-depositional mass movement. These features appear to be unrelated to the deposition of the coarser-grained units, and therefore rule out dewatering from differential overloading.

WMM-3 sandstone units are interpreted to be low- to moderate-concentration Tb, Tbc or Tbcd turbidites. They are isolated or stacked beds intercalated within mudstone of WMM-2, lateral equivalents of WMM-1 or WMM-8, and overlie WMM-1 or WMM-8. At Frances Creek (PM1) ~20 m of WMM-3 sandstone overlie WMM-2 in the western section. Towards the east, however, WMM-3 sandstone overlie and/or grade laterally into WMM-8 breccia. At this location, WMM-3 consists mainly of massive sandstone uncommonly capped with planar laminated sandstone, and are interpreted to be S2 – S3 (Lowe, 1982) or

Ta(bcd) (Bouma, 1962) turbidites. Common soft-sediment deformation features between sandstone-rich units (no mudstone) suggesting high sedimentation rates and differential overloading within the semi-consolidated (water-rich) sediments.

WMM-8 breccia to conglomerate is commonly intercalated with WMM-1, but consistently overlies it when the two lithofacies are present together. Lithologically, WMM-8 differs from WMM-1 by its characteristic quartz-sandstone matrix and non-OFP, shallow-marine carbonate clasts. Coarse-grained WMM-8 strata, therefore, are interpreted to be high density turbidites classified as Ta (Bouma, 1962), R1 - R3 (gravel) or S1 - S3 (sand) division (Lowe, 1982). Sediment in these flows was transported in suspension and transported into the deep-marine environments where it deposited rapidly from suspension with possibly minor bedload transport (Sylvester and Lowe, 2004). Unlike the locally remobilized debrites of WMM-1, the more diverse assemblage of intrabasinal clasts, especially shallow-water carbonate, suggests that flow originated further upslope and in a quartz-rich staging area on the shelf margin. This sediment was then transported downslope and eroded older seafloor deposits (OFP or WSG) prior to deposition. Breccia to conglomerate units with a more restricted clast assemblage likely originated further downslope, and were associated with less erosive flows.

At the well-exposed LL4 ridgeline section, coarse-grained units (WMM-1, WMM-3, WMM-8) that make up the heterolithic submarine canyon fill appear to show an upward-fining trend intercalated within ~125 m of monotonous laminated mudstone (WMM-2). At the base, WMM strata directly overlie WSG "grits" and consist of two diamictite to breccia (WMM-1) units overlain by a thick (~10 m) sandstone-matrix breccia to conglomerate (WMM-8) containing a lithologically diverse assemblage of large clasts. Approximately 40 m upsection, WMM-1 is overlain directly by a similar WMM-8 bed, but with comparatively smaller clasts with a more restricted clast assemblage, which subsequently is overlain by WMM-3 sandstone. A further 35 m upwards, three stacked, 30 cm-thick WMM-3 Tb beds are observed. Downslope from the ridgeline outcrop, these strata are capped by a ~4 m

mudstone-matrix breccia to conglomerate (WMM-8) consisting mostly of limestone clasts of WMM-7 interpreted to represent a local slope failure. In this section, the timing of local slope-collapse and deposition of WMM-1 consistently preceded the sediment gravity flows that deposited the upslope-sourced WMM-8 breccia to conglomerate and WMM-3 sandstone. This pattern suggests a consistent change in sediment source from local, lower-slope to a more upslope, shallower-water environment. The stratal trend also suggests that the flows bringing material into the basin become less intense (and/or less erosive) with an overall upward-fining trend manifested by decreasing clast size (and diversity) in breccia to conglomerate units and the transition from breccia and/or conglomerate to Tb turbidite sandstone. Overall, this lithofacies association is laterally discontinuous, and transport was inferred as generally confined to sediment fairways such as canyons (or splays).

3.7.2.2 Quartzose siliciclastic and carbonate association

At McKale River, the upper portion of Frances Creek (also Dogtooth Range: Kubli, 1990) and the Cariboo Mountains, WMM strata consist of intercalated coarse-grained, quartzose facies (WMM-4, WMM-5, WMM-8) and organic-rich limestone and mudstone (WMM-6 and WMM-7). At McKale River (MK1), this association forms a relatively thick stratal succession (~125 m) that overlies directly older WSG strata (lower two members and/or heterolithic association deposits are absent). At Frances Creek (PM1), strata of the quartzose siliciclastic and carbonate association compose the upper ~125 m of the section and gradationally overlie the heterolithic association. Similar to Lake Louise (LL2, LL3, LL4) and Jasper (JP2, JP3), these locations are interpreted to be part of a submarine canyon likely formed by upslope erosional mass wasting. In the Cariboo Mountains these strata are interpreted to have accumulated on the basin-floor based on their “sheet-like” character, the lack of evidence of gravitational slope instability (e.g. slump or slide) and general absence of large-scale erosional features.

Quartz arenite beds of WMM-4 are interpreted to be S2 - S3 or Ta, Tad, Ta(bcd) turbidites. They were deposited by rapid suspension fallout from high concentration turbidity flows that formed the Ta portion of the bed with subsequent tractional deposition that locally was preserved. Unlike WMM-3, the well-sorted, well-rounded and quartz-rich nature of this lithofacies suggests that sediment was first extensively re-worked prior to re-mobilization into the basin by sediment gravity flows. These deposits are prevalent in the basinal environments, laterally continuous for over 500 m ("sheet-like"), and compose the bulk of the WMM succession. Load and de-watering features are common sandstone-on-sandstone and sandstone-on-mudstone contacts suggest rapid deposition of coarse-grained sediment and differential overloading on a previously deposited, poorly consolidated (water-rich) substrate.

Although WMM-5 encompasses a range of compositions between its two end-members (WMM-4 Ta quartz arenite and WMM-6 Tde limestone), it always consists of Tb, Tbc, Tbd or Tbcd Bouma turbidites. Each turbidite is partitioned vertically with the lower part having a consistently higher proportion of quartz-sand and the upper part having a higher proportion of carbonate. These beds are interpreted to have deposited from waning, low concentration turbidity flows with a well-developed, longitudinal grain-size grading. Sharp-based units of these strata exhibit upward changes in bed thickness, grain-size and framework composition (e.g. percent carbonate vs. quartz), which are not recognized at locations where the WMM is thinly developed. In basinal settings, WMM-5 may represent the low-energy lateral equivalents of coarse-grained WMM-4 turbidites. The lack of obvious tractional structures in WMM-6 limestone and WMM-7 organic-rich mudstone suggests these strata accumulated from suspension fall-out of hemipelagic and/or pelagic material. Both lithofacies formed when conditions that promoted organic-matter preservation (e.g. slow sedimentation rate), but unlike organic-rich strata of GSM, these conditions were frequently interrupted by coarser-grained, sediment gravity flows and mass movement events.

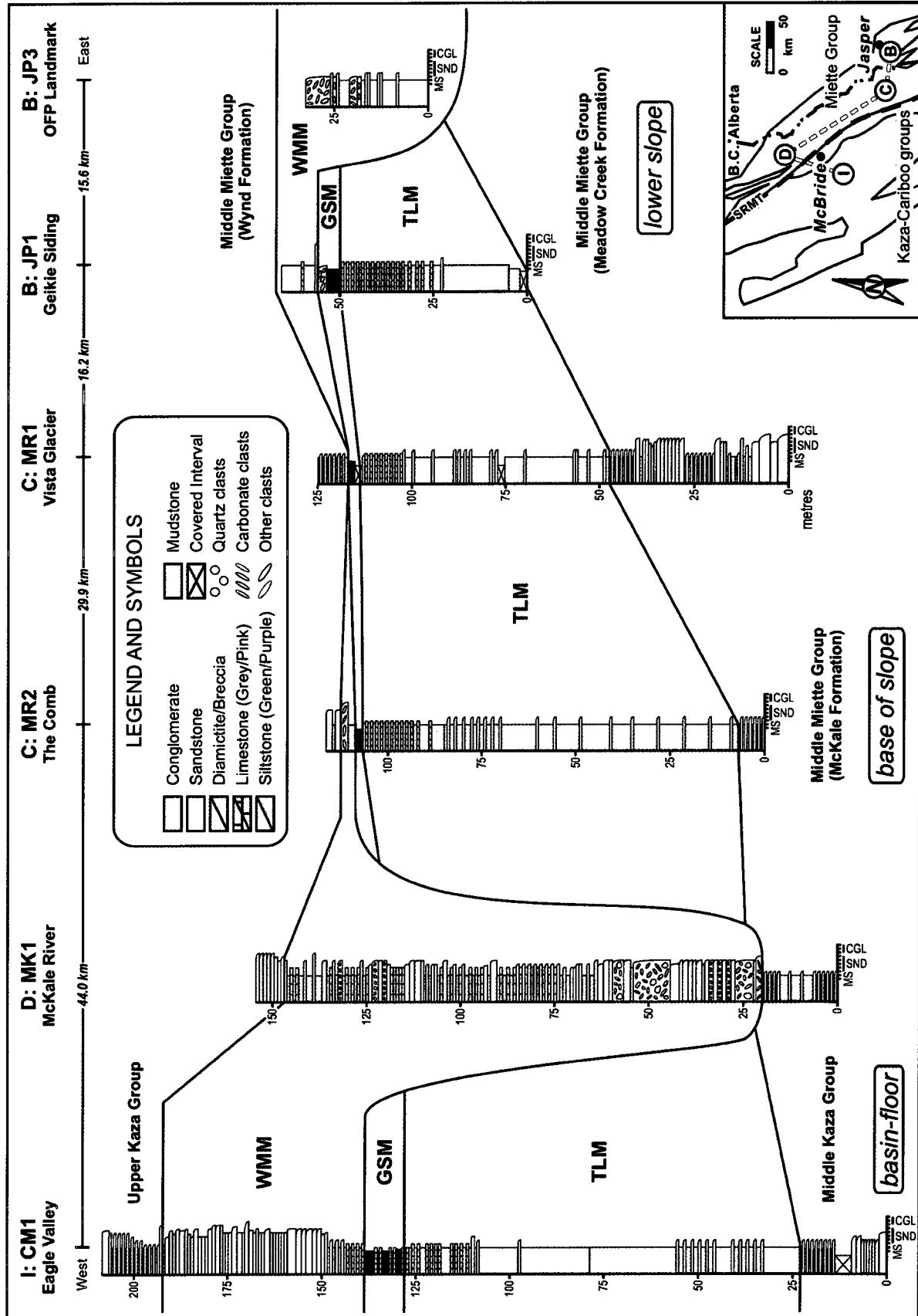
Two types of WMM-8 breccia to conglomerate are found within the quartzose siliciclastic-carbonate association: 1) in lower portions of WMM strata as high density turbidity current deposits (Ta, R1 – R3, or S1 – S3; similar to previously described above in the heterolithic association); or 2) in upper portions of WMM strata as locally derived, mass movement processes such as sandstone-rich slump or slide units, or remobilized sandy, high concentration turbidity flows (possibly sandy debrites?) made up exclusively of quartzose and carbonate debris. In slope settings, some of these WMM-8 flows were highly cannibalistic and channel-like forms are observed at the outcrop-scale within larger-scale sediment transport fairways.

Strata of this lithofacies association are interpreted to have been sourced from a mixed siliciclastic and carbonate shelf area with subsequent sediment gravity flow transport and suspension fallout into basin-slope and basin-floor settings. The quartzose composition contrasts the typical background WSG turbidites, which are feldspathic, and interpreted to reflect earlier winnowing and maturation in shallow marine environments. Dark, organic-rich limestone beds associated with the quartz arenite become more frequent upsection and suggest the development of an active upslope carbonate source. The thickness and persistence of soft-sediment deformation features suggests relatively rapid rates of deposition and delivery of a significant volume of coarse-grained quartz sand.

3.8 DEPOSITIONAL MODEL OF THE OLD FORT POINT FORMATION

The OFP was deposited along a deep-marine, basin-slope to basin-floor transect and is sandwiched between fine- and coarse-grained turbidites of the background WSG (Fig. 3.19). Basin-floor strata were likely deposited in water depths of approximately 2500 m to 4000 m (lower bathyal to upper abyssal plain) with basin-slope deposits in water depths of approximately 500 m to 2500 m (upper to lower bathyal). Paleogeographically, the relatively common slump and slide

Figure 3.19: Simplified stratigraphic columns of the OFP and correlated cross-section in an east to west direction, along a basin-slope to basin-floor transect from Jasper National Park to the Cariboo Mountains. In certain basin-slope settings, prominent incision events are evident with the complete removal of the lower two members (TLM and GSM) and deposition of the WMM in submarine canyons. Stratigraphic column MK1 is projected into the the cross-section line of Jasper National Park to the Cariboo Mountains. Location map is modified from Figure 3.2.



deposits in the OFP at Lake Louise, Jasper and Frances Creek suggest that these areas are mid- to lower-slope environments (continental slope to continental rise), the most proximal in the Windermere basin at this time. Proceeding westward, the Mount Robson and McKale River areas are characterized by rare mass movement deposits, although prominent erosional features are common in the WMM. These locations are interpreted to have been at or near the base of slope and mark the transition to the upper abyssal plain and basin-floor settings in the Cariboo Mountains where units are laterally extensive, lack significant erosional features and no mass movement deposits were observed.

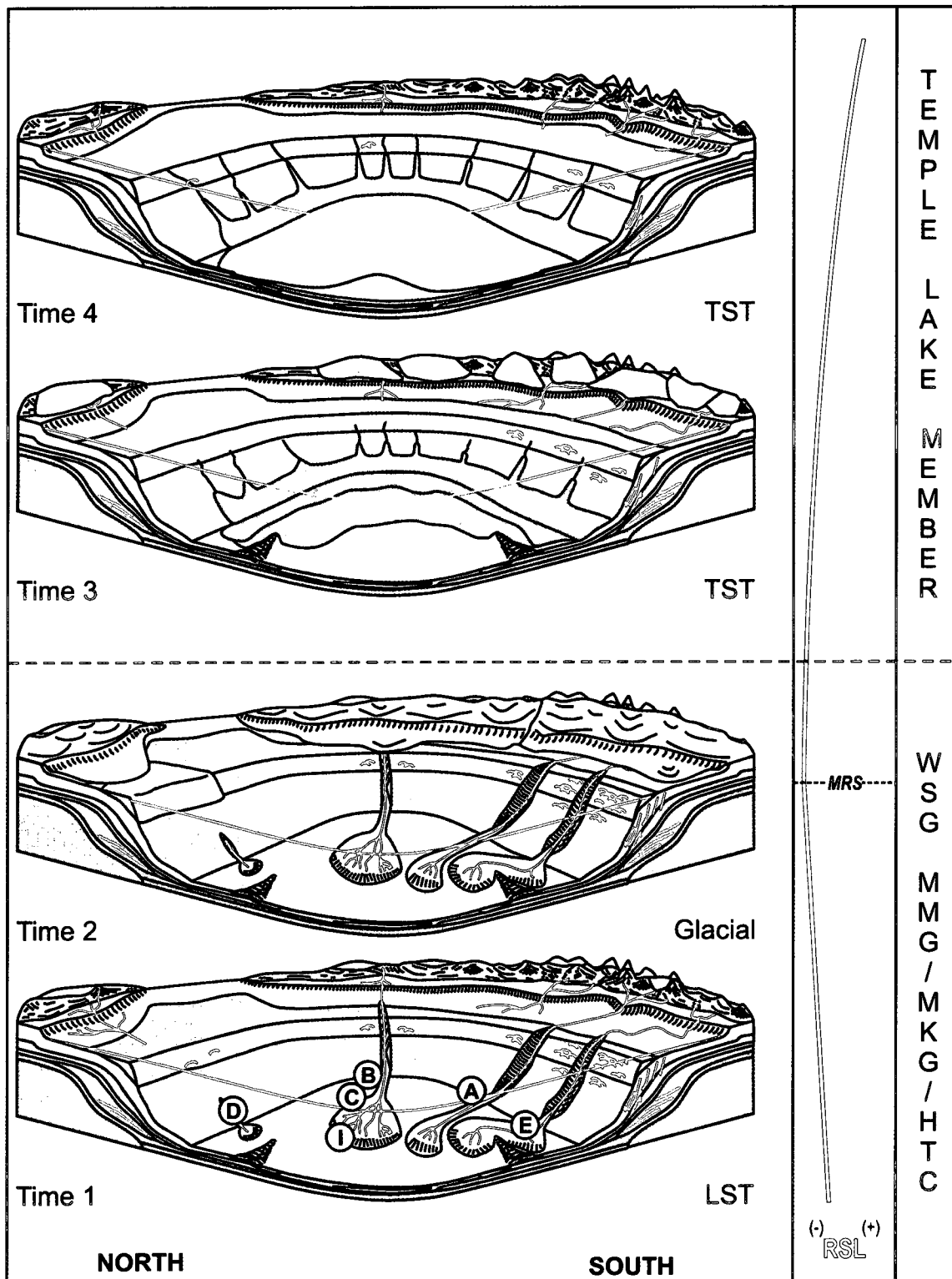
The depositional model and sequence stratigraphic framework proposed here for the widespread OFP builds on ideas and concepts presented by previous authors for specific areas (e.g. Ross and Murphy, 1988; Kubli, 1990; Warren, 1997), and incorporates the new detailed information obtained from this regional study (Fig. 3.20).

3.8.1 Temple Lake Member

Fine-grained, mostly turbiditic strata of the Temple Lake Member (TLM) are regionally uniform in thickness and lithofacies, have gradational contacts and imply synchronous, line-sourced, basin-wide deep-marine sedimentation (Fig. 3.20). The basal siltstone units are interpreted to have been deposited during the transgressive system tract (TST) from a eustatic rise that terminated the supply of coarse-grained sediment into the Windermere basin (Ross and Murphy, 1988; Ross et al., 1995). The maximum regressive surface (mrs), which represents the switch from regressive to transgressive deposition, is a challenging surface to identify in deep-marine rocks. This surface is likely located within the WSG units below the base of TLM, but above the recognizable, thick-bedded coarse-grained WSG turbidites.

With continued eustatic rise, siltstone grades upward into the limestone - siltstone rhythmites with limestone beds becoming more abundant and increasing in calcite percent up-section (Fig. 3.20). The original calcite (and detrital) grains in

Figure 3.20: Schematic depositional model, relative sea-level curve and sequence stratigraphic framework of the OFP. Abbreviations: WSG - Windermere Supergroup; MMG - Middle Miette Group; MKG - Middle Kaza Group; UKG - Upper Kaza Group; HTC - Horsethief Creek Group; TST - transgressive systems tract; CS - condensed section; HST - highstand systems tract; FSST - falling-stage systems tract; LST - lowstand systems tract; BSFR - basal surface of forced regression; MFS - maximum flooding surface; MRS - maximum regressive surface; SB - sequence boundary. (Localities: A - Lake Louise; B - Jasper National Park; C - Mount Robson Provincial Park; D - McKale River; E - Frances Creek; I - Cariboo Mountains)



limestone and siliciclastic beds eroded from an upslope shallow-marine source with subsequent transport into the basin by turbidity currents. The calcite grains lack any physical characteristics that unequivocally point to their origin (e.g. ooids, stromatolitic debris; bioclastic debris common in Paleozoic to recent carbonate turbidites) and potentially are a direct precipitate from coeval local seawater or oxic pore-water based on their chemical composition (Chapter 5); although alternatively they could be a mixture of carbonate platform components. The episodic influx of calcite-rich turbidites suggests deposition linked to a higher order control such as relative sea-level (e.g. Coniglio and James, 1990; Coniglio and Dix, 1992) or climate change superimposed on a long-term eustatic rise (Ross and Murphy, 1988; Chapter 5). Purple-coloured units grade upward (<0.5 m) into green-coloured units, which implies a progressive shift from oxic to reducing conditions at the seafloor during the ongoing transgression, and perhaps a reduction in the episodic influx of oxygen-rich surface waters.

3.8.2 Geikie Siding Member

The TLM grades-upward into the organic-rich, Geikie Siding Member (GSM), which is interpreted to have been deposited during the terminal transgressive phase and the onset of the earliest highstand system tract (HST) (Fig. 3.20). The rapid transition (over a few metres) from limestone rhythmite into mudstone of the GSM implies the shutdown (drowning) of the active, shallow-water carbonate factory, perhaps in response to an increase in the rate of the eustatic rise or change in seawater chemistry. The regionally extensive, basin-wide maximum flooding surface (mfs) is located within the organic-rich condensed section (CS) of the GSM. This surface represents the maximum shoreline transgression and possibly deepest water conditions in the entire WSG succession. Organic-rich GSM deposition is interpreted to be the result of an increase in productivity from the input of nutrient-rich freshwaters in conjunction with short-lived episodes of water column

stratification and development of anoxic bottom-water conditions below a postulated pycnocline throughout the basin (Ross and Murphy, 1988).

3.8.3 Glacial Connection and Age Constraints

Strata of the lower two members of the OFP are interpreted to have accumulated during transgression and highstand of a eustatic rise which resulted from a major glacial melting episode (Ross and Murphy, 1988; Ross et al., 1995). The unusual (at least for the WSG succession) siltstone-rich units of the TLM are interpreted to represent the transport of glacially abraded material into deeper water settings. The dominance of traction transport and deposition and lack of unequivocal indicators of glacial influence (e.g. ice-rafted debris) suggests that the mid- to lower-slope setting may be too distal for more readily identifiable glaciomarine deposits (e.g. Eyles and Eyles, 1985). The single lonestone in a laminated siltstone clast within breccia of the WMM at Frances Creek suggests that more glacial processes may have been ongoing, but upslope of preserved outcrops of the OFP. The distinctive purple colour (from diagenetic hematite) in the TLM at the more proximal locations is the result of the unusual event (at least within the WSG succession) of the voluminous input of oxygen-rich, surface water by turbidity currents into the deep-marine realm and its reaction with reduced iron (possibly from upwelling deep-waters) in the ocean. These oxygen-rich flows related to the continental deglaciation may have increased the nutrient supply to deep-marine environments leading to elevated productivity levels and organic-rich deposition of the GSM.

The OFP is interpreted as a post-glacial succession linked with the glacial Vreeland Formation in the Monkman Pass area (e.g. Ross et al., 1995) and correlative to post-glacial carbonate strata (Ravensthorpe and Hayhook formations) overlying glacial diamictite of the Icebrook Formation in the Mackenzie Mountains (e.g. Ross et al., 1995; James et al., 2001; Chapter 5). The correlative link

between the three locations is based primarily regional stratigraphic relationships and on the consistent stratigraphic presence of carbonate units and carbonate olistoliths possessing distinctive bladed calcite crystals (Aitken, 1991a, b; Ross et al., 1995; James et al., 2001; Chapter 5). In the OFP, these bladed-calcite crystals are found as clasts in the overlying WMM breccia to conglomerate units and have similar physical and isotopic characteristics (Chapter 5) to those present in the post-glacial limestone of the Hayhook Formation, Mackenzie Mountains (James et al., 2001). These bladed-calcite crystals interpreted as seafloor precipitates are commonly, but not exclusively found in Neoproterozoic post-glacial carbonate strata (e.g. James et al., 2001; Lorentz et al., 2004).

Although there are no absolute age constraints available for glaciogenic deposits of the Vreeland or Icebrook formations, both are interpreted to be linked to the globally synchronous, terminal Cryogenian glacial episode which has been dated elsewhere at ca. 635 Ma (Hofmann et al., 2004, Condon et al., 2005). The minimum timing of deposition of the OFP is constrained by an Re-Os isochron age of 607.8 ± 4.7 Ma from the GSM condensed section using the $\text{CrO}_3\text{-H}_2\text{SO}_4$ digestion technique (Kendall et al., 2004). This date from the GSM places the OFP in the Ediacaran Period and thus, broadly correlates the underlying TLM to other basal Ediacaran post-glacial carbonate successions. However, if the ~608 Ma date is accurate, this would suggest that the accumulation of the TLM-GSM succession during the basal Ediacaran eustatic rise represents an unreasonable >25 Myr of time. Interestingly, Kendall et al. (2004) obtained an imprecise date of 634 ± 57 Ma from the GSM using the conventional Re-OS inverse aqua regia digestion method which would suggest a more reasonable (~1 Myr) duration of TLM-GSM deposition if the OFP is indeed linked to the terminal Cryogenian glacial event.

The paucity of absolute age constraints in other Canadian Cordillera WSG successions of the Cryogenian to Ediacaran, glacial to post-glacial transition combined with the apparent discrepancy in timing of OFP deposition (~608 Ma) and currently accepted age of the terminal Cryogenian glacial episode (ca. 635 Ma)

suggests a number of alternate scenarios are possible. The first is that the ~608 Ma Re-Os date is accurate, the OFP is younger than other basal Ediacaran post-glacial carbonate successions and its link to a glacial melting event remains speculative. In this scenario, the broad regional correlation of the OFP to the Vreeland Formation and/or post-glacial strata in the Mackenzie Mountains remains viable, but then one or both of the glaciogenic diamictite units are also not part of the ca. 635 Ma terminal Cryogenian event. The second relies on the strength of the regional correlation across the Canadian Cordillera based on stratal stacking similarities, the unique presence in all three WSG successions of the bladed-calcite crystals with similar negative $\delta^{13}\text{C}_{\text{carb}}$ isotopic signatures (Ross et al., 1995; Chapter 5) and the global correlation of the Mackenzie Mountains strata with other recognized basal Ediacaran cap carbonate strata (e.g. James et al., 2001; Hoffmann et al., 2007). In this scenario, the OFP correlates with other globally widespread basal Ediacaran post-glacial strata, and the ~608 Ma Re-Os date (Kendall et al., 2004) is simply too young, and thus, represents the minimum timing of OFP deposition. Currently, the second hypothesis is the preferred interpretation for the OFP based on the stratal correlations and isotopic data (Chapter 5). However, the lack of absolute age constraints for WSG strata requires that these regional and global stratal correlations remain open to other interpretations should new pertinent data become available.

3.8.4 Whitehorn Mountain Member

In contrast to the synchronous, eustatically controlled, regionally line-sourced deposition of the lower two members (TLM and GSM), the complex sedimentologic and stratigraphic characteristics of the Whitehorn Mountain Member (WMM) strata suggest accumulation downslope from multiple sediment transport pathways (Fig. 3.20). Characteristics of the WMM sedimentary pile were influenced by a diverse mix of sedimentary controls, including local source

material, paleogeographic location, tectonism, mass wasting, basin topography, and/or position and changes of relative sea-level.

Early instability and associated mass wasting is interpreted to have coincided with an abrupt fall of relative sea-level that temporarily interrupted the overall long-term eustatic rise (Fig. 3.20). This led to the localized formation of submarine canyons that became the preferential conduits for subsequent sediment gravity flows. In slope settings, the base of the WMM is commonly a surface of erosion and may represent a basal surface of forced regression (bsfr) and/or a sequence boundary (SB). At their base, canyon fills consist of intraformational carbonate-clast diamictite to breccia derived from slope instability and canyon-wall collapse of TLM (and GSM?) strata. In some cases, these mass movements evolved into debris flows and transported sediment further basinward. These strata are assigned to part of the falling-stage systems tract (FSST) and are confined to submarine canyons. These deposits tend to be thinly developed because their formative flows likely bypassed the proximal slope settings and/or were eroded locally by later coarse-grained, high-energy debris flows and turbidity currents.

The initial canyon erosion and subsequent early stages of FSST deposition propagated progressively upslope perhaps causing mass movement collapses of the pre-existing shallow-marine carbonates on the upper slope and/or shelf margin that led to the erosive, high-energy sediment gravity flows. This upslope evolution of destabilization and stratigraphic expression of mass movement deposits is a recurrent theme in deep-marine settings (e.g. Pickering and Corregidor, 2005). The resultant thick breccia to conglomerate deposits (large and diverse clast assemblage) are interpreted to be part of the latest stage of the FSST to early lowstand system tract (LST). The base is marked by the sequence boundary (SB), which in some locations may coincide with the base of the WMM (e.g. MK1), or above it where FSST diamictite to breccia is preserved (e.g. LL4). Repetition of FSST-LST deposits within the thin, variably coloured mudstone turbidites make up the transgressive system tract (TST). Periodic deposition and an upward-thinning trend of the

interpreted FSST-LST units during the renewed transgression suggest that the flows bringing material into the basin were characterized by progressively lower energy and lower sediment volume (also less erosive). They also may have been influenced by higher-order falls of relative sea-level leading to the repetitive FSST-LST deposits superimposed on the overall TST. Thin turbidites of the TST subsequently infilled the remnant topography in the submarine canyons. Strata of this heterolithic association are laterally discontinuous and transport was inferred as generally confined to sediment fairways such as canyons.

The intercalated association of quartz-rich siliciclastic and carbonate strata consistently overlies FSST-LST-TST deposits of the WMM and is interpreted to reflect deposition during the latest stages of transgression and subsequent highstand (HST). According to classical sequence stratigraphic models, clastic sediment supply onto the deep-marine slope and into the basin occurs during lowstand when sand bypasses the shelf (e.g. Posamentier and Vail, 1988). However, a number of recent studies document submarine fan buildup and/or delivery of sand into the deep ocean during highstand (e.g. Weber et al, 1997; Normark et al., 1998; Carvajal and Steel, 2006; Covault et al., 2007; Boyd et al., 2008). In these examples, alternative mechanisms to sea-level lowstand are key for the delivery of coarse-grained sediment into deep-marine settings including: high sediment supply (e.g. Weber et al., 1997; Carvajal and Steel, 2006); littoral sand transport and change in margin orientation (Boyd et al., 2008); or a narrow shelf width with landward eroded submarine canyon heads that intersect littoral transport pathways (Covault et al., 2007).

The recent observations by Boyd et al. (2008) from modern day offshore southeast Australia documents the active delivery of a significant volume of marine sand into submarine canyons and abyssal plain environments during highstand conditions. In this example, sediment is reworked and transported along a ~1500 km longshore current system until it reaches the intersection point of a barrier spit and the shelf-break margin. At this location, the longshore currents mix with

estuarine tidal flows forming a quartz-rich sand staging area that delivers sand into the upper slope gullies, bypassing the carbonate platform (Boyd et al., 2008). Boyd et al. (2008) also noted that this reworked quartz sand was not present in all canyons, but instead in gullies that had exploited pre-existing sediment transport pathways. In the case of the WMM, quartz-rich sand matured during residence in the shallow nearshore marine environment during the earlier transgression (TLM) and highstand (GSM). During renewed transgressive and highstand conditions the quartz-rich material is postulated to have traveled by littoral drift along the coastline of Laurentia (also suggested by Kubli, 1990) until it encountered some type of physiographic element or staging area that intersected the existing active carbonate shallow-marine environment (e.g. platform). This physiographic element may have been a topographic high, but more probably a shoreline-proximal submarine canyon head (possibly fault-bounded), similar to the Holocene example described by Covault et al. (2007).

Although the establishment of submarine canyons was probably synchronous and related to an abrupt fall in relative sea-level, the lithological diversity in the canyons fills is a direct result of the evolution of the system (Fig. 3.21). Local upslope provenance also likely influenced fill composition, but to a lesser degree. During the initial phase of relative sea-level fall, only select submarine canyons (e.g. Lake Louise, Jasper, Frances Creek?) were active transport conduits where deposition occurred. These were locations where canyon heads had cut upslope into the (subaerially?) exposed shelf and were supplied with mostly immature sediment sourced from continental fluvial systems (e.g. heterolithic association) that primarily bypassed the intervening nearshore shallow marine environments. These canyons would have filled first during the initial relative fall of sea-level and subsequent transgression before eventually shutting down when the shelf flooded (e.g. Covault et al., 2007). During late transgression and highstand conditions new, more landward canyon conduits were activated and transported texturally and compositionally mature palimpsest sediment into slope and basin-

floor settings (e.g. McKale River, Frances Creek). The ancient outcrop example provided by the WMM is similar to the recent observations from recent deep-marine deposits of offshore California by Covault et al. (2007), where the Oceanside and Carlsbad submarine fans were active during periods of lowstand but deposition of the La Jolla fan occurred during highstand. The mix of quartz-rich siliciclastic sediment and the dark, organic-rich limestone in the WMM suggests the development of an upslope carbonate factory during this period, perhaps located over pre-existing paleo-topographic highs. The process of carbonate highstand shedding (e.g. Schlager et al., 1994) was active at the same time and delivered material that utilized the same sediment transport fairways. At these locations, measurable upward changes (e.g. thinning-upward) in the turbidite strata suggest a higher order relative sea-level control or climatic influence that may not be recognized at locations where the WMM is only thinly developed (e.g. Mount Robson).

Basin-floor strata of the WMM are interpreted to have accumulated primarily during late transgression and highstand. If correct, the WMM represents a rare ancient outcrop example of a deep-water highstand fan (e.g. Weber et al., 1997; Carvajal and Steel, 2006; Covault et al., 2007), and further study would generate two important contributions: 1) an exceptional outcrop analogue for deep-water petroleum exploration in similar systems; and 2) direct comparison with the encompassing lowstand deposits of the Kaza Group (e.g. Meyer, 2004; Terlaky and Arnott, 2008) to understand the role of relative sea-level on the detailed architectural elements in deep-marine basinal environments. In basinal settings, the contact with the underlying GSM is usually sharp and conformable, although local erosion is observed (e.g. Ross and Ferguson, 2003a, 2003b). This surface is interpreted as a correlative conformity to the both the basal surface of forced regression and sequence boundary.

An interesting feature of the OFP is that irrespective of thickness, it overlies and is overlain by WSG rocks with similar mineralogy and textures. Thus, in spite

of the anomalous lithological and mineralogical characteristics of the OFP, suggesting exceptional geological conditions, there appears to have been no significant progradation or retgradation of the shelf margin during OFP time. Sedimentary conditions within the WSG basin returned to similar background conditions following deposition of the OFP.

3.9 TECTONIC INFLUENCE

Overall, the influence of tectonism on the accumulation of the WSG (and OFP) is more apparent in the southern Purcell Mountains (e.g. Aalto, 1971; Root, 1987; Warren, 1997) than in other parts of the basin (e.g. McDonough, 1989; Ross and Arnott, 2007). Earlier mapping in the west-central Purcell anticlinorium by Warren (1996, 1997) identified two distinctive stratigraphic domains of the WSG (Horsethief Creek Group). The WSG succession in the southeastern domain was defined by thinner, but mappable sedimentary units including the laterally extensive TLM (“lower marker” of Warren, 1997: ~100 m thick) + GSM (lower part of the “upper marker” of Warren, 1997). Conversely, the northwestern domain was defined by a succession almost twice as thick with laterally variable and discontinuous units (Warren, 1997). In the southeastern domain the WMM (upper part of the “upper marker” of Warren, 1997) was discontinuous at the map-scale but laterally continuous and up to 140 m thick in the northeastern domain (Warren, 1997). Similar to previous studies (e.g. Aalto, 1971; Root, 1987), Warren (1997) suggested that the deep-marine sedimentation in the lower part of the Windermere Supergroup was controlled by syn-sedimentary extensional faults associated with the initial rift phase. However, the identification of the stratigraphic domains and identification of later Neoproterozoic normal faults led to the suggestion of a second episode of tectonic uplift, which resulted in an erosional unconformity and accumulation of the WSG coarse arkose unit overlying the regional highstand deposit of the OFP (Warren, 1997). Tectonically controlled sedimentation contrasts

the model of Ross (1991) where WSG deposition was related to a major eustatic fall along a tectonically passive continental margin.

The anomalously thick OFP section (>450 m) at Frances Creek (PM1) lies within the northwestern domain identified by Warren (1996, 1997) and consists of an unusual section of the otherwise regionally consistent TLM + GSM in addition to a relatively thick WMM (~165 m) (Fig. 3.21). Here, the TLM (~135 m) and an organic-poor GSM (>200 m) are significantly thicker and lack the typical upward gradation from limestone-siltstone rhythmites to organic-rich mudstone. The deposition of a comparatively larger volume of sand in both members is interpreted to reflect important differences in sediment flux and net sedimentation rate, which in turn is attributed to syn-depositional faulting. The tectonic influence would have overwhelmed the eustatic signal that controlled deposition of the TLM + GSM in the other study areas. This locality is interpreted to be a local area of unusually high accommodation produced by growth faults that became active following deposition of the TLM.

These observations suggest a slightly modified version of the scenario proposed by Warren (1997). In the model proposed here, uplift began soon after deposition of the TLM limestone-siltstone rhythmites and continued throughout the GSM highstand and deposition of the WMM. The abrupt relative sea-level fall at the base of the WMM is interpreted to reflect the episodic tectonic extension along the continental margin. Additional evidence from elsewhere in the Windermere basin (e.g. Lake Louise, Jasper) is the interesting presence of detrital chlorite, either as large, foliated metamorphic flakes in the suspension-dominated mudstone units of the GSM and WMM or as chlorite-rich turbidites of the WMM. The presence of transported chlorite in the low-latitude, deep-marine slope environment of the OFP suggests more intense physical weathering as opposed to chemical weathering. This may be a function of rapid mechanical weathering and transport of pre-OFP glacially abraded sediment (e.g. Chamley, 1989), from unroofed of low-grade metamorphic rocks, an increase in relief due to uplift (e.g. Egger et al., 2002), or a

Figure 3.21: Simplified stratigraphic column of the anomalously thick OFP section (>450 m) at Frances Creek (PM1) in the Purcell Mountains, and for comparative purposes, stratigraphic columns at Temple Lake (LL1) and McKale River (MK1). At Frances Creek, the TLM and GSM are significantly thicker and lack the typical upward gradation from limestone-siltstone rhythmites to organic-rich mudstone. This locality is interpreted to be a local area of unusually high accommodation produced by growth faults that became active following deposition of the TLM. Note the overall similarity of the lower part of the TLM at PM1 to LL1 and the WMM at PM1 to MK1. Location map is modified from Figure 3.2.

combination of both (e.g. Brass and Raman, 1990). Regional uplift causing faults and/or gravitational instability leading to erosional mass wasting is interpreted to have been important in forming deep-marine sediment transport fairways. These preferential pathways acted as point-source conduits for sediment gravity flows and subsequent WMM accumulation. Areas where syn-sedimentary growth faults are interpreted to have been the dominant control (e.g. Frances Creek) may have been locations of active sediment transport and deposition throughout the long-term rise of relative sea-level.

Lithofacies and thickness variations coupled with inferred syn-sedimentary structural features (e.g. growth faults) in the upper portions of the OFP support an episodic extensional history in parts of the southern Canadian Cordillera, and as a consequence are inconsistent with a passive margin continental setting. These observations would then be more in concert with the intracontinental rift model proposed by Colpron et al. (2002), however a number of problematic issues remain. For example, the lack of evidence for coeval volcanism and associated volcanoclastic sediments, and the overall size of the Windermere basin (100s km wide), which is significantly larger than intracontinental rift basins that typically are on the order of 10s of km wide. The post-rift North Atlantic margin is viewed as a classic example of a passive margin, but many studies have documented epeirogenic movement unrelated to rifting (see Praeg et al. 2005 and reference therein). This type of tectonic adjustment has the potential to cause significant uplift, syn-sedimentary faulting and/or rapid subsidence, which in turn controls sedimentation patterns and formation of unconformities in the rock record. A renewed episode of extension along the passive continental margin of Laurentia is interpreted to have occurred during the Neoproterozoic post-rift phase and was instrumental in controlling sedimentation patterns in the OFP: basin-wide in the WMM, and locally in the TLM + GSM (e.g. Frances Creek). Similar tectonic reactivation has also been proposed for younger Paleozoic rocks of the Canadian Cordillera (Pyles and Barnes, 2003). Possible mechanisms driving the tectonic reactivation could be intra-plate

stresses (e.g. Cloetingh et al., 1990; Cloetingh and Kooi, 1992) upper mantle convective flow (e.g. Praeg et al., 2005) or mantle plume doming (e.g. Williams and Gostin, 2000). Similar Ediacaran-aged (>585 Ma) uplift and erosion features not related to continental separation have also been documented from canyons of Australia (Von der Borch et al., 1982; Christie-Blick et al., 1990; Christie-Blick et al., 1998; Williams and Gostin, 2000) and incised valleys of the western United States (Christie-Blick and Levy, 1989; Fedo and Cooper 2001; Clapham and Corsetti 2005).

3.10 CONCLUSIONS

The Ediacaran Old Fort Point Formation (OFP) is a unique siliciclastic and carbonate deep-marine succession that forms a key regional stratigraphic marker in the Neoproterozoic Windermere Supergroup, southern Canadian Cordillera. The OFP comprises three lithostratigraphic members, which stratigraphically upward order are: Temple Lake, Geikie Siding and Whitehorn Mountain members. Each member is characterized by a distinctive assemblage of lithofacies, which exhibit a consistent stratigraphic relationship across the Windermere basin. The Temple Lake Member (TLM) is composed of variably-coloured siltstone to mudstone that grades upward into rhythmically interstratified limestone-siltstone. The dominant depositional mechanism for the TLM is low- to moderate concentration turbidity currents. Gradationally overlying the TLM is the Geikie Siding Member (GSM), a thin, organic-rich mudstone that locally, is sulfidic. The GSM accumulated in a quiescent environment, mainly from suspension settling. The TLM and GSM are reasonably consistent in lithologic character and stratigraphic thickness, a feature recognized by previous authors and used as a correlation tool throughout the southern Canadian Cordillera. Unlike the lower two members, Whitehorn Mountain Member (WMM) varies in thickness and is usually characterized by a sharp basal contact, commonly exhibiting significant erosion. The WMM consists of variable, sometimes location-specific lithofacies that includes: diamictite, breccia to

conglomerate, mudstone to siltstone, sandstone, quartz arenite, calcareous arenite, arenaceous limestone, and limestone. Depositional mechanisms include nearly the entire spectrum of deep-marine processes: debris flows, slump and slides, high- to low-energy turbidity flows and suspension fallout.

The OFP is interpreted to have accumulated in deep-marine basin-slope to basin-floor environments (upper bathyal to upper abyssal plain) along the ancient continental margin of Laurentia. It punctuates two thick successions composed of fine- and coarse-grained arkose turbidites, typical of the WSG. The fine-grained strata of the TLM and GSM are regionally uniform in thickness and lithofacies suggesting synchronous, basin-wide deep-marine deposition. These two members are interpreted to have accumulated during transgression and highstand related to a eustatic rise and a shutdown of the supply of coarse-grained feldspar-rich sediment into the Windermere basin. Based on regional stratal correlations across the Canadian Cordillera, TLM and GSM deposition during this eustatic rise is linked to the ca. 635 Ma terminal Cryogenian glacial episode. Although other viable scenarios exist, this interpretation means the ~608 Ma age is too young and likely represents a minimum depositional constraint. Compared to the lower two members, WMM deposition was controlled mostly by local factors including: paleogeographic location, mass wasting, submarine canyons, topography along the slope, structural activity, and/or relative sea-level. Regional tectonic uplift led to an abrupt fall of relative sea-level, erosional mass wasting, submarine canyon incision, and syn-sedimentary growth faulting. Newly created sediment transport fairways controlled the timing and location of the subsequent WMM deposition during renewed relative sea-level rise. Canyons active during the initial falling-stage, lowstand and transgressive conditions were filled with mostly immature, hinterland-sourced sediment. These canyons shut down after flooding of the shelf and new, more landward canyon conduits became active during late transgression and highstand. These canyons were filled with mixed quartz-rich siliciclastic and carbonate sediment that was winnowed and matured during residence on the shelf

coupled with longshore transport processes. Deposition of these WMM strata in basin-floor environments may represent a rare ancient outcrop example of a deep-marine highstand fan.

CHAPTER 4: Deep-marine perspective of provenance, weathering and paleoredox conditions along the continental margin of Laurentia: insights from fine-grained sedimentary rocks of the Neoproterozoic Windermere Supergroup, southern Canadian Cordillera.

4.1 INTRODUCTION

The Neoproterozoic was a time of dynamic paleo-environments in Earth history including the breakup of the supercontinent Rodinia, widespread glaciations causing extreme climatic fluctuations, dramatic changes in geochemical cycles and the emergence of metazoan life (see recent summary in Fairchild and Kennedy, 2007 and references therein). The Windermere Supergroup (WSG) is a thick (~9 km) succession of predominantly siliciclastic meta-sedimentary rocks that are well-exposed over an area of 35,000 km² in the southern Canadian Cordillera (Fig. 4.1). The WSG provides a critical window into Neoproterozoic Earth because it offers a rare opportunity to examine this period of proposed climatic and oceanic perturbations (e.g. Hoffman and Schrag, 2002; Halverson et al., 2005; Hurtgen et al., 2006; Canfield et al., 2008) from a deep-marine perspective. Most current models rely on stable isotopic seawater proxies from the shallow-marine carbonate record and their associated glacigenic deposits (e.g. Kennedy et al., 1998; James et al., 2001; Hoffman and Schrag, 2002; Halverson et al., 2005; Shields, 2005). However, these severe Neoproterozoic climatic shifts should also be reflected in the corresponding proxies from the siliciclastic (e.g. Rieu et al., 2007) and also the deep ocean sedimentary record from bathyal and upper abyssal plain environments. Thus, an investigation of the deep-marine WSG geochemical reservoir should provide an alternate viewpoint to Neoproterozoic continental to shallow-marine strata prevalent throughout the world (e.g. Ross et al., 1995).

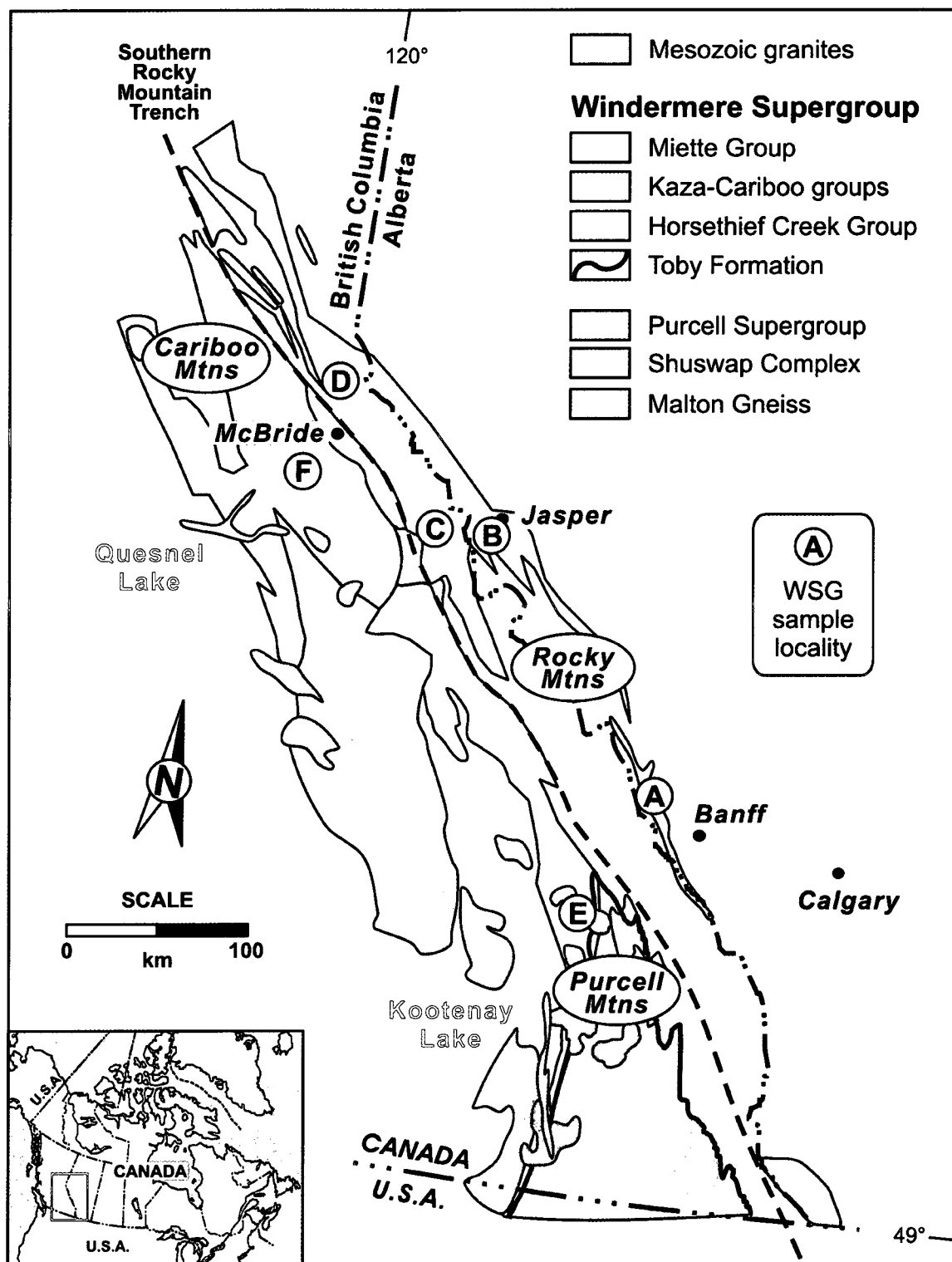


Figure 4.1: Location of study area and simplified geological map of the WSG, southern Canadian Cordillera (modified from Ross and Murphy, 1988). Sample localities: A - Lake Louise; B - Jasper National Park; C - Mount Robson Provincial Park; D - McKale River; E - Frances Creek, Purcell Mountains; F - Cariboo Mountains. SRMT: Southern Rocky Mountain Trench.

Geochemical data obtained from fine-grained siliciclastic sedimentary rocks (mudstone, siltstone) are commonly used to evaluate environmental conditions, especially in ancient Precambrian successions. Sediment chemistry has been shown to be effective in identifying and understanding provenance evolution of the transported source material (e.g. McLennan et al., 2003; McLennan et al., 1993; Taylor and McLennan, 1985) and has successfully illustrated changes in weathering intensity and paleo-climatic conditions (e.g. Nesbitt, 2003; Nesbitt and Young, 1982). Certain elements can also be used as indicators of changes in the redox environment and thus are employed as proxies to assess oxygen fluctuations in oceanic waters (e.g. Algeo and Lyons, 2006; Rimmer, 2004; Cruse and Lyons, 2004; Algeo and Maynard, 2004). Although the sedimentary systems may have been disturbed by diagenesis and metamorphism, these too can usually be assessed and isolated from the primary depositional geochemical signatures (e.g. Fedo et al, 1995).

The purpose of this investigation is to present, for the first time, a regional geochemical characterization of the fine-grained meta-sedimentary rocks of the WSG in the southern Canadian Cordillera. Despite its importance in assessing global Neoproterozoic environmental change, geochemical research focused specifically on the WSG has been limited and includes: U-Pb detrital zircon analyses (Ross and Bowring, 1990; Ross and Parrish, 1991; Ross, 2000; Ross and Heaman, 2005); $\delta^{34}\text{S}$ pyrite isotopic analyses (Ross et al., 1995); and some $\delta^{13}\text{C}$ carbonate analyses (Ross, 2003; Meyer, 2004). Other tectonic or regional studies that also included WSG samples are: U-Pb detrital zircon (Smith and Gehrels, 1991; Gehrels and Ross, 1998; Lemieux et al., 2007); Nd radiogenic isotopes (Boghossian et al., 1996); and geochemical analyses of amphibolite-grade mafic volcanic rocks (Sevigny, 1988).

The WSG geochemical data enables assessment of the sedimentary history of this large, deep-marine continental margin system including: sediment provenance (lateral variations and vertical changes through time); paleoclimate with degree and type of weathering; paleoredox conditions (e.g. anoxia); secondary effects such as

diagenesis, metasomatism (e.g. potassic) and low-grade metamorphism. This study will complement the existing U-Pb detrital zircon data, provide insights into the post-rift tectonic history of the WSG, and test many of the current hypotheses which invoke long-term, deep-water anoxia in Neoproterozoic oceans to explain the chemical and isotopic signatures recorded from shallow-marine sedimentary rocks (Canfield, 1998; Hurtgen et al., 2002; Jiang et al., 2007; Canfield et al., 2008).

4.2 GEOLOGICAL SETTING

The Neoproterozoic WSG accumulated in a tectonic setting that is interpreted to consist of two main components (Stewart, 1972; Ross, 1991). The initial rift phase was linked with the break-up of the supercontinent Rodinia and strata deposited synchronously with this event tend to be laterally discontinuous. The second phase represents subsequent post-rift thermal relaxation with regionally widespread, predominantly turbiditic strata. In the southern Canadian Cordillera, there are no direct geochronological constraints on the age or duration of the rift phase. The local maximum timing of rifting and deposition of the WSG is constrained by a U-Pb zircon date of $736 \pm 23/-17$ Ma from the Malton Gneiss Complex (McDonough and Parrish, 1991). This age corresponds well with U-Pb zircon dates of 740 ± 36 Ma (Parrish and Scamell 1988) and $728 \pm 8/-7$ Ma (Evenchick et al. 1984) obtained from other basement rocks in the Canadian Cordillera (Fig. 4.2). Rift-related volcanic rocks of the Irene Formation are present in the southern Canadian Cordillera, but their timing is postulated from ages of potential volcanic correlatives located elsewhere. These include: a U-Pb zircon age of $688.9 \pm 9.5/-6.2$ Ma from the Gataga Volcanics, northern British Columbia (Ferri et al. 1999); an imprecise Sm-Nd isochron age of 762 ± 44 Ma from the Huckleberry Formation in northeastern Washington (Devlin et al. 1988); and SHRIMP U-Pb zircon ages of 684 ± 4 Ma, 685 ± 7 Ma (Lund et al., 2003), and 709 ± 5 Ma (Fanning and Link 2004) from Idaho. The more recent age-dates are similar, but their slight disparity suggests a non-

synchronous, potentially protracted WSG rifting event (Fanning and Link 2004). Continental configurations during the time of rifting of Rodinia remain unsettled, and offer numerous possible candidates for the rifted conjugate margin of western Laurentia, including: eastern Australia (e.g. Dalziel, 1991; Moores, 1991; Hoffman, 1991); northern eastern Australia (e.g. Karlstrom et al., 1999); Siberia (Sears and Price, 2003); South China (Li et al., 1995; Li et al., 1999); or unidentified/open ocean (Wingate et al., 2002).

Although there is general agreement on the two-phase tectonic model for the WSG, the specific post-rift setting of the basin during deposition of the upper WSG strata is disputed. The first model proposes a passive continental margin with a substantial Proto-Pacific Ocean and that deposition occurred in an elongate, northwest-flowing turbidite system (Ross 1991; Ross et al. 1995; Dalrymple and Narbonne 1996). Support for this model is based on: contourites in the Sheepbed Formation, Mackenzie Mountains suggesting open ocean deposition (Dalrymple and Narbonne, 1996); consistent regional turbidite paleocurrent transport towards the west-northwest (e.g. Ross and Arnott, 2007 and references therein; Mountjoy and Aitken, 1963); a homogeneous, predominantly bimodal U-Pb detrital zircon age pattern (>2.5 Ga or 1.9 to 1.75 Ga; minor 2.3 to 1.9 Ga contribution) implying common provenance for the WSG turbidites from adjacent basement domains in southern Alberta (Ross and Bowring, 1990; Ross and Parrish, 1991; Ross and Heaman, 2005; Lemieux et al., 2007); and current lack of equivocal evidence supporting the existence of a western margin due to Cordilleran deformation.

The alternative model of Colpron et al. (2002) prefers a ~2500 km-long intracontinental rift system where the upper part of the WSG was deposited during a period of crustal extension culminating in a later rift event that led to the break-up of an unknown crustal fragment from the margin of Laurentia. This second rift episode is well constrained from a U-Pb zircon age of 569.6 ± 5.3 Ma from synrift felsic volcanic rocks of the Hamill Group (Colpron et al., 2002), that unconformably overlie the WSG and provide a minimum depositional constraint on the succession

(e.g. Devlin and Bond, 1988; Warren, 1997). In the scenario of Colpron et al. (2002), WSG turbidites in the southern Canadian Cordillera accumulated in a restricted basin that opened up to a passive margin in the northern Canadian Cordillera. Support for this model comes from syn-depositional extensional tectonic activity in the WSG of the southern Canadian Cordillera (Warren, 1997) as well as the observation of similar uplift-related features in the western United States (e.g. Prave, 1999; Fedo and Cooper, 2001; Clapham and Corsetti, 2005); and the recently proposed crustal block that defined the western margin of the Windermere basin during the Neoproterozoic (Thompson et al., 2006). However, the syn-rift volcanism from 700-690 Ma (Evans et al, 1997; Ferri et al, 1999) used by Colpron et al. (2002) as additional evidence for sporadic extension is no longer valid as these rocks are now correlated with the basal rifting event (e.g. Lund et al, 2003).

Currently, there are no published paleolatitude data for the WSG in the southern Canadian Canada. A near-equatorial paleogeographic position is inferred based on paleomagnetic data obtained from Neoproterozoic strata in the Mackenzie Mountains (Park, 1997) in addition to most continental reconstructions that appear to locate Laurentia <30° latitude (e.g. Moores, 1991; Dalziel, 1991; Karlstrom et al., 1999; Wingate et al., 2002).

4.3 STRATIGRAPHIC SETTING

In the southern Canadian Cordillera, the WSG consists of a thick unconformity-bounded succession (~9 km) that is exposed over an area of 35,000 km² in a series of thrust sheets of the Cordilleran orogen (Fig. 4.1). The WSG consists primarily of deep-marine siliciclastic sedimentary rocks with subordinate carbonate, diamictite and mafic volcanics. All WSG strata were subjected to Mesozoic orogenesis that has presented challenges in stratigraphic correlations across structural panels and the variable effects of metamorphism (e.g. Pell and Simony, 1987). However, many areas of uncomplicated tectonic deformation exist

with metamorphic grade ranging from sub-greenschist in the western Main Ranges of the Rocky Mountains, to greenschist in the northern Cariboo Mountains and eastern Purcell Mountains. Regional mapping and detailed stratigraphic work has identified a number of key marker horizons in the WSG that has led to the development of a consistent internal stratigraphy and reconstruction of the Windermere basin in the southern Canadian Cordillera (Fig. 4.2) (Ross and Murphy, 1988; Ross et al., 1989, 1995; Ross and Arnott, 2007).

In the Purcell Mountains, the Toby Formation is at the base of the WSG and is intercalated with volcanic rocks of the Irene Formation (Aalto, 1971; Root, 1987). The Toby Formation is characterized by its highly variable thickness range (0 to >2000 m) and consists of a heterogeneous succession of diamictite interbedded with conglomerate, sandstone, carbonate and mudstone (Aalto, 1971). The Irene Formation consists of mafic volcanic rocks (massive or pillow basalt, tuff, tuff breccia, sills and dikes) that are up to 2000 m thick (Glover, 1978; Brown et al., 1995). These basal units of the WSG are limited in their areal extent, show measurable thickness changes across faults with their deposition is controlled by these syn-sedimentary faulting during the active rift phase (Aalto, 1971; Root, 1987; Warren, 1997). Although stratigraphic control is poor, potential high-grade metamorphic equivalents of the two units may be in the Shuswap Complex and northern Cariboo Mountains (e.g. Simony et al., 1980; Sevigny, 1988; Murphy et al., 1991).

In the southern Canadian Cordillera, a ~5 km thick sedimentary succession of thick-bedded immature turbidites conformably overlies the rift-related assemblage (e.g. Ross et al. 1989; 1995; Ross and Arnott, 2007) (Fig. 4.3). These strata are interpreted as basin-slope to basin-floor facies (upper bathyal to upper abyssal plain) and dominated by coarse-grained arkose and granule conglomerate interbedded with mudstone-dominated intervals or minor carbonate (e.g. Ross and Arnott, 2007). Nomenclature of the post-rift WSG varies from region to region (Fig. 4.2, 4.3) and includes: the Horsethief Creek Group, Purcell Mountains (e.g. Reesor, 1973, Root, 1987; Kubli, 1990; Warren, 1997); Kaza and Cariboo groups, Cariboo

COLUMBIA MOUNTAINS				
CARIBOO MOUNTAINS		PURCELL MOUNTAINS		
Cariboo Group	Yankee Belle Fm.			
	Cunningham Fm.			
	Isaac Formation (<i>n</i> = 7)	Horsethief Group	Upper Clastic Div.	
Kaza Group	Upper (<i>n</i> = 8)		Carbonate Div.	
	OFP (<i>n</i> = 6)		Slate Division	
	Middle (<i>n</i> = 7)		Upper Grit Division	
	Lower		OFP (<i>n</i> = 6)	
	Middle Marble Unit		Lower Grit Division	
	Semipelite Amphibolite Unit		Basal Pelite Division & Carbonate Unit	
	Lower Pelite Unit		Irene Formation	
			Toby Formation	

Figure 4.2: Stratigraphy of the WSG, southern Canadian Cordillera (from Chapter 2 and references therein). OFP is used across the Windermere basin as opposed to other terminology (Chapter 2). Notes: *n* = number of samples collected for stratal division; no thickness implied in figure.

SOUTHERN ROCKY MOUNTAIN TRENCH	ROCKY MOUNTAINS				
	SELWYN AND MAIN RANGES		JASPER		LAKE LOUISE
	Miette Group	Upper Miette (<i>n</i> = 7)			
		Middle Miette (<i>n</i> = 2)	Miette Group	Middle Miette (<i>n</i> = 11)	Middle Miette (<i>n</i> = 11)
		OFP (<i>n</i> = 4)		OFP (<i>n</i> = 5)	OFP (<i>n</i> = 3)
		Middle Miette (<i>n</i> = 4)		Middle Miette	Middle Miette (<i>n</i> = 6)
		Lower Miette			

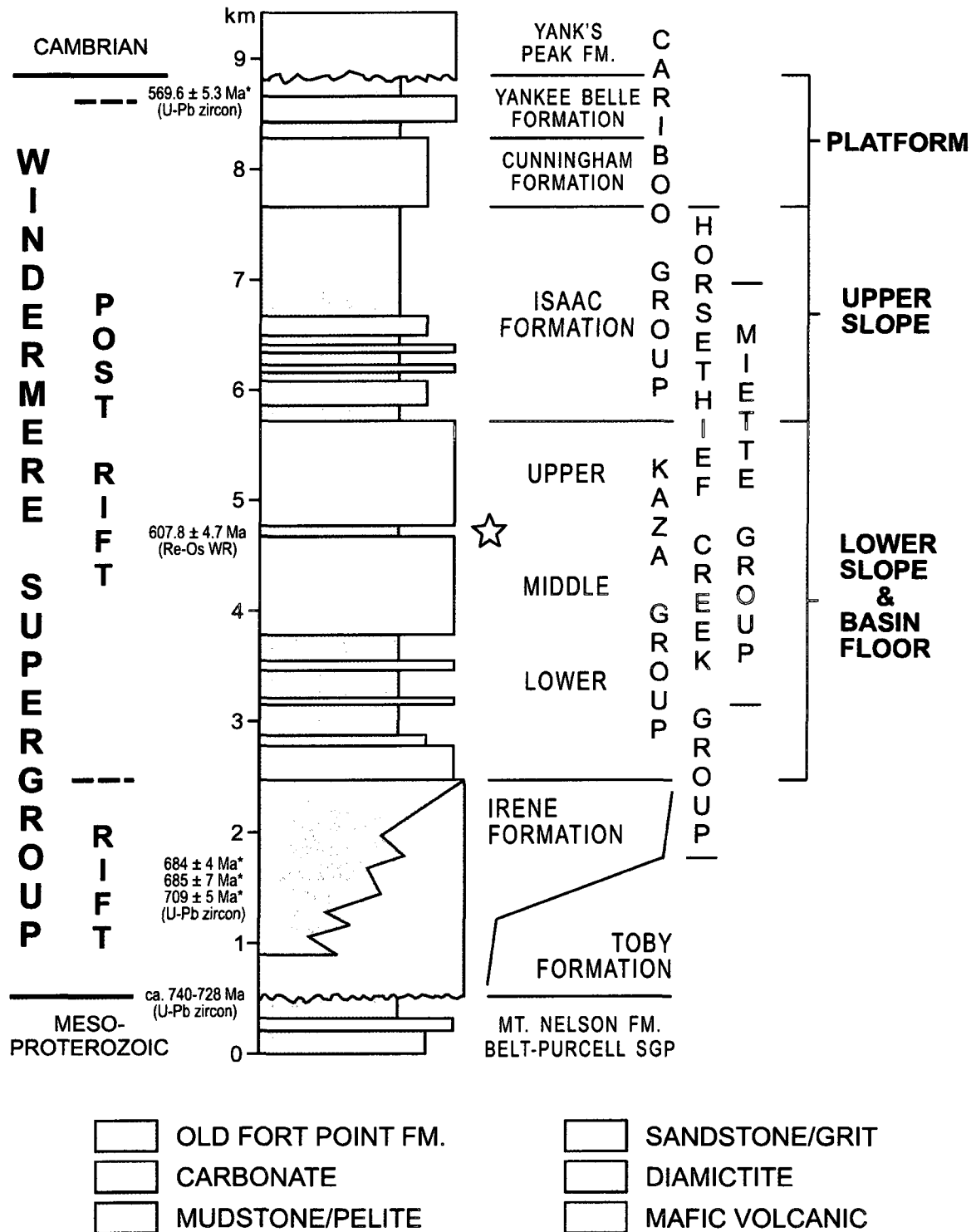


Figure 4.3: Stratigraphic column for the WSG from the Cariboo-Purcell-Rocky Mountains in the southern Canadian Cordillera (modified from Ross et al. 1995). Rift and post-rift strata, paleogeographic environment and relative stratigraphic position of the OFP are shown. Ages shown in stratigraphic order are from McDonough and Parrish (1991), Lund et al. (2003), Kendall et al. (2004) and Colpron et al. (2002). Asterisk indicates the age is from correlative strata to the column.

Mountains (e.g. Campbell et al., 1973; Ferguson, 1994; Ross et al., 1995); and Miette Group, Rocky Mountains (e.g. Mountjoy, 1962; Aitken, 1969; Carey and Simony, 1985; McDonough, 1989). Deposition of these monotonous, mostly coarse-grained units (Lower Grit Division, Horsethief Creek Group; McKale Formation/Middle Miette Group; and Middle Kaza Group) is interrupted by the distinctive, Old Fort Point Formation (OFP) (Charlesworth et al, 1967; Chapter 3). The three members of the OFP form a distinctive tripartite that is recognized as the lowest regional marker horizon in the WSG of the southern Canadian Cordillera (Ross and Murphy, 1988; Chapter 2, 3). The minimum timing of deposition for the OFP is constrained by a 607.8 ± 4.7 Ma age (Kendall, et al., 2004) from organic-rich mudstone of the Geikie Siding Member (GSM) (Chapter 2), and is interpreted to be a deep-marine post-glacial, predominantly fine-grained unit potentially associated with the terminal Cryogenian glaciation event (e.g. Ross and Murphy, 1988; Ross et al., 1995; Chapter 3). The OFP is subsequently overlain by a resumption of nearly identical coarse-grained turbidite deposition (Upper Grit Division, Horsethief Creek Group; McKale Formation / Middle Miette Group; and Upper Kaza Group). These units exhibit a kilometre-scale upward-shoaling trend to mudstone-dominated upper slope units (Slate and Carbonate Division, Horsethief Creek Group; East Twin Formation/ Upper Miette Group; Isaac Formation, Cariboo Group) that are punctuated by two regionally mappable carbonate marker units (e.g. Ross et al. 1989; Ross et al., 1995; Ross and Arnott, 2007). Overlying the fine-grained units are shelf carbonates associated with several platforms (e.g. Poulton, 1973; Campbell et al., 1973; Teitz and Mountjoy, 1989). The termination of WSG deposition is marked by a locally subtle, but widespread regional unconformity that is succeeded by deposits of a latest Neoproterozoic to Cambrian rift-drift succession (Devlin and Bond, 1988; Kubli, 1990; Warren, 1997; Colpron et al., 2002).

4.4 SAMPLING AND ANALYTICAL METHODS

A total of 87 representative samples of deep-marine WSG fine-grained meta-sedimentary rocks (Tde turbidites) from the southern Canadian Cordillera were collected for organic carbon, major, trace and rare earth element analyses (Fig. 4.2, Appendix H). From these samples, 30 were initially collected by Gerald M. Ross (GMR) and form the 2001 sample set; 57 additional samples were collected by Mark D. Smith (MDS) and GMR and form the 2003-2005 sample set. Samples were subdivided based on stratigraphic unit and geographic location relative to the southern Rocky Mountain Trench (SRMT): 53 from the Main Ranges of the Rocky Mountains, east of the SRMT and 34 from the Cariboo and Purcell Mountains, west of the SRMT. Sampling localities are listed in Table 4.1 and were selected in conjunction with sedimentologic and stratigraphic studies (e.g. Ross and Arnott, 2007 and references therein; Chapter 3). Primary sedimentary structures and textures are well preserved in regions of relatively low structural deformation with sub-greenschist to greenschist grade metamorphism (e.g. Ross and Arnott, 2007 and references therein; Chapter 3) and thus, sedimentary (e.g. mudstone), rather than metamorphic (e.g. pelite) terminology is used throughout this paper.

The samples were first broken into small chip fragments of unweathered, fresh material. Samples were pulverized in a tungsten carbide ring mill for major element x-ray fluorescence analyses (XRF), whereas a ceramic ring mill was used for samples analyzed for organic carbon and trace elements using induced coupled plasma mass spectrometry (ICP-MS). Prior to analyses for organic carbon, samples were treated with HCl to remove carbonate.

For the 2001 sample set, total organic carbon (TOC) content was determined by Rock Eval pyrolysis using Delsi Rock-Eval 6® unit at the Geological Survey of Canada, Calgary, Alberta. Analytical procedures follow those presented in Stasiuk and Fowler (2004) and are not repeated here. For the 2003-2005 sample set, TOC content was determined by flash combustion of samples at 1800°C using a VarioEL

Lct.	Regional Area	Section	Code	Easting	Northing
<u>Alberta</u>					
A	Lake Louise	Temple Lake	LL1	557379	5690015
		Railway/Bath Creek	LL2	551641	5701337
		Redoubt SW Spur	LL3	562261	5700626
		Upper Boomerang	LL4	559666	5702403
		Wolverine Bowl	LL5	563943	5698491
		Taylor Lake	LL6	563860	5682541
		Icefields Parkway	LL7	549902	5709796
		Arnica Lake	LL8	570447	5674427
		Icefields Turnoff	LL9	555798	5698844
B	Jasper National Park	Geikie Siding	JP1	412974	5858644
		Athabasca River	JP2	428416	5857171
		OFP Landmark	JP3	428577	5858240
		Marmot Ski Road	JP4	430208	5848258
		Yellowhead 0.7 km	JP5	425494	5857331
		Yellowhead 8.7 km	JP6	417300	5857279
<u>British Columbia</u>					
C	Mount Robson Provincial Park	Vista Glacier	MR1	400911	5847859
		The Comb	MR2	374335	5861575
		Highway Big Hill	MR3	373911	6545597
D	McKale River	McKale River	MK1	692091	5929423
E	Purcell Mountains	Frances Creek	PM1	525658	5613170
F	Cariboo Mountains	Eagle Valley	CM1	678846	5887412
		Mount Quanstrom	CM2	693512	5867836
		Castle Creek	CM3	672020	5880850

Notes: Location letters refer to Figure 4.1. UTM coordinates in grid system NAD27. Locations A, B, C, E and F are in Zone 11; locations E and I are in Zone 10.

Table 4.1: Locations of WSG sample locations in the southern Canadian Cordillera.

II elemental analyzer at the G. G. Hatch Stable Isotope Laboratory, University of Ottawa. Resultant gases are carried through a column of chemicals and a series of traps to separate the gases that are then measured using a thermoconductivity detector. Total carbon (%C) to measure CO₂ contents was determined from untreated samples in the same manner (Appendix I). Analytical precision (2 σ) for the data is $\pm 0.1\%$ with duplicate analyses consistently within 10%.

Major elements from the 2003-2005 samples were determined on fused disks using a Philips PW 2400 x-ray fluorescence (XRF) spectrometer at the Department of Earth Sciences, University of Ottawa. Each sample was weighed at 1.0000 g then mixed with 4.0000 g of lithium metaborate flux and melted in a platinum crucible at approximately 1050° C for 10-15 minutes. The resulting melt was then cooled to form a glass disk. Accuracy monitored using international references MRG-1 and Sy-2 was better than 1% for major elements with duplicate analyses within <10%. Loss of ignition was determined by comparing the mass of the disk to original weight measured. Major elements from the 2001 sample set were analyzed by fused disk, XRF spectrometry at X-ray Assay Laboratories (XRAL) Inc., Don Mills, Ontario.

Trace and rare-earth elements from all samples were analyzed using ICP-MS on a Perkin Elmer Elan 5000 mass spectrometer by Dr. J. Fan, Department of Geological Sciences, University of Saskatchewan, Saskatoon, Saskatchewan. Analytical procedures are outlined in Fan and Kerrich (1997) and follow the protocol of Jenner et al. (1990) and Longerich et al. (1990). A sodium peroxide sinter was used for Th, Nb, Ta, Zr, Hf, Y, Sc and REE, and an HF-HNO₃ digestion on a separate aliquot was used for the remaining trace elements. Wet chemistry operations were conducted under clean laboratory conditions with analyses of acids, distilled deionized water and procedural blanks giving levels of < 1 ppb for REE, Nb, Zr, and Hf, relative to their concentration in the rocks (Xie et al., 1994). A basalt sample (BCR-2) was used as a reference material with long-term reproducibility in this laboratory reported in Manikyamba and Kerrich (2006).

Duplicate analyses are generally within 5%. Detection limits (in ppm) defined as 3 σ of the calibration blank for some key elements are as follows: Nb (0.01), Mo (0.04), Zr (0.103), La (0.01), Ce (0.02), U (0.02) and Sb (0.07).

4.5 RESULTS

Complete analytical results of the WSG fine-grained meta-sedimentary rocks ($n = 87$) are located in Appendix H. Average concentration, range and standard deviation values for the WSG and each stratal unit are summarized in Table 4.2. Statistical treatment of the WSG mudstone ($n = 87$) geochemical data was conducted using the software PAST (Hammer et al., 2001). Both Pearson's (r) and Spearman rank order (ρ) correlation coefficients were calculated to test the quality of linearity between different elements and identify correlations of high statistical significance ($p = 0.001$). A Shapiro-Wilk's test (W) was conducted on each elemental dataset to measure its deviation from the normal distribution in order to determine if the Spearman rank order correlation coefficient should be applied. Most major element oxides and trace elements deviate little from the normal distribution with the exceptions of CaO, P₂O₅, Sr, U, Mo, Sb and TOC. Correlation coefficients and W -values from WSG major and selected trace elements are presented in Table 4.3.

Abbreviations used in the text and figures to describe WSG stratal units in the southern Canadian Cordillera are as follows: Temple Lake (TLM), Geikie Siding (GSM) and Whitehorn Mountain (WMM) members, Old Fort Point Formation (OFP); Middle Miette Group, below OFP (MMGB) and above OFP (MMGA); Upper Miette Group (UMG); Middle Kaza Group (MKG); Upper Kaza Group (UKG); and Isaac Formation, Cariboo Group (IF). In all subsequent geochemical plots of the mudstone units, stratal units interpreted to be correlative (e.g. MMGB and MKG) are denoted by the same symbol; the difference is that the "open" symbols represent samples collected east of the SRMT and "closed" symbols west of the SRMT. The North American Shale Composite (NASC) (Gromet et al., 1984) and Post-Archean

	UMG (<i>n</i> = 7)				IF (<i>n</i> = 7)				MMGA (<i>n</i> = 24)			
	Avg.	2σ	Min.	Max.	Avg.	2σ	Min.	Max.	Avg.	2σ	Min.	Max.
SiO ₂	61.72	4.03	56.56	67.21	55.42	6.76	49.39	68.14	58.83	4.19	54.28	66.86
TiO ₂	0.79	0.16	0.60	1.01	0.91	0.22	0.54	1.21	0.77	0.15	0.55	1.09
Al ₂ O ₃	22.49	2.35	19.98	25.37	21.77	6.69	12.64	29.53	24.59	2.19	19.13	28.88
Fe ₂ O ₃	5.22	1.33	3.46	7.17	8.91	1.42	7.30	11.48	6.33	1.85	2.06	9.27
MnO	0.01	0.01	0.01	0.04	0.07	0.04	0.02	0.12	0.03	0.02	0.00	0.08
MgO	1.61	0.36	1.13	2.13	3.27	0.66	2.50	4.37	2.18	0.45	0.98	3.01
CaO	1.44	3.13	0.03	8.52	3.84	7.48	0.17	20.66	0.31	0.55	0.01	2.49
Na ₂ O	2.48	0.33	2.10	2.92	1.18	0.39	0.65	1.80	0.87	0.51	0.22	1.71
K ₂ O	3.89	0.54	3.08	4.62	4.09	1.30	2.48	6.46	5.77	1.52	3.44	9.65
P ₂ O ₅	0.14	0.12	0.03	0.37	0.33	0.49	0.06	1.43	0.10	0.04	0.03	0.25
LOI	5.14	1.38	3.59	7.49	6.67	4.92	3.72	17.72	5.12	1.36	3.94	10.68
CIA	71.00	2.24	67.36	73.65	76.32	4.80	67.19	81.13	75.55	2.39	67.69	79.82
Rb	173.61	33.35	124.52	212.37	135.77	43.44	86.83	215.67	222.13	61.55	137.87	385.05
Cs	5.35	1.77	2.20	7.38	4.90	1.12	3.36	6.09	5.49	1.26	2.77	9.14
Ba	787.85	101.55	574.86	878.42	663.08	253.56	377.54	1123.40	1062.09	394.14	496.59	2056.84
Sr	454.29	180.14	210.66	648.63	231.08	136.30	78.02	509.81	86.20	47.88	23.55	198.44
Pb	29.66	16.45	8.33	52.07	24.66	3.60	21.65	30.84	16.95	11.14	b.d.	39.68
Th	18.44	5.48	10.11	24.91	17.00	3.43	9.77	19.99	22.83	5.82	13.65	37.01
U	3.08	0.89	2.18	4.32	3.72	1.10	2.12	5.31	4.22	1.05	2.23	6.46
Y	31.75	10.78	17.45	48.41	28.20	5.78	20.48	38.64	26.03	6.38	16.14	42.23
Zr	108.04	25.97	79.87	144.15	216.32	100.09	94.09	390.79	131.26	46.03	72.40	259.27
Hf	3.65	1.12	2.07	5.11	6.46	2.81	3.11	11.37	4.26	1.21	2.52	6.34
Nb	20.53	5.06	14.68	26.24	18.37	4.25	11.39	24.60	18.23	4.03	12.02	25.97
Ta	1.65	0.47	1.12	2.29	1.33	0.33	0.76	1.74	1.49	0.43	0.92	2.43
Cr	113.25	38.81	69.10	168.34	148.55	67.45	47.93	228.12	88.33	18.43	55.18	121.93
Co	7.62	7.45	0.98	21.56	23.05	8.32	9.52	35.76	9.32	6.76	0.24	24.91
Ni	23.90	11.01	12.10	43.17	56.43	16.67	26.68	77.93	27.41	10.92	6.75	49.14
Cu	15.48	7.92	4.42	25.47	36.72	14.61	23.75	64.86	21.80	10.99	2.50	48.64
Zn	54.18	9.67	41.67	69.70	98.47	34.75	55.98	164.15	80.45	14.23	49.80	113.45
Sc	17.01	2.44	14.23	19.80	22.41	4.32	14.76	28.71	20.95	2.37	17.05	27.55
V	123.86	30.24	90.03	168.62	116.35	43.05	52.11	163.88	102.77	29.66	66.27	212.20
Mo	1.17	1.28	0.40	4.05	0.63	0.23	0.33	0.94	1.12	1.55	b.d.	6.28
Sb	0.53	0.44	0.09	1.29	0.45	0.21	0.15	0.84	0.44	0.56	b.d.	2.49
As	n/a	n/a	n/a	n/a	6.77	3.00	4.65	8.89	15.45	9.54	2.22	34.98
La	79.92	18.83	55.83	104.82	52.82	12.30	31.57	69.77	82.55	24.91	47.66	183.23
Ce	147.60	38.48	100.28	207.81	103.34	24.13	67.77	137.74	152.87	43.53	71.84	311.98
Pr	18.00	5.13	12.26	26.98	11.72	2.94	7.69	15.87	18.04	4.82	8.77	35.37
Nd	66.61	20.34	45.16	103.39	41.63	10.16	27.21	53.41	62.52	17.21	30.12	126.44
Sm	10.51	3.07	7.41	16.10	7.79	2.09	4.73	10.30	9.88	2.72	4.50	18.95
Eu	1.46	0.33	1.10	1.95	1.63	0.47	1.06	2.30	1.67	0.45	0.76	3.10
Gd	7.80	2.56	4.80	11.55	7.14	1.72	5.19	9.27	7.38	1.85	3.83	11.52
Tb	1.01	0.34	0.59	1.50	0.96	0.21	0.69	1.33	0.93	0.25	0.50	1.51
Dy	6.11	2.07	3.51	9.07	5.76	1.35	4.10	8.42	5.46	1.42	3.31	9.09
Ho	1.19	0.40	0.68	1.79	1.13	0.27	0.77	1.63	1.04	0.25	0.68	1.63
Er	3.33	1.05	1.92	4.85	3.25	0.78	2.22	4.70	2.96	0.65	1.95	4.49
Tm	0.47	0.14	0.29	0.66	0.47	0.10	0.32	0.63	0.43	0.08	0.30	0.61
Yb	2.90	0.71	1.88	3.73	3.12	0.62	2.15	4.08	2.79	0.49	1.95	3.92
Lu	0.39	0.09	0.26	0.49	0.44	0.07	0.29	0.52	0.39	0.06	0.29	0.52
Eu/Eu*	0.51	0.05	0.44	0.58	0.67	0.06	0.61	0.79	0.60	0.04	0.53	0.65
TOC (%)	0.52	0.65	0.02	1.78	0.11	0.12	b.d.	0.30	0.18	0.20	b.d.	0.58

Table 4.2: Compositional average (avg.), standard deviation (2σ), minimum (min.) and maximum (max.) values for stratal divisions of the WSG in the southern Canadian Cordillera. Notes: *n* = number of samples; n/a = not analyzed; b.d. = below detection limits. Stratal abbreviations are listed in the text.

	UKG (<i>n</i> = 8)				MMGB (<i>n</i> = 10)				MKG (<i>n</i> = 7)			
	Avg.	2σ	Min.	Max.	Avg.	2σ	Min.	Max.	Avg.	2σ	Min.	Max.
SiO ₂	55.58	5.16	47.11	63.90	57.59	3.28	52.94	63.15	57.30	4.18	50.58	63.78
TiO ₂	0.82	0.18	0.54	1.09	0.78	0.10	0.59	0.92	0.72	0.08	0.63	0.87
Al ₂ O ₃	25.48	4.21	20.57	33.48	24.77	2.86	19.32	28.63	23.56	3.36	18.05	28.68
Fe ₂ O ₃	7.03	1.59	4.84	9.69	7.39	2.78	3.27	14.41	8.28	0.77	7.41	9.28
MnO	0.05	0.02	0.01	0.07	0.05	0.05	0.01	0.17	0.09	0.03	0.05	0.13
MgO	2.89	0.60	1.92	3.49	2.28	0.62	1.55	3.71	3.01	0.46	2.53	3.73
CaO	0.21	0.16	0.03	0.54	0.34	0.28	0.14	0.91	0.38	0.35	0.14	1.13
Na ₂ O	0.51	0.24	0.19	0.85	1.08	0.30	0.71	1.63	0.62	0.31	0.34	1.13
K ₂ O	7.05	1.71	5.36	10.31	5.36	1.18	3.73	7.83	5.69	1.05	4.24	7.49
P ₂ O ₅	0.13	0.06	0.04	0.21	0.14	0.04	0.07	0.21	0.13	0.04	0.08	0.21
LOI	4.52	0.42	3.74	5.01	5.64	2.17	4.42	11.64	4.66	0.32	4.27	5.12
CIA	75.17	1.58	73.97	78.25	75.58	2.54	70.38	78.69	76.18	1.41	73.12	77.35
Rb	247.07	62.18	189.28	368.54	211.22	31.29	165.61	267.98	208.32	21.12	177.93	233.70
Cs	7.07	1.50	5.06	9.92	6.28	1.06	4.86	8.42	7.18	1.10	5.43	8.72
Ba	1391.16	350.37	1028.68	2039.71	790.28	172.53	548.22	1066.66	1063.56	164.29	855.80	1333.59
Sr	60.90	18.58	41.35	94.02	118.64	32.59	73.13	176.22	76.83	20.49	52.10	103.55
Pb	9.66	10.11	1.04	30.12	14.23	10.00	3.17	38.62	12.11	15.34	3.20	41.10
Th	20.96	6.69	15.04	32.05	23.75	4.47	16.81	31.63	18.60	2.16	15.61	21.99
U	3.18	0.54	2.61	4.17	4.16	0.76	2.97	5.69	2.66	0.52	2.07	3.50
Y	29.19	16.83	16.79	64.27	27.34	6.72	19.38	37.73	27.77	2.72	23.82	30.79
Zr	125.89	35.95	86.88	183.38	141.82	52.18	69.55	226.87	123.94	38.63	78.80	169.37
Hf	4.33	1.33	2.36	6.06	4.23	1.44	2.23	6.57	3.67	1.03	2.48	4.93
Nb	15.67	3.61	10.64	22.53	19.26	2.83	13.86	22.58	14.19	1.49	11.54	15.90
Ta	1.26	0.28	0.77	1.70	1.48	0.24	1.06	1.84	1.01	0.10	0.82	1.10
Cr	137.50	33.40	83.27	175.70	106.27	14.38	79.79	126.96	123.51	32.57	88.64	183.34
Co	15.70	10.59	6.83	37.70	12.34	5.32	2.95	20.84	17.90	5.16	12.36	24.72
Ni	49.92	32.75	13.85	122.86	38.60	15.98	3.90	56.87	58.71	21.56	31.89	90.96
Cu	21.14	17.74	3.00	60.00	31.13	12.02	8.68	47.32	26.91	18.99	3.46	54.20
Zn	70.87	12.10	55.28	93.08	96.06	18.72	66.46	114.73	118.31	7.31	111.19	129.12
Sc	23.16	5.08	16.49	30.99	24.39	3.32	19.20	28.84	24.94	1.72	23.55	28.62
V	110.97	20.65	82.06	136.30	91.20	15.81	74.15	123.49	99.42	11.22	86.78	114.53
Mo	0.42	0.20	b.d.	0.70	0.63	0.33	0.21	1.35	0.42	0.27	0.20	0.94
Sb	0.62	0.25	0.29	0.91	0.53	0.50	b.d.	1.41	0.50	0.22	0.34	0.96
As	8.58	8.14	2.82	14.34	9.89	6.53	1.80	19.72	2.29	2.92	0.23	4.36
La	77.84	45.21	29.91	155.89	81.06	16.66	52.40	99.46	66.97	16.17	37.78	85.95
Ce	149.35	97.55	51.20	325.70	154.74	27.32	109.70	194.18	123.48	25.41	72.36	149.45
Pr	16.87	10.27	5.69	34.58	19.04	3.68	13.04	23.53	15.41	3.75	8.61	19.90
Nd	60.74	33.56	21.64	116.96	65.44	11.78	44.74	78.79	51.96	11.88	30.07	65.70
Sm	10.38	5.74	4.08	20.10	11.14	2.03	8.51	14.78	9.14	1.65	6.26	11.34
Eu	1.99	1.07	0.81	3.81	1.94	0.40	1.44	2.63	1.81	0.23	1.56	2.16
Gd	8.27	4.84	4.10	16.35	8.10	1.65	6.14	10.97	7.80	0.78	6.51	8.59
Tb	1.07	0.63	0.66	2.24	0.99	0.25	0.69	1.40	1.04	0.09	0.86	1.14
Dy	6.25	3.75	3.69	13.16	5.72	1.42	4.25	8.20	6.09	0.67	5.04	6.82
Ho	1.23	0.74	0.72	2.59	1.10	0.28	0.80	1.58	1.15	0.13	0.94	1.30
Er	3.49	1.97	2.06	7.21	3.15	0.75	2.32	4.40	3.24	0.31	2.84	3.62
Tm	0.51	0.25	0.32	0.99	0.45	0.11	0.32	0.61	0.48	0.05	0.39	0.54
Yb	3.23	1.36	2.13	5.90	3.01	0.68	2.30	4.10	3.06	0.28	2.71	3.56
Lu	0.46	0.16	0.32	0.78	0.40	0.09	0.30	0.54	0.42	0.04	0.37	0.49
Eu/Eu*	0.66	0.06	0.58	0.77	0.63	0.04	0.57	0.70	0.66	0.06	0.58	0.77
TOC (%)	0.03	0.06	b.d.	0.16	0.32	0.38	0.06	1.24	0.05	0.01	0.04	0.06

Table 4.2 (cont.): Compositional average (avg.), standard deviation (2σ), minimum (min.) and maximum (max.) values for stratal divisions of the WSG in the southern Canadian Cordillera. Notes: *n* = number of samples; n/a = not analyzed; b.d. = below detection limits. Stratal abbreviations are listed in the text.

	OFP: GSM east (<i>n</i> = 11)				OFP: GSM west (<i>n</i> = 5)				OFP: WMM (<i>n</i> = 4)			
	Avg.	2σ	Min.	Max.	Avg.	2σ	Min.	Max.	Avg.	2σ	Min.	Max.
SiO ₂	62.91	2.54	58.13	65.84	61.24	2.29	59.22	65.18	64.21	2.72	61.81	67.68
TiO ₂	0.69	0.05	0.58	0.77	0.75	0.07	0.71	0.86	0.73	0.03	0.69	0.75
Al ₂ O ₃	21.86	2.29	18.47	25.59	20.75	2.51	18.94	25.00	20.24	2.48	18.36	23.87
Fe ₂ O ₃	5.26	1.45	2.55	7.81	6.04	1.20	4.63	7.35	5.29	1.56	4.10	7.51
MnO	0.04	0.03	0.01	0.09	0.06	0.02	0.05	0.10	0.03	0.02	0.02	0.05
MgO	2.06	0.80	0.65	3.01	3.15	0.61	2.50	4.10	2.54	1.35	0.63	3.53
CaO	1.12	1.64	0.05	5.60	4.40	2.13	2.36	7.54	0.89	0.62	0.07	1.56
Na ₂ O	1.26	0.39	0.47	1.86	0.85	0.24	0.43	1.01	1.32	0.33	0.90	1.63
K ₂ O	4.49	0.84	3.31	6.05	5.18	0.46	4.67	5.92	4.41	0.79	3.80	5.52
P ₂ O ₅	0.10	0.02	0.06	0.13	0.11	0.01	0.10	0.12	0.12	0.01	0.10	0.13
LOI	6.18	1.91	4.20	10.16	7.48	2.09	5.17	10.14	4.79	0.77	3.89	5.72
CIA	73.92	3.01	68.82	77.49	70.13	3.11	65.66	73.82	73.20	2.38	70.95	75.59
Rb	180.87	28.21	138.72	224.53	154.22	31.43	100.48	181.53	165.26	45.35	132.81	229.78
Cs	6.11	1.55	3.85	9.03	5.10	0.62	4.09	5.63	4.53	1.82	3.36	7.24
Ba	796.88	160.62	570.52	1121.31	764.25	52.11	702.83	845.63	832.90	175.65	614.55	1036.19
Sr	142.97	62.10	60.29	250.75	188.99	75.66	114.80	275.44	111.89	40.82	82.56	169.83
Pb	19.98	9.31	5.16	33.88	23.30	31.55	2.23	78.64	9.65	3.13	6.48	13.83
Th	21.50	2.08	17.26	24.56	17.09	1.19	15.79	18.25	20.67	5.00	17.72	28.11
U	5.78	2.78	2.50	12.60	4.51	1.35	3.20	6.61	4.10	1.13	2.88	5.37
Y	30.74	9.48	23.04	56.20	27.85	6.19	20.67	34.83	26.50	4.56	20.44	31.48
Zr	170.11	25.37	103.02	195.98	154.74	6.59	148.71	162.29	162.27	28.56	128.39	191.29
Hf	4.95	0.63	3.14	5.49	4.42	0.40	4.11	5.11	4.84	0.72	3.87	5.53
Nb	16.30	1.80	13.10	18.59	14.65	0.30	14.13	14.86	15.49	2.30	14.20	18.94
Ta	1.28	0.13	1.04	1.48	1.04	0.10	0.94	1.19	1.18	0.28	1.02	1.59
Cr	84.32	15.45	63.79	110.32	102.57	9.88	87.90	113.34	91.62	11.42	82.11	106.23
Co	14.51	6.97	1.95	26.49	17.20	9.25	4.49	28.36	12.60	4.26	7.39	17.22
Ni	40.39	21.55	10.83	75.92	62.40	48.19	25.02	145.45	44.92	12.68	36.24	63.74
Cu	36.50	15.03	10.38	59.89	45.07	40.16	7.44	112.75	13.82	6.67	7.61	20.58
Zn	81.89	24.72	50.06	119.70	90.99	17.72	67.44	111.47	100.11	15.32	88.02	122.22
Sc	21.29	3.15	15.93	26.85	19.44	1.60	17.28	21.01	21.77	4.08	18.59	27.70
V	119.69	28.63	76.13	161.12	141.69	41.97	97.12	198.51	150.90	21.70	124.89	177.96
Mo	3.59	1.61	0.75	6.39	7.75	6.36	3.34	18.98	5.13	2.79	1.69	8.45
Sb	2.76	2.96	0.29	8.83	1.55	0.77	0.83	2.67	0.64	0.16	0.52	0.86
As	29.31	22.91	4.97	87.51	11.61	10.11	5.53	23.28	22.49	16.74	10.65	34.33
La	72.92	7.28	64.94	90.19	54.51	7.99	43.82	64.39	59.84	13.75	50.73	80.03
Ce	134.39	13.01	120.31	164.39	100.51	17.60	75.34	118.63	115.73	26.96	97.31	155.07
Pr	16.44	1.91	14.28	20.19	12.61	2.47	9.07	15.29	13.90	3.17	11.75	18.56
Nd	56.42	6.61	47.22	68.75	44.32	9.01	29.54	53.14	47.90	10.32	41.25	63.02
Sm	9.52	2.42	6.29	15.72	7.63	1.45	5.27	8.95	7.97	1.66	6.44	10.24
Eu	1.52	0.65	1.04	3.35	1.42	0.26	1.04	1.74	1.43	0.14	1.26	1.59
Gd	7.69	3.18	4.72	16.77	6.39	1.02	4.99	7.36	6.65	1.24	5.05	8.04
Tb	1.03	0.41	0.65	2.19	0.88	0.13	0.70	1.00	0.89	0.16	0.68	1.07
Dy	6.17	2.08	4.52	11.87	5.31	0.90	4.09	6.28	5.32	1.04	4.14	6.67
Ho	1.20	0.36	0.89	2.17	1.06	0.18	0.82	1.25	1.05	0.18	0.83	1.28
Er	3.38	0.89	2.66	5.73	3.09	0.47	2.45	3.63	3.08	0.60	2.43	3.87
Tm	0.48	0.12	0.38	0.78	0.44	0.05	0.36	0.50	0.44	0.08	0.35	0.54
Yb	3.09	0.65	2.52	4.79	2.87	0.28	2.43	3.12	2.84	0.52	2.32	3.57
Lu	0.44	0.09	0.34	0.66	0.40	0.05	0.35	0.47	0.39	0.08	0.31	0.49
Eu/Eu*	0.54	0.08	0.42	0.63	0.63	0.02	0.60	0.66	0.61	0.08	0.50	0.68
TOC (%)	0.73	0.47	0.18	1.82	0.96	0.55	0.38	1.66	0.62	0.37	0.15	1.05

Table 4.2 (cont.): Compositional average (avg.), standard deviation (2σ), minimum (min.) and maximum (max.) values for stratal divisions of the WSG in the southern Canadian Cordillera. Notes: *n* = number of samples; n/a = not analyzed; b.d. = below detection limits. Stratal abbreviations are listed in the text.

W	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Rb	Cs	Ba	Sr	Th	U	Y	Zr
SiO ₂	0.98	-0.53	-0.63	-0.53	-0.11	-0.25	-0.14	0.38	-0.59	-0.22	-0.51	-0.33	-0.51	0.01	-0.27	0.09	0.01	0.16
TiO ₂	-0.52	0.95	0.46	0.38	0.00	0.11	-0.19	-0.09	0.33	0.34	0.32	0.14	0.31	0.08	0.38	0.10	0.07	0.36
Al ₂ O ₃	-0.69	0.42	0.98	0.04	-0.40	-0.32	-0.49	-0.27	0.71	0.11	0.68	0.49	0.60	-0.18	0.43	0.05	0.11	-0.38
Fe ₂ O ₃	-0.57	0.39	0.15	0.97	0.60	0.62	-0.02	-0.28	-0.02	0.17	-0.05	-0.01	-0.02	-0.14	0.09	0.03	-0.23	0.16
MnO	-0.17	0.05	-0.27	0.63	0.89	0.57	0.24	-0.16	-0.23	-0.05	-0.28	-0.05	-0.24	-0.11	-0.17	-0.10	-0.06	0.28
MgO	-0.24	0.12	-0.28	0.63	0.63	0.99	0.29	-0.36	-0.07	0.04	-0.28	-0.31	-0.08	-0.20	-0.23	-0.13	-0.27	0.20
CaO	0.06	0.02	-0.45	0.15	0.44	0.39	0.39	0.13	-0.27	0.02	-0.34	-0.27	-0.27	0.46	-0.31	-0.15	0.03	0.16
Na ₂ O	0.44	-0.13	-0.28	-0.27	-0.18	-0.31	0.15	0.94	-0.67	0.01	-0.49	-0.23	-0.54	0.73	-0.18	0.01	0.22	0.08
K ₂ O	-0.56	0.30	0.62	0.09	-0.15	-0.02	-0.41	-0.77	0.95	-0.03	0.88	0.53	0.88	-0.45	0.37	-0.08	0.03	-0.30
P ₂ O ₅	-0.27	0.35	0.11	0.17	0.08	0.17	0.38	0.01	0.04	0.35	-0.07	0.01	-0.08	0.15	0.05	0.10	0.03	0.23
Rb	-0.52	0.33	0.63	0.05	-0.24	-0.24	-0.50	-0.59	0.87	-0.01	0.96	0.62	0.88	-0.33	0.45	-0.05	0.01	-0.33
Cs	-0.34	0.18	0.43	0.07	-0.05	-0.23	-0.33	-0.28	0.48	0.07	0.60	0.99	0.52	-0.16	0.13	-0.05	0.20	-0.31
Ba	-0.46	0.27	0.50	0.08	-0.19	-0.05	-0.44	-0.64	0.84	-0.04	0.84	0.47	0.92	-0.38	0.28	-0.15	-0.05	-0.32
Sr	0.19	-0.02	-0.21	-0.17	-0.06	-0.18	0.44	0.64	-0.61	0.25	-0.52	-0.14	-0.58	0.72	-0.22	-0.12	0.18	0.00
Th	-0.22	0.33	0.34	0.08	-0.13	-0.24	-0.09	-0.04	0.21	0.21	0.37	0.08	0.13	-0.17	0.95	0.24	0.16	0.12
U	0.09	0.12	0.05	-0.05	-0.15	-0.06	0.05	0.06	-0.02	0.12	-0.04	-0.20	-0.15	-0.03	0.35	0.85	-0.06	0.23
Y	0.13	0.01	-0.06	-0.24	-0.07	-0.20	0.19	0.21	-0.17	0.21	-0.17	0.04	-0.25	0.31	0.09	-0.09	0.88	0.10
Zr	0.17	0.29	-0.36	0.07	0.20	0.23	0.44	0.20	-0.26	0.17	-0.27	-0.30	-0.33	0.11	0.20	0.30	0.22	0.90
Hf	0.05	0.43	-0.25	0.15	0.15	0.20	0.28	0.09	-0.12	0.09	-0.10	-0.27	-0.15	-0.03	0.28	0.30	0.07	0.91
Nb	-0.30	0.73	0.38	0.13	-0.18	-0.27	-0.09	0.06	0.16	0.19	0.34	0.13	0.11	0.09	0.58	0.23	0.15	0.27
Ta	-0.28	0.70	0.39	0.09	-0.28	-0.33	-0.19	0.03	0.23	0.09	0.42	0.14	0.20	-0.03	0.62	0.27	0.02	0.24
Cr	-0.50	0.68	0.30	0.54	0.23	0.37	0.06	-0.14	0.25	0.33	0.23	0.34	0.28	0.00	-0.01	-0.05	-0.04	0.10
Co	-0.15	0.08	-0.15	0.58	0.56	0.47	0.45	-0.01	-0.19	0.23	-0.28	-0.04	-0.22	0.16	-0.10	0.12	0.01	0.26
Ni	-0.09	0.03	-0.12	0.50	0.51	0.54	0.30	0.00	-0.14	0.22	-0.25	-0.01	-0.12	0.05	-0.19	0.16	-0.21	0.15
Cu	0.04	-0.03	-0.15	0.16	0.34	0.14	0.32	0.07	-0.24	0.12	-0.23	-0.12	-0.31	0.19	0.13	0.41	0.06	0.36
Zn	-0.02	-0.15	-0.03	0.34	0.43	0.33	0.23	0.00	-0.11	0.27	-0.21	0.01	-0.23	0.03	0.04	-0.03	0.14	0.04
Sc	-0.45	0.39	0.45	0.38	0.23	0.03	-0.04	-0.21	0.35	0.34	0.38	0.47	0.28	-0.12	0.37	-0.04	0.16	0.08
V	-0.06	0.44	0.11	-0.05	-0.25	0.03	-0.04	0.05	0.13	0.04	0.10	0.13	0.28	0.09	0.05	0.15	0.07	0.16
Mo	0.62	-0.22	-0.47	-0.49	-0.17	-0.19	0.21	0.43	-0.43	-0.04	-0.46	-0.20	-0.42	0.36	-0.23	0.25	0.26	0.26
Sb	0.30	-0.15	-0.38	-0.21	0.02	-0.02	0.32	0.20	-0.27	0.05	-0.27	0.16	-0.26	0.32	-0.25	-0.12	0.36	0.18
Pb	0.22	0.00	-0.20	-0.10	-0.23	-0.25	0.08	0.44	-0.35	0.13	-0.28	-0.09	-0.34	0.34	-0.10	0.09	0.26	0.16
TOC	0.55	-0.38	-0.33	-0.62	-0.25	-0.37	0.21	0.46	-0.39	-0.10	-0.39	-0.16	-0.49	0.50	-0.09	0.14	0.40	0.14
ΣREE	-0.20	0.15	0.49	-0.25	-0.35	-0.43	-0.23	-0.01	0.42	0.00	0.35	0.22	0.15	-0.02	0.53	0.14	0.37	-0.13
ΣLREE	-0.20	0.15	0.49	-0.25	-0.36	-0.43	-0.23	-0.01	0.43	-0.01	0.37	0.22	0.17	-0.04	0.54	0.14	0.32	-0.15
ΣHREE	-0.10	0.08	0.24	-0.18	-0.06	-0.26	-0.05	0.07	0.18	0.11	0.01	0.19	-0.10	0.16	0.21	-0.07	0.88	0.11

Table 4.3: Correlation coefficients between major and selected trace elements for WSG mudstone samples ($n = 87$). Pearson's correlation coefficient (r) listed in upper right triangle of matrix, Spearman's rank order correlation coefficient (ρ) listed in lower left triangle of matrix. Correlation coefficients with p -values < 0.001 are highlighted in bold: positive in red, negative in blue. Shapiro-Wilk's test (W) values are presented in the shaded diagonal that separates the two triangles.

W	Hf	Nb	Ta	Cr	Co	Ni	Cu	Zn	Sc	V	Mo	Sb	Pb	TOC	ΣREE	ΣLREE	ΣHREE
SiO ₂	0.08	-0.26	-0.26	-0.47	-0.19	-0.07	0.05	-0.05	-0.45	0.02	0.44	0.16	0.16	0.40	-0.20	-0.20	-0.10
TiO ₂	0.45	0.72	0.70	0.69	0.15	0.01	-0.06	-0.17	0.36	0.37	-0.19	-0.11	-0.01	-0.25	0.15	0.15	0.08
Al ₂ O ₃	-0.30	0.33	0.37	0.35	-0.12	-0.16	-0.21	-0.05	0.53	0.14	-0.28	-0.04	-0.20	-0.21	0.49	0.49	0.24
Fe ₂ O ₃	0.19	0.12	0.08	0.46	0.55	0.39	0.16	0.38	0.27	-0.11	-0.29	-0.11	-0.06	-0.46	-0.25	-0.25	-0.18
MnO	0.22	-0.13	-0.24	0.13	0.44	0.39	0.26	0.40	0.12	-0.27	-0.13	-0.07	-0.10	-0.18	-0.35	-0.36	-0.06
MgO	0.17	-0.25	-0.29	0.27	0.40	0.45	0.16	0.35	-0.07	-0.02	-0.02	-0.27	-0.23	-0.34	-0.43	-0.43	-0.26
CaO	0.11	-0.22	-0.27	-0.20	0.03	0.01	0.16	-0.09	-0.31	-0.13	0.12	0.04	0.12	0.20	-0.23	-0.23	-0.05
Na ₂ O	0.04	0.15	0.09	-0.04	-0.11	-0.09	-0.03	-0.14	-0.29	0.14	0.12	0.20	0.41	0.30	-0.01	-0.01	0.07
K ₂ O	-0.19	0.19	0.26	0.17	-0.21	-0.19	-0.27	-0.16	0.40	0.08	-0.19	-0.18	-0.29	-0.24	0.42	0.43	0.18
P ₂ O ₅	0.24	0.11	0.10	0.37	0.23	0.11	0.05	0.05	0.15	0.08	-0.10	-0.06	0.12	-0.14	0.00	-0.01	0.11
Rb	-0.20	0.35	0.43	0.13	-0.29	-0.26	-0.28	-0.25	0.37	0.03	-0.25	-0.08	-0.23	-0.24	0.47	0.48	0.14
Cs	-0.27	0.06	0.08	0.25	-0.05	-0.04	-0.12	-0.01	0.49	0.08	-0.13	0.29	-0.04	0.06	0.36	0.36	0.29
Ba	-0.17	0.15	0.26	0.22	-0.23	-0.15	-0.32	-0.24	0.28	0.17	-0.22	-0.15	-0.29	-0.30	0.34	0.36	0.07
Sr	0.00	0.24	0.16	0.07	-0.04	-0.08	0.02	-0.22	-0.27	0.10	0.02	0.16	0.39	0.23	-0.06	-0.07	0.03
Th	0.18	0.59	0.63	-0.07	-0.16	-0.23	-0.01	0.02	0.42	0.02	-0.16	-0.03	-0.15	-0.13	0.59	0.59	0.29
U	0.20	0.18	0.19	-0.07	0.19	0.19	0.29	-0.02	0.03	0.10	0.32	0.41	0.10	0.15	0.02	0.02	-0.06
Y	0.02	0.16	0.05	0.01	-0.07	-0.15	-0.01	0.06	0.23	0.10	0.00	0.13	0.15	0.28	0.52	0.47	0.93
Zr	0.94	0.32	0.25	0.13	0.30	0.16	0.30	0.04	0.04	0.10	0.09	0.12	0.11	0.04	-0.15	-0.17	0.05
Hf	0.92	0.42	0.40	0.19	0.26	0.10	0.22	-0.07	0.03	0.11	0.04	0.06	0.17	-0.07	-0.15	-0.16	-0.01
Nb	0.41	0.94	0.94	0.24	-0.16	-0.26	-0.07	-0.23	0.20	0.16	-0.22	-0.05	0.05	-0.12	0.36	0.36	0.16
Ta	0.45	0.94	0.93	0.21	-0.19	-0.31	-0.13	-0.31	0.17	0.18	-0.21	-0.08	0.09	-0.15	0.35	0.36	0.07
Cr	0.14	0.33	0.27	0.90	0.39	0.34	0.05	0.03	0.34	0.41	-0.17	-0.06	0.00	-0.23	-0.09	-0.09	0.01
Co	0.20	-0.13	-0.17	0.35	0.97	0.77	0.50	0.38	0.19	0.02	-0.03	0.13	0.09	-0.13	-0.37	-0.38	-0.09
Ni	0.07	-0.23	-0.27	0.40	0.77	0.90	0.53	0.48	0.16	0.09	0.07	0.09	-0.09	-0.18	-0.42	-0.43	-0.19
Cu	0.27	0.02	0.00	0.03	0.49	0.40	0.89	0.26	0.09	0.02	0.16	0.17	0.03	0.10	-0.20	-0.20	-0.07
Zn	-0.13	-0.19	-0.30	0.06	0.40	0.52	0.23	0.98	0.48	-0.09	-0.03	-0.04	-0.10	-0.18	-0.14	-0.15	0.12
Sc	0.04	0.26	0.22	0.43	0.24	0.26	0.16	0.48	0.99	0.11	-0.17	0.12	-0.17	-0.11	0.29	0.28	0.37
V	0.20	0.23	0.25	0.40	-0.01	0.02	-0.08	-0.15	0.17	0.95	0.40	0.15	0.06	0.31	0.00	0.00	0.00
Mo	0.17	-0.18	-0.17	-0.28	-0.08	-0.12	0.14	-0.07	-0.27	0.33	0.59	0.37	0.17	0.41	-0.14	-0.14	-0.07
Sb	0.07	-0.21	-0.24	-0.05	0.17	0.03	0.08	0.05	0.01	0.19	0.56	0.51	0.26	0.53	-0.03	-0.04	0.05
Pb	0.20	0.06	0.09	-0.06	0.07	-0.11	0.09	-0.08	-0.14	0.07	0.42	0.32	0.90	0.12	0.00	0.00	0.08
TOC	-0.04	-0.13	-0.18	-0.44	-0.17	-0.27	0.15	0.00	-0.22	0.11	0.75	0.47	0.29	0.75	0.04	0.03	0.13
ΣREE	-0.15	0.38	0.38	-0.16	-0.36	-0.46	-0.06	-0.07	0.21	-0.08	-0.10	-0.21	0.09	0.19	0.87	1.00	0.68
ΣLREE	-0.16	0.38	0.38	-0.17	-0.38	-0.48	-0.08	-0.09	0.19	-0.07	-0.12	-0.23	0.08	0.18	1.00	0.87	0.64
ΣHREE	0.00	0.18	0.09	-0.03	-0.05	-0.24	0.04	0.17	0.30	-0.05	0.08	0.18	0.19	0.27	0.60	0.56	0.84

Table 4.3 (cont.): Correlation coefficients between major and selected trace elements for WSG mudstone samples ($n = 87$). Pearson's correlation coefficient (r) listed in upper right triangle of matrix, Spearman's rank order correlation coefficient (ρ) listed in lower left triangle of matrix. Correlation coefficients with p -values < 0.001 are highlighted in bold: positive in red, negative in blue. Shapiro-Wilk's test (W) values are presented in the shaded diagonal that separates the two triangles.

Australian Shales (PAAS) (Taylor and McLennan, 1985; McLennan et al., 2001) are also plotted for reference with their symbols a plus-sign (+) and an asterisk (*), respectively.

4.5.1 Major elements

The low-grade metamorphic WSG samples ($n = 87$) all plot within the “shale” field on the sedimentary geochemical classification diagram of Herron (1988) confirming their selection as mudstone units (Fig. 4.4). Variations in major element chemistry are plotted in Figure 4.5 and 4.6. For example, the WSG samples are characterized by SiO_2 contents ranging from 47.11 to 68.14% (average: 59.15%), Al_2O_3 contents ranging from 12.64 to 33.48% (average: 23.29%), Fe_2O_3 contents ranging from 2.06 to 14.41% (average: 6.69%), and K_2O contents ranging from 2.48 to 10.31% (average: 5.23%) (Table 4.2).

When compared with the shale standards NASC and PAAS, mudstone units of the WSG are distinguished by a number of characteristics. The most striking are elevated values of Al_2O_3 and K_2O , with lower SiO_2 . The WSG samples generally display relatively low CaO , MnO and P_2O_5 and exhibit a wide range of Fe_2O_3 and Na_2O concentrations. The remainder of the major element contents are fairly comparable to the NASC and PAAS standards.

For all WSG samples, SiO_2 exhibits negative correlation with Al_2O_3 ($r = -0.63$), TiO_2 ($r = -0.53$), Fe_2O_3 ($r = -0.53$) and K_2O ($r = 0.59$), and weak positive correlation with Na_2O ($r = 0.38$). Scatter in the Na_2O values likely reflects variable alteration of plagioclase feldspar during weathering or transport. Al_2O_3 has a positive correlation with K_2O ($r = 0.71$) and TiO_2 ($r = 0.46$), and negative correlation with MnO ($r = -0.40$). The high Al_2O_3 - K_2O positive correlation suggests that illite was the dominant clay mineral prior to metamorphism. Fe_2O_3 is characterized by positive correlation with MgO ($r = 0.62$), MnO ($r = 0.60$) and TiO_2 ($r = 0.38$). TiO_2 correlation with both Al_2O_3 and Fe_2O_3 implies that it is associated with both the clay mineral and heavy mineral fraction. Other statistical significant correlation

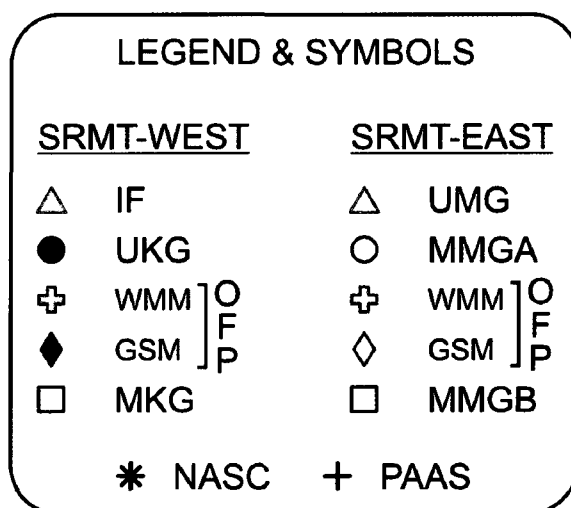
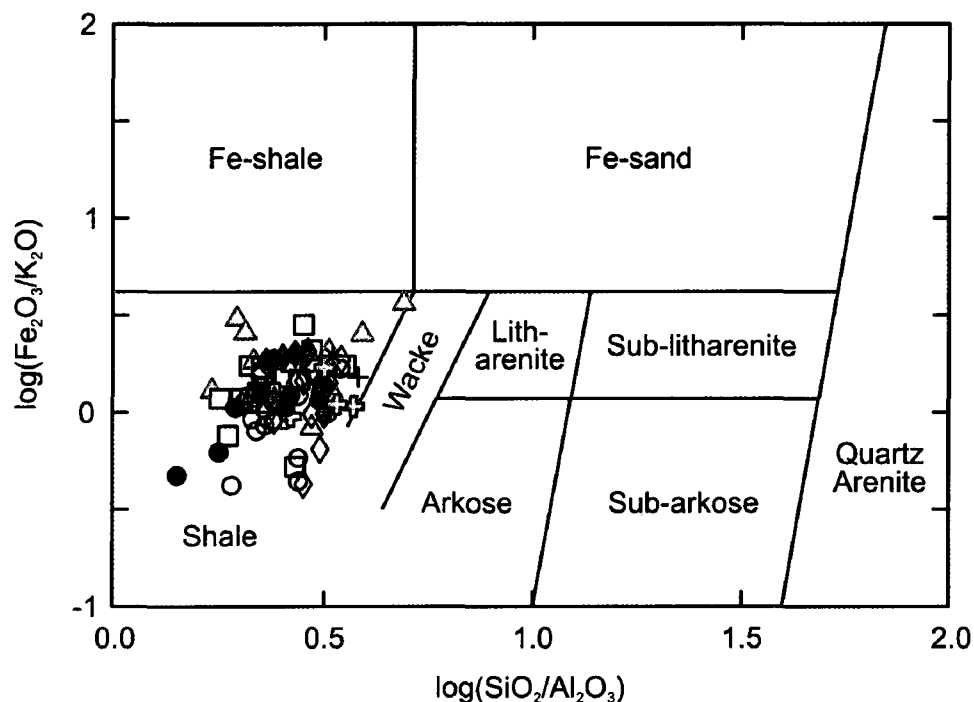


Figure 4.4: Sedimentary geochemical classification after Herron (1988) for WSG samples ($n = 87$). Legend abbreviations: OFP = Old Fort Point Formation; WMM = Whitehorn Mountain Member; GSM = Geikie Siding Member; IF = Isaac Formation, Cariboo Group; UKG = Upper Kaza Group; MKG = Middle Kaza Group; UMG = Upper Miette Group; MMGA = Middle Miette Group above OFP; MMGB = Middle Miette Group below OFP; SRMT = Southern Rocky Mountain Trench; NASC = North American Shale Composite (Gromet et. al., 1984); and PAAS = Post-Archean Australian Shale (Taylor and McLennan, 1985).

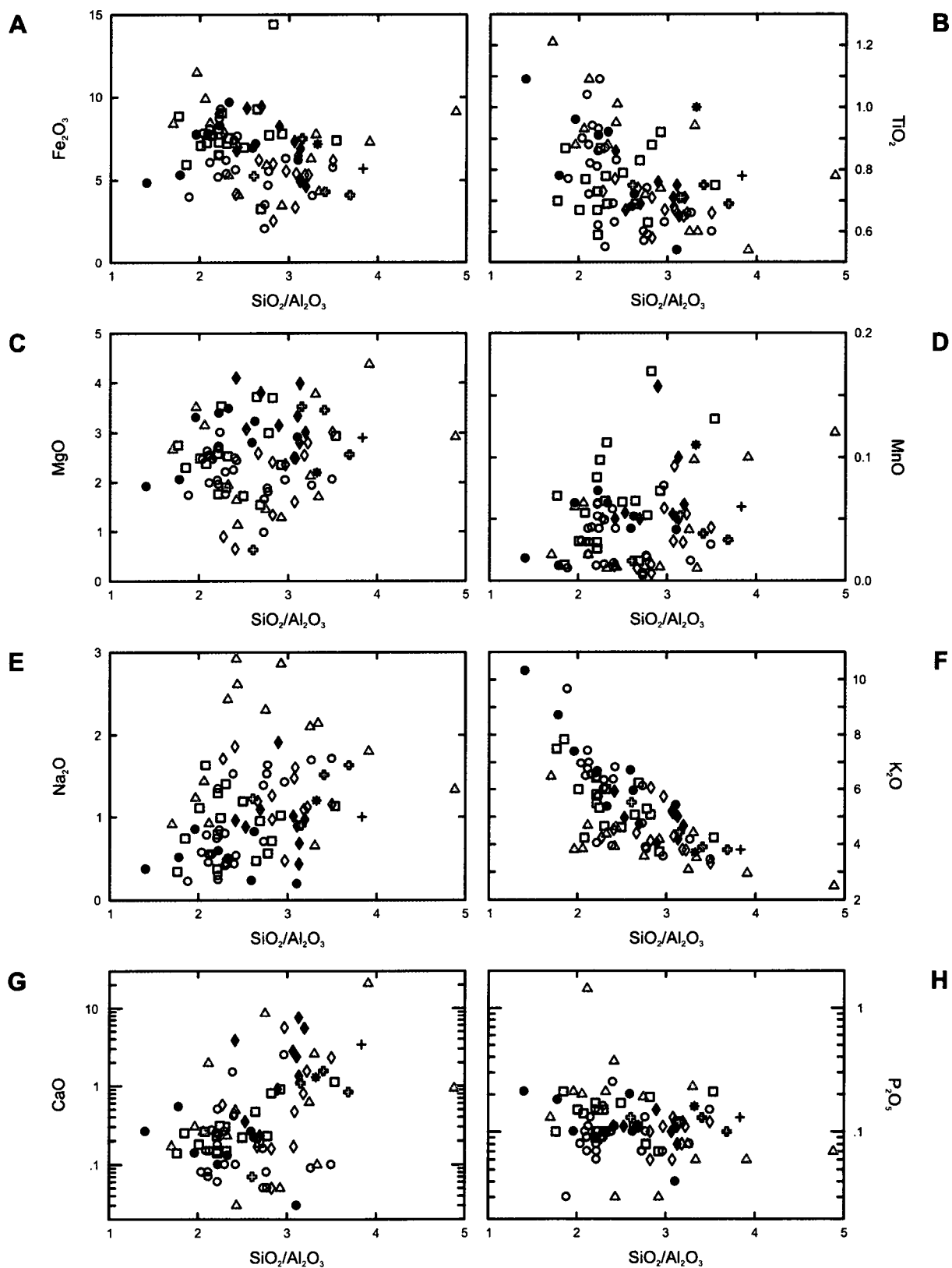


Figure 4.5: Major element (wt%) diagrams of $\text{SiO}_2/\text{Al}_2\text{O}_3$ vs.: A) Fe_2O_3 ; B) TiO_2 ; C) MgO ; D) MnO ; E) Na_2O ; F) K_2O ; G) CaO ; and H) P_2O_5 . Legend of symbols is the same as Fig. 4.4.

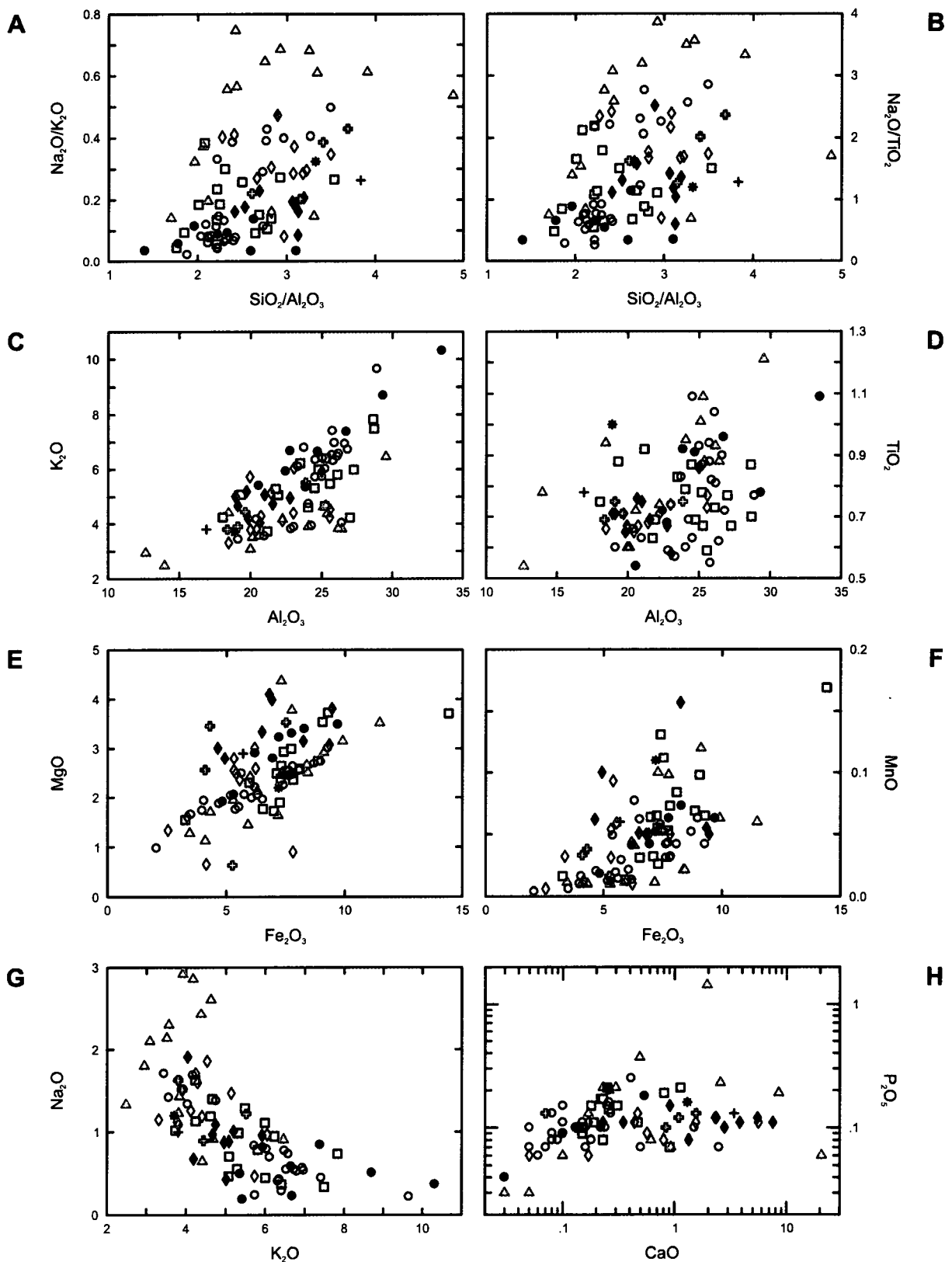


Figure 4.6: Selected major (wt%) element diagrams: A) $\text{SiO}_2/\text{Al}_2\text{O}_3$ vs. $\text{K}_2\text{O}/\text{Na}_2\text{O}$; B) $\text{SiO}_2/\text{Al}_2\text{O}_3$ vs. $\text{Na}_2\text{O}/\text{TiO}_2$; C) Al_2O_3 vs. K_2O ; D) Al_2O_3 vs. TiO_2 ; E) Fe_2O_3 vs. MgO ; F) Fe_2O_3 vs. MnO ; G) K_2O vs. Na_2O ; and H) CaO vs. P_2O_5 . Legend of symbols is the same as Fig. 4.4.

coefficients include MgO - MnO ($r = 0.57$), MgO - Na₂O ($r = -0.36$), and Na₂O - K₂O ($r = -0.67$). Both CaO and P₂O₅ concentrations possess low W -values and thus, Spearman rank order correlation coefficients are used. CaO positively correlates with MnO ($\rho = 0.44$) and MgO ($\rho = 0.39$) suggesting some control of these elements by carbonate minerals with the weak correlation with P₂O₅ ($\rho = 0.38$) implying the minor presence of apatite. CaO also negatively correlates with Al₂O₃ ($\rho = -0.45$) and K₂O ($\rho = -0.41$).

Overall, the stratal divisions of the WSG exhibit considerable compositional overlap in major element chemistry, with subtle differences in the average or range of values. When compared to the other units of the WSG, the MKG and MMGB possess elevated Fe₂O₃ contents. The OFP is characterized by higher SiO₂ and CaO, lower Al₂O₃ and a wider range of CaO content. The IF and UMG samples have low K₂O values and a wide range in CaO, with the IF also characterized by higher Fe₂O₃ and TiO₂. Most samples collected west of the SRMT (Cariboo and Purcell Mountains) are relatively enriched in MgO and depleted in Na₂O compared to locations east of the SRMT (Lake Louise, Jasper, Mount Robson, McKale River).

4.5.2 Large ion lithophile elements (LILE): Rb, Cs, Ba, Sr, Th, U, Pb

Concentrations of the LILE in the WSG are variable, generally displaying a wide range when compared to NASC and PAAS values (Figs. 4.7 and 4.8). Contents of Rb (86.03 to 385.05 ppm), Ba (377.54 to 2056.84), Th (9.77 to 37.01 ppm) and U (1.74 to 12.60 ppm) mostly show relative enrichment compared to the shale standards. Sr (23.55 to 648.63 ppm) and Pb (1.04 to 78.64 ppm) show both enriched and depleted concentrations. Cs (2.20 to 9.92 ppm) values are consistent with NASC and depleted when compared to PAAS.

From the LILE, Rb and Ba exhibit nearly identical geochemical trends, with Cs and Th to a lesser extent. For example, Rb shows good positive correlation Ba ($r = 0.88$), and also ($r = 0.62$) and Th ($r = 0.45$). When compared to the major elements, Rb and Ba are characterized by negative correlation with SiO₂ ($r = -0.51$ for both)

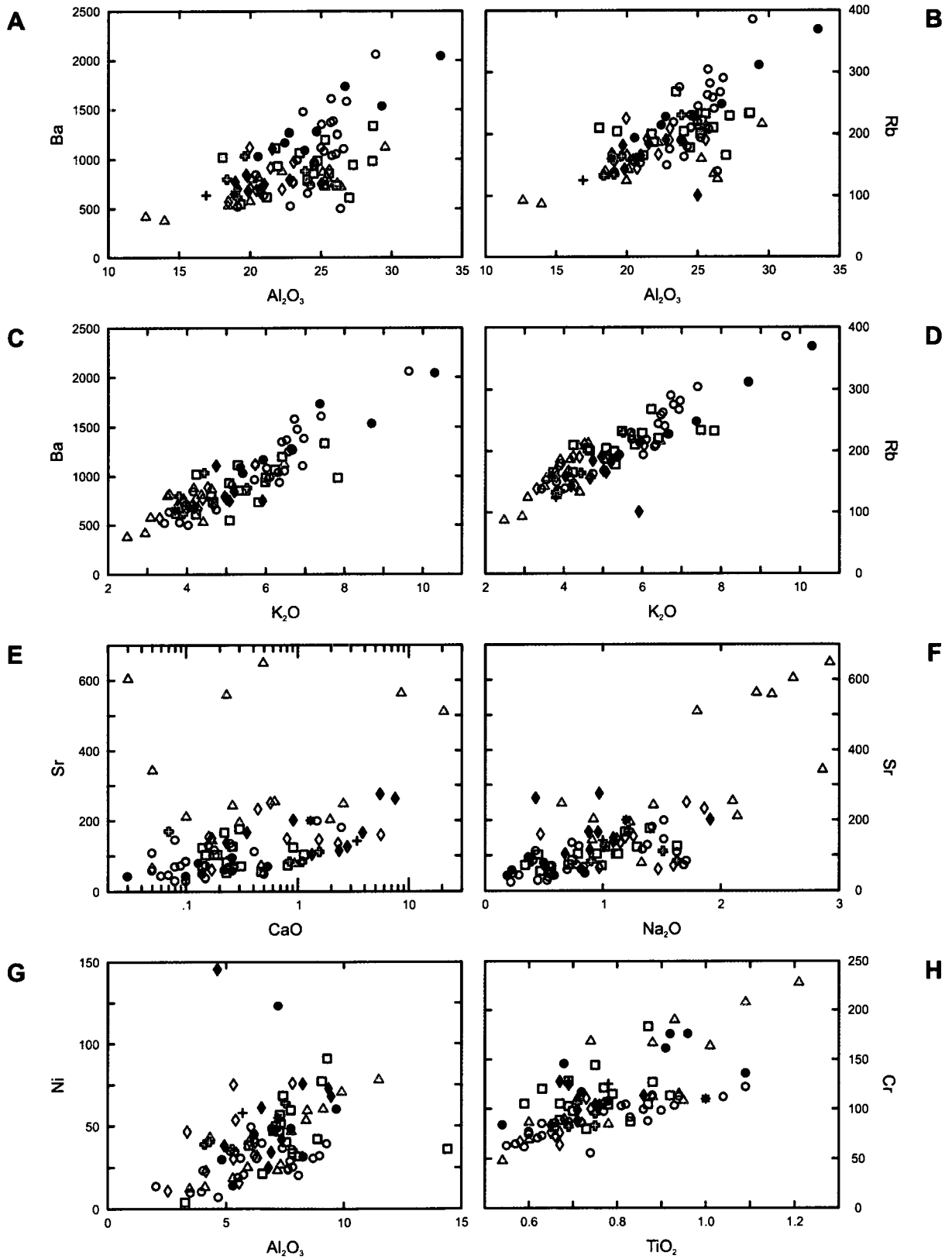


Figure 4.7: Selected major (wt%) and trace (ppm) element diagrams: A) Al_2O_3 vs. Ba; B) Al_2O_3 vs. Rb; C) K_2O vs. Ba; D) K_2O vs. Rb; E) CaO vs. Sr; F) Na_2O vs. Sr; G) Fe_2O_3 vs. Ni; and H) TiO_2 vs. Cr. Legend of symbols is the same as Fig. 4.4.

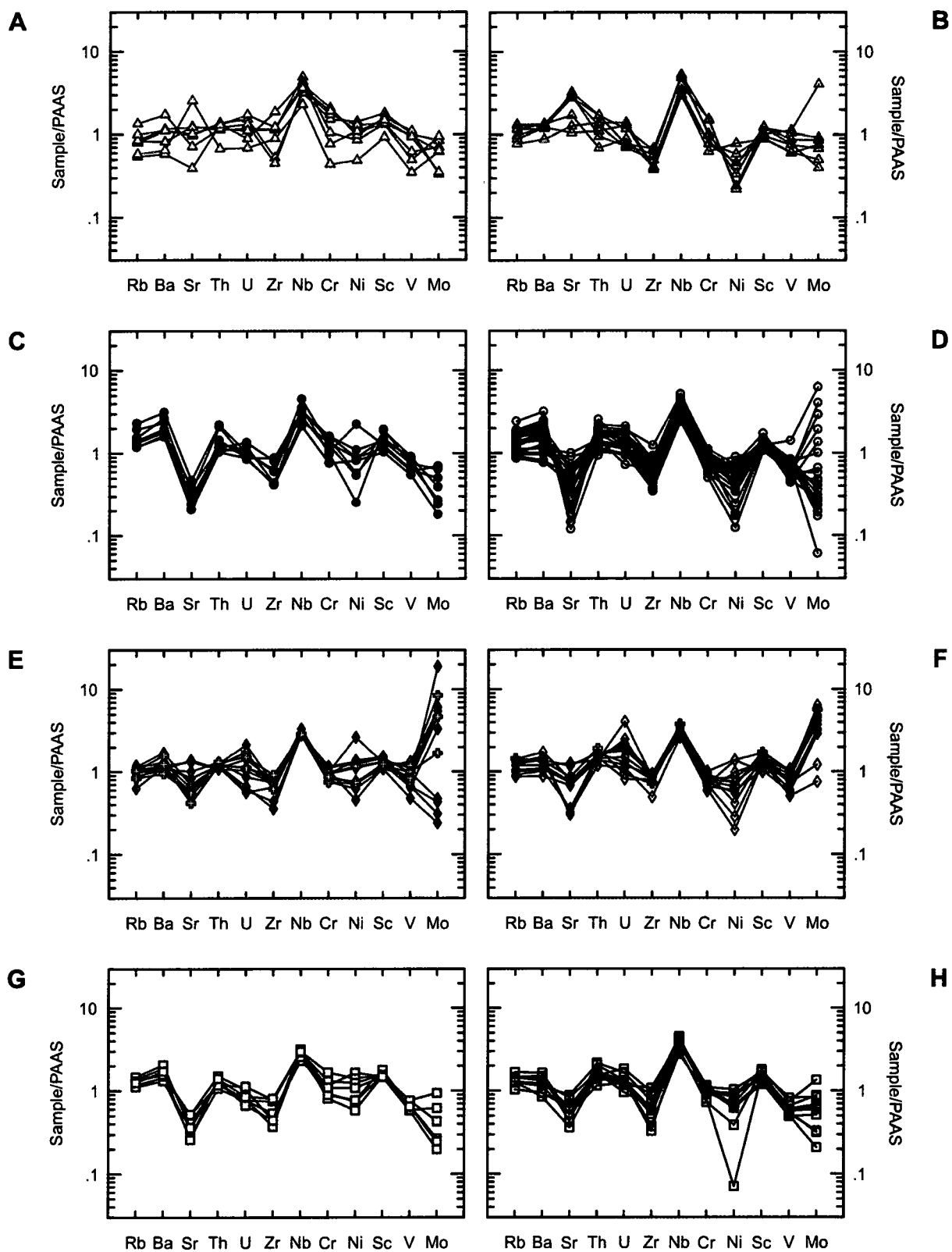


Figure 4.8: Spider diagram of selected trace elements (Rb, Ba, Sr, Th, U, Zr, Nb, Cr, Ni, Sc, V, Mo) normalized to Post-Archean Australian Shale (PAAS) (Taylor and McLennan, 1985). Legend of symbols is the same as Fig. 4.4.

and Na₂O ($r = -0.49$ and -0.54 , respectively), and positive correlation with Al₂O₃ ($r = 0.68$ and 0.61 , respectively) and K₂O ($r = 0.88$ for both). The association of Rb and Ba with Al and K suggests these elements are fixed into clay minerals. Th shows low positive correlations with Al₂O₃ ($r = 0.43$), TiO₂ ($r = 0.38$) and K₂O ($r = 0.37$) suggesting fixation in both clay and/or heavy minerals. Sr behaves independently from SiO₂ and Al₂O₃ and shows opposing trends compared to its LILE counterparts: positive correlation with CaO ($\rho = 0.44$) and Na₂O ($\rho = 0.64$); negative correlation with K₂O ($\rho = -0.61$), Rb ($\rho = -0.52$) and Ba ($\rho = -0.58$). Unlike the other LILE, Sr is associated with carbonate phases or plagioclase feldspar that has not undergone significant alteration/leaching to form clay minerals. U only exhibits a low positive correlation with Th ($\rho = -0.35$) suggesting a somewhat dissimilar geochemical behaviour for these two elements. Pb shows only a positive correlation with Na₂O ($r = 0.41$) perhaps implying minor substitution in plagioclase feldspar.

Unlike the major elements, the stratal divisions of the WSG show considerable variation in a number of LILE. The MKG and MMGA are characterized by a wide range, and significant enrichment of Rb and Ba concentrations, whereas in the IF and UMG these elements tend to plot at the lower end of the WSG spectrum. Sr content in many of the IF, UMG and OFP samples is enriched but is depleted in the MKG, MMGB, UKG, and MMGA. Cs, Th, U and Pb concentrations show no obvious differences between WSG units, although sample collected east of the SRMT are generally higher in Th.

4.5.3 High-field strength elements (HFSE): Y, Zr, Hf, Nb, Ta

Concentrations of the HFSE in the WSG are relatively consistent with similar or slightly depleted concentrations compared to NASC and PAAS values (Figs. 4.7 and 4.8). For example, Y (10.55 to 64.27 ppm), Zr (69.55 to 259.27 ppm, one sample 390.79 ppm), Hf (2.07 to 11.37 ppm), Nb (10.64 to 26.24 ppm) and Ta (0.76 to 2.43 ppm).

With the exception of Y, the HFSE all exhibit positive correlation with TiO_2 : Zr ($r = 0.36$); Hf ($r = 0.45$); Nb ($r = 0.72$); and Ta ($r = 0.70$). These positive correlations suggest the HFSE contents are controlled mainly by Ti-bearing minerals (e.g. rutile, ilmenite), but the lack of positive correlation with SiO_2 imply that the elements, notably Zr, are not in the quartz grain-size fraction. Weak correlations between Al_2O_3 and Ta ($r = 0.37$) and Zr ($r = -0.38$) are also noted. As expected, high correlation coefficients result from the similar geochemical behaviour of Zr - Hf ($r = 0.94$) and Nb - Ta ($r = 0.94$). Nb and Ta also show positive correlation with Rb ($r = 0.35$ and 0.34 , respectively) and Th ($r = 0.59$ and 0.63 , respectively), Hf ($r = 0.42$ and 0.40 , respectively), but not Zr. Yttrium behaves independently from other elements, with the exception of the REE.

The WSG shows little variation from one another in HFSE content with only the IF samples having slightly elevated Zr and HF concentrations. Stratal units east of the SRMT display relative enrichments in Nb/Ti compared to their eastern counterparts.

4.5.4 Transition trace elements (TTE): Cr, Co, Ni, Cu, Zn, Sc, V

From the WSG samples, none of the TTE display significant enrichments when compared to PAAS and NASC (Figs. 4.7 and 4.8). Concentrations of Cr (47.93 to 228.12 ppm), Zn (41.67 to 164.15 ppm), Sc (14.23 to 30.99 ppm), and V (52.11 to 212.20 ppm) are all fairly consistent with the shale standards. However, many samples show depletions in Co (0.24 to 37.70 ppm), Ni (3.90 to 145.45 ppm), and Cu (2.50 to 112.75 ppm).

The TTE exhibit a fair amount of scatter with mostly moderate positive correlation coefficients. Co correlates with Ni ($r = 0.77$), Cu ($r = 0.50$) Cr ($r = 0.39$) and Zn ($r = 0.38$). Other statistical significant associations include: Ni - Cu ($r = 0.53$); Ni - Zn ($r = 0.48$); Sc - Zn ($r = 0.48$); and Cr - V ($r = 0.41$). When compared to the major elements: Co, Ni, and Zn tend to be associated with Fe_2O_3 ($r = 0.55$, 0.39 and 0.38 , respectively), MgO ($r = 0.40$, 0.45 and 0.35 , respectively) and MnO ($r =$

0.44, 0.39 and 0.40, respectively) suggesting their fixation in chlorite or Fe-oxides and/or sulfides. On the other hand, Cr ($r = 0.69$), Sc ($r = 0.36$), and V ($r = 0.37$) are associated with TiO_2 suggesting fixation with Ti-oxides such as rutile or ilmenite. Cr also shows positive correlation with Fe_2O_3 ($r = 0.46$), but a negative correlation with SiO_2 ($r = -0.47$). Sc also shows a negative correlation with SiO_2 ($r = -0.45$), but behaves somewhat unusually when compared to the other TTE with its positive correlations: Al_2O_3 ($r = 0.53$) and K_2O ($r = 0.40$); select LILE, such as Rb ($r = 0.37$), Cs ($r = 0.49$) and Th ($r = 0.42$); and Eu ($r = 0.42$) and ΣHREE ($r = 0.37$). From the TTE, only the Sc content appears to have a certain portion coupled to the clay or mica minerals.

As with the HFSE, there is considerable scatter among the TTE, and they do not readily discriminate individual WSG units. Elevated concentrations of V is observed in samples of the OFP, UMG and IF, with Cr enrichment in some samples of the IF, UM, UKG and MKG. Cr and Ni contents are generally higher in samples collected west of the SRMT.

4.5.5. Mo, Sb, As, TOC

Concentrations for the elements Mo (b.d. to 18.98 ppm), Sb (b.d. to 8.83 ppm) and As (b.d. to 87.51 ppm; only analyzed for the 2003 – 2005 sample set) are generally low with a few samples showing enrichment from the shale standards. Total organic carbon (TOC) contents from WSG mudstone samples selected for geochemical analyses in this paper range from (<0.05 to 1.82%). These concentrations are after the effects of low-grade metamorphism and it is probable that <25% of the original organic carbon deposition was preserved (e.g. Tissot and Welte, 1978; Hayes et al., 1983). Higher TOC contents (~2 to 7%) in WSG rocks have been recorded, but they are usually from the non-carbonate residue in organic-rich limestones or from mudstone clasts within coarse-grained facies (G. M. Ross, unpublished data; Appendix G).

For all the WSG samples, Mo exhibits positive Spearman's rank order correlation coefficients and TOC ($\rho = 0.75$) suggesting preferential fixation in the organic fraction. Mo and TOC also show similar correlation coefficient trends: positive with SiO_2 ($\rho = 0.62$ and 0.55 , respectively), Na_2O ($\rho = 0.43$ and 0.46 , respectively), Sr ($\rho = 0.36$ and 0.50 , respectively) and Sb ($\rho = 0.56$ and 0.47 , respectively); and negative with Fe_2O_3 ($\rho = -0.49$ and -0.62 , respectively), Ba ($\rho = -0.42$ and -0.49 , respectively), and TiO_2 , Al_2O_3 , MgO , K_2O , Rb and Cr (although both Mo and TOC are not statistically significant for all these elements). Interestingly, these associations suggest that the organic fraction (TOC, Mo) is more strongly linked to the detrital (quartz, plagioclase feldspar), rather than the clay mineral or Fe-sulfide fraction. Sb also shows low positive correlation with Y ($\rho = 0.36$) and low negative correlation with Al_2O_3 ($\rho = -0.38$). As contents show negative correlation with Fe_2O_3 ($\rho = -0.43$) and MgO ($\rho = -0.58$), and low positive correlation with Mo ($\rho = 0.40$), Sb ($\rho = 0.45$) and TOC ($\rho = 0.55$). These data suggest that As may have a greater association with the organic fraction than Fe-sulfide minerals such as pyrite or arsenopyrite.

The OFP shows enrichment in Mo, Sb, and TOC contents when compared to the bulk of the WSG samples. Individual samples from other units also show enrichments in these elements, but not consistently as a stratal group. Enrichment of As is present primarily in the OFP and MMGA samples collected east of the SRMT suggesting local control of this element, but the dataset is limited.

4.5.6 Rare earth elements (REE)

The REE are normalized to PAAS in Figure 4.9 (A to H). Overall, the REE profiles from the WSG mudstone units are remarkably consistent displaying variable degrees of LREE enrichment and relatively flat HREE pattern near PAAS values. The samples are characterized by variable negative Eu anomalies with Eu/Eu^* ranging from 0.42 to 0.79 (average: 0.61) with most near, or slightly greater to that of PAAS (~ 0.66).

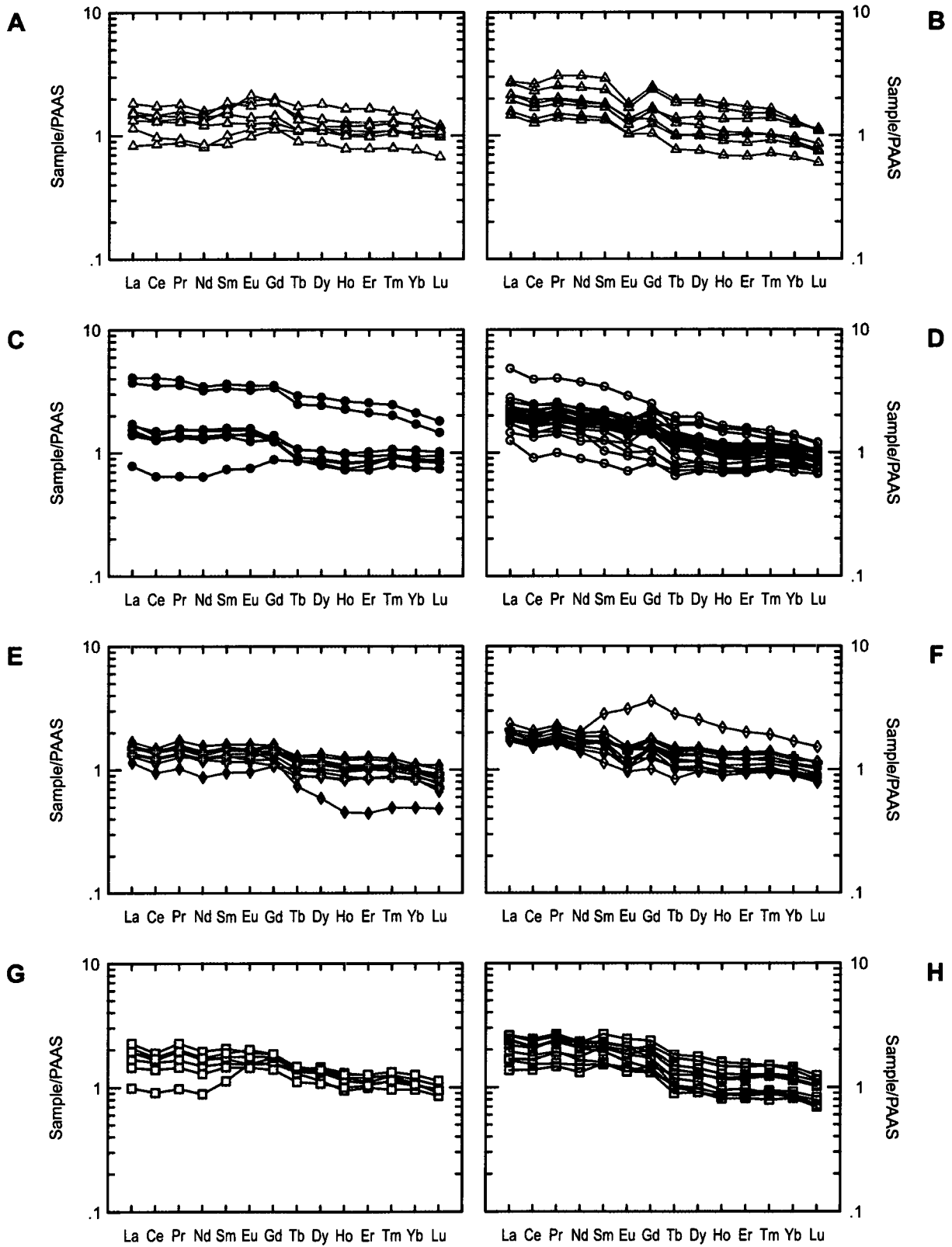


Figure 4.9: Spider diagram for rare earth elements (REE) normalized to Post-Archean Australian Shale (PAAS) (Taylor and McLennan, 1985). Legend of symbols is the same as Fig. 4.4.

Total LREE contents show a number of positive elemental correlations: Al_2O_3 ($r = 0.49$) and K_2O ($r = 0.43$); the LILE, including Rb ($r = 0.48$), Cs ($r = 0.36$), Ba ($r = 0.36$) and Th ($r = 0.59$); the HFSE, including Y ($r = 0.47$), Nb ($r = 0.36$) and Ta ($r = 0.36$). These suggest REE fixation mainly in clay minerals (e.g. illite), but also possibly certain heavy minerals (e.g. ilmenite). ΣLREE also shows negative correlation coefficients with MgO ($r = -0.43$), MnO ($r = -0.36$), Co ($r = -0.38$) and Ni ($r = -0.43$). The similar geochemical behaviour of Y to the rare earths results in its high positive correlation to ΣHREE ($r = 0.93$).

A number of discrete differences in the REE profiles of the WSG stratal divisions are present. On a PAAS-normalized diagram, samples from the UKG and MMGA generally show the highest LREE enrichment and the UMG a negative Eu/Eu* (Eu anomaly). Samples collected east of the SRMT are generally characterized by higher ΣREE , ΣLREE , $(\text{La}/\text{Yb})_n$, and a more prominent negative Eu anomaly compared to those collected west of the SRMT. The differences in the Eu anomaly possibly reflect the amount of preserved plagioclase feldspar in the mudstone. A number of individual samples display distinctive REE profiles when compared to the remainder of the WSG: relatively flat LREE profile (UKG: RAR-R01-34; MKG: MDS04-212); HREE enrichment from a Y-bearing phosphate mineral (OFP: MDS05-007); and depleted HREE (OFP: MDS05-025) from fluid mobilization (see below).

4.6 DISCUSSION

4.6.1 Effect of metamorphism

Sample locations in this study were selected based on relatively low metamorphic grade, simple tectonic deformation and preservation of primary sedimentary textures and structures. However, it is still necessary to determine if an element has become mobile during secondary processes (e.g. diagenesis or

metamorphism), or instead accurately reflects original (primary) depositional conditions (e.g. original source material, bottom-water redox conditions).

The elevated values of Al_2O_3 and K_2O compared to lower SiO_2 (and possibly CaO) do suggest remobilization of certain major elements (e.g. SiO_2 into quartz veins) during structural deformation and/or low-grade metamorphism, but these effects on the overall geochemistry of the samples are interpreted to have been minor. The only element that perhaps shows a distinctive metamorphic trend is MgO : samples west of the SRMT (Figs. 4.5C and 4.6E: closed symbols) are enriched in MgO relative to their eastern counterparts, irrespective of stratigraphic position. This MgO enrichment may be linked to the increase in chlorite related to greenschist metamorphism. Although attempts were made to avoid collecting altered strata, certain individual samples have had specific elements affected compared to others from the same stratal unit. For example: MDS04-173 (MMGB) with anomalously high Fe_2O_3 (14.41%) related to metamorphic siderite; and MDS05-025 (OFP) with an unusual REE profile, and depleted Mo (0.24), Sb (0.46 ppm), TOC (0.08%) likely because of fluid migration along a structural conduit.

The overall similarity of most major and trace elements, in addition to the lack of significant variations between areas of sub-greenschist and greenschist grade metamorphism, suggests that the low-grade regional metamorphism did not greatly alter the depositional WSG mudstone composition. Other studies of metamorphosed mudstone units have demonstrated similar undisrupted sedimentary geochemical signatures in low- to high-grade metamorphic rocks (e.g. Condie and Martell, 1983; Taylor et al., 1986; Girty et al., 1994; Fedo et al., 1996; Li et al., 2005). The geochemical robustness of WSG strata may provide a useful tool for correlating these strata with enigmatic high-grade metamorphic rocks present elsewhere, especially those interpreted to be possible WSG equivalents based principally on mapped relationships and bimodal U-Pb detrital zircon signatures (e.g. Lemieux et al., 2007; Thompson et al., 2006).

4.6.2 Mineralogy and sedimentary sorting

Strata of the WSG consist predominantly of immature basin-slope to basin-floor siliciclastic sedimentary rocks interpreted to be first-order sediments (e.g. Ross et al., 1989; Ross and Arnott, 2007). Prior to interpretation of primary or secondary sedimentary geochemical signals, it is important to understand the mineralogical and sorting controls on elemental distribution. A hierarchical cluster analysis dendrogram (Fig. 4.10) was generated using the Spearman rank order correlation coefficient as the distance matrix and amalgamated/agglomerated by the unweighted pair group average (uses mean distances). Strong correlations show low linkage distances (similarity ~ 1) between amalgamated element clusters whereas a lack, or negative correlation results from high distance linkages (similarity ~ 0). Presentation of the geochemical data in this fashion can be effective for understanding elemental associations that are linked with significant mineral phases beyond the correlation coefficients. The cluster analysis of TOC with selected major and trace elements of the WSG mudstone units shows three main clusters with the negative correlation of these three evident from high linkage distances (similarity < 0) (Fig. 4.10).

The element cluster of Cs, Al_2O_3 , K_2O , Rb, Ba, Sc, Th, Nb, Ta, TiO_2 , ΣLREE , ΣHREE and V is interpreted to represent the clay/mica mineral fraction (Fig. 4.10). Within this group are two sub-groups that show strong similarity. Cs, Al_2O_3 , K_2O , Rb, Ba exhibit short linkages and are likely associated with illite, with Sc linking slightly later to this sub-group. The second sub-group is composed of Th, Nb, Ta and TiO_2 with these elements associated with rutile (possibly titanite and/or ilmenite). Rutile tends to break down at greenschist grade metamorphism (Zack et al., 2004) and so the incorporation of these elements into altered clay minerals (illite, kaolinite) and later recrystallized metamorphic muscovite may have occurred. REE and V show late amalgamation with this cluster suggesting a weak association with the clay/mica fraction and perhaps reflect additional controls on their fixation.

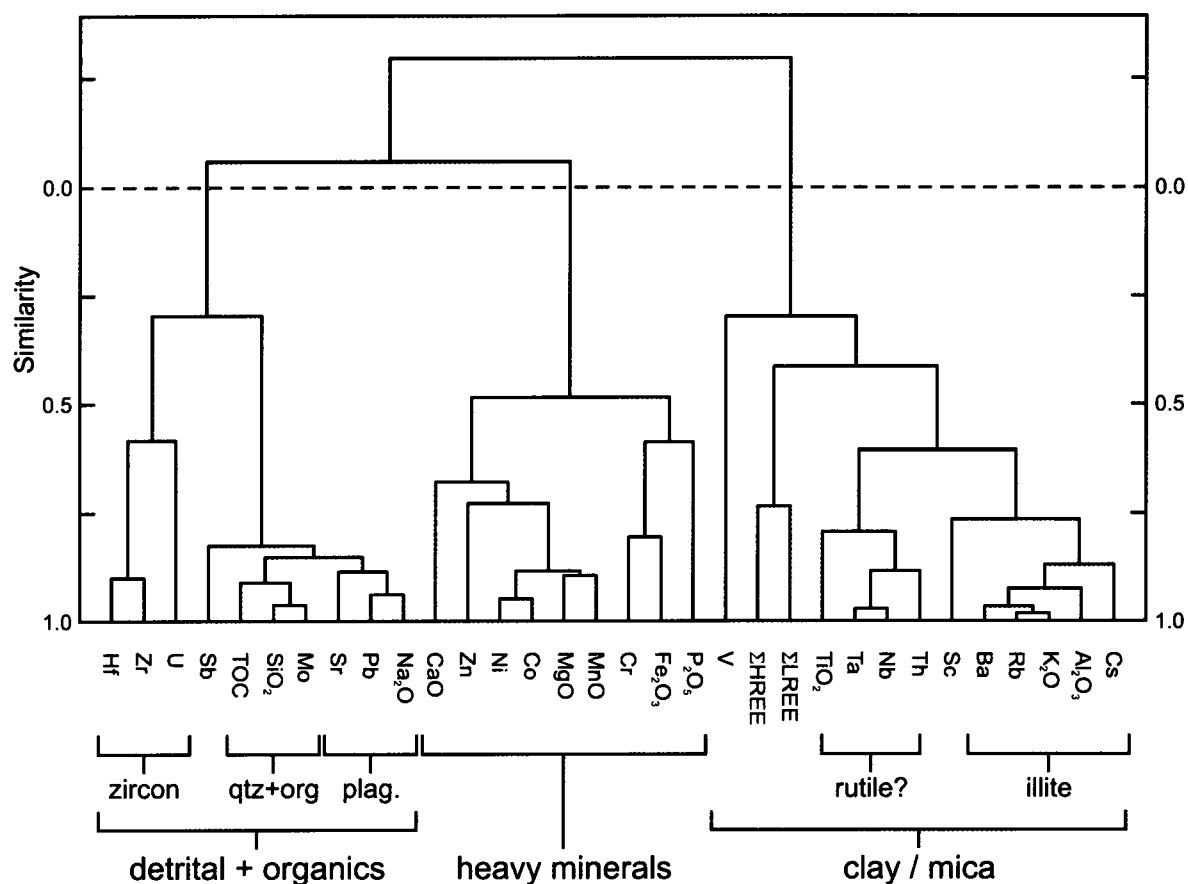


Figure 4.10: Cluster analysis dendrogram of TOC and selected major and trace elements with three main clusters and their interpreted mineral associations. The dendrogram was generated using the Spearman rank order correlation coefficient as the distance matrix and amalgamated/agglomerated by the unweighted pair group average (uses mean distances). Strong correlations show low linkage distances (similarity ~1) between amalgamated element clusters whereas a lack, or negative correlation results from high distance linkages (similarity ~0). Presentation of the geochemical data in this fashion can be effective for understanding elemental associations that are linked with significant mineral phases beyond the correlation coefficients.

The second main element cluster includes P_2O_5 , Fe_2O_3 , Cr, MnO, Co, Ni, MgO, Zn and CaO (Fig. 4.10). This grouping is interpreted to be made up mostly of the detrital (“heavy”) mineral fraction represented by phosphates (e.g. apatite, monazite) and Fe-oxides and sulfides (e.g. hematite, ilmenite, pyrite) that were transported into the basin. Secondary diagenetic minerals such as pyrite and carbonate cements (e.g. calcite, dolomite, ankerite) may also be associated with this fraction. The amalgamation of MgO into this cluster instead of the first cluster (i.e. Al_2O_3 and K_2O) indicates chlorite is not the main controlling mineral phase for Mg.

The final element cluster consists of Na_2O , Pb, Sr, Mo, SiO_2 , TOC, Sb, U, Zr, and Hf with this grouping suggesting a counter-intuitive mineral phase association (Fig. 4.10). The sub-group of U, Zr and Hf most probably indicates their incorporation into zircon. The second sub-group amalgamates two well-defined element clusters. The first is Na_2O with Pb and Sr with the latter two elements likely substituting into plagioclase. The second is quartz (SiO_2) with the organic fraction (TOC, Mo, Sb). This suggests an apparent contradiction of a slow sedimentation rate, likely under reducing conditions (organic fraction) associated with detrital minerals (quartz-plagioclase) that were transported into deep-water. The zircon-related cluster shows a late amalgamation with the quartz-organics-plagioclase component, which perhaps suggests a grain size and/or density control on these mineral phases.

The Th/Sc ratio is thought to represent the overall bulk composition of the source material (McLennan and Taylor, 1991) and combined in a plot with Zr/Sc illustrates the amount of sediment recycling (McLennan et al, 1993). The WSG is characterized by a relatively narrow range for both Th/Sc (0.60 to 1.78, average: 0.97) and Zr/Sc (2.96 to 18.60, average: 6.74) with the samples clustering near an upper crust composition (e.g. Taylor and McLennan, 1985; McLennan et al., 1990) (Fig. 4.11A). The Zr/Sc does not show an independent increase from Th/Sc suggesting a lack of significant sediment recycling (e.g. McLennan et al., 1993).

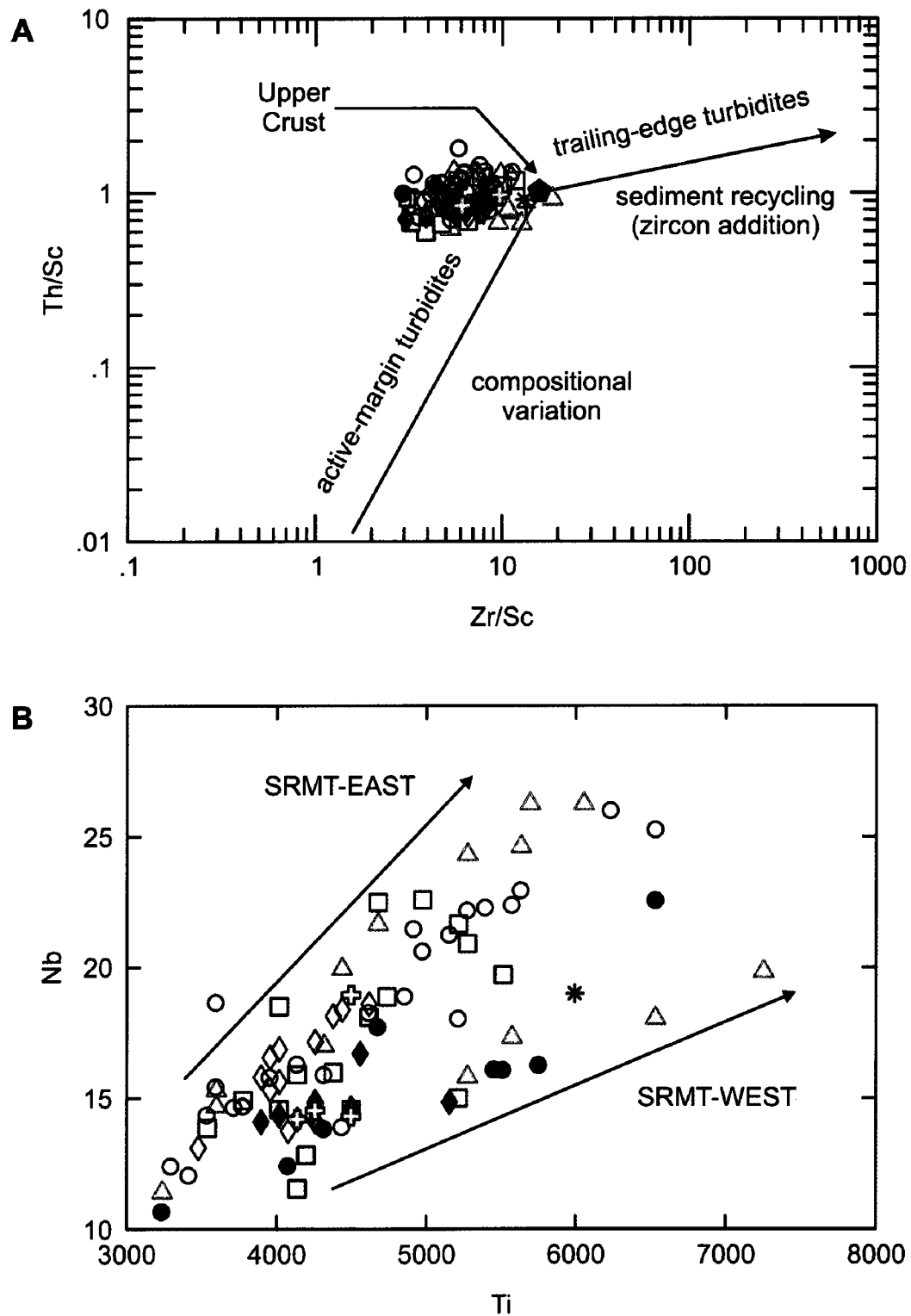


Figure 4.11: Sedimentary sorting diagrams: A) Plot of Zr/Sc vs. Th/Sc after McLennan et al. (1993). B) Plot of Ti vs. Nb. SRMT = Southern Rocky Mountain Trench. Legend of symbols is the same as Fig. 4.4.

For the WSG a plot of Ti vs. Nb defines two separate positive trends that are interpreted to be related to sedimentary sorting during transport of the heavy mineral fraction (Fig. 4.11B). Paleogeographically, samples collected east of the SRMT (open symbols) are interpreted as more proximal than those west of the SRMT (closed symbols) and show a steeper positive slope on the Ti vs. Nb plot (Fig. 4.11B). This may suggest that the heavy mineral fraction is preferentially sequestered in proximal settings during mass flow transport. It is also interesting to note that two of the samples collected from the IF higher in the stratigraphy (west of the SRMT) plot along the proximal trend which is consistent with the notion of an upward gradation from basin-floor facies (MKG + UKG) to basin-slope facies (IF) caused by continent-margin progradation (e.g. Ross et al., 1989; Ross et al., 1995; Ross and Arnott, 2007). Stratal divisions west of the SRMT have consistently lower average Th/Sc and higher average Cr/Th than their equivalent stratigraphy east of the SRMT (e.g. UKG = 0.89, 7.05 versus MMGA = 1.09, 4.02). Similar to the Ti vs. Nb plot these slight differences may also reflect the effect of mineral sorting during sediment transport. These observations may serve as a proxy for delineating proximal vs. distal positions along a depositional transect and offer a complementary dataset to detailed stratigraphic studies.

4.6.3 Provenance and tectonic setting

The methodology for determining sediment provenance (i.e. source of detritus) in siliciclastic sedimentary rocks is well established using specific proxies of trace elements (e.g. REE, Th, Sc, HFSE) or elemental ratios (e.g. La/Sm, Eu/Eu*, Cr/Th, Th/Sc) (e.g. Taylor and McLennan, 1985; McLennan et al., 1990, 1993, 2003; Condie and Wronkiewicz, 1990; McLennan and Taylor, 1991; Cullers, 1994, 2000). These elements are characterized by short residence time in the water column, and/or thought to be relatively immobile during most secondary processes such as diagenesis. Thus, their chemical signatures are inherited from direct transfer of the weathered parent rock into the deposited sedimentary pile. Most siliciclastic

sedimentary rocks are a complex residuum from the mixing and homogenization of the primary source materials. The use of the HFSE and ratios of incompatible vs. compatible elements has also proven to be effective at delineating the proportions of felsic versus mafic source components (e.g. Taylor and McLennan, 1985; Feng and Kerrich, 1990; McLennan et al., 1993; Cullers, 1994, 2000; Fedo et al., 1996; Roddaz et al., 2006, 2007).

In general, samples of the WSG are characterized by consistent Th/Sc, Cr/Th, Eu/Eu* and REE profiles suggesting a common sediment provenance, irrespective of stratigraphic position (Fig. 4.9, 4.12). The relatively high concentration of LREE and low Cr and Ni contents indicate an overall low contribution from mafic volcanics. Some samples from the upper part of the WSG (IF and UMG) show slightly elevated Cr and Ni contents, suggesting possible unroofing and minor contribution of a mafic volcanic source component during later stages of deposition. The presence of a Eu anomaly (0.42 to 0.79) and fractionated LREE profile ($(La/Yb)_n$ 8.30 to 45.55) have been regarded as evidence for a differentiated felsic component (e.g. Taylor and McLennan, 1985; McLennan et al., 1993). These observations are in good agreement with Cr/Th values (range: 2.79 to 16.65) that implies that these are felsic-derived sediments (McLennan et al., 1993; Cullers, 1994, 2000). However, the range in the WSG negative Eu anomaly (0.42 to 0.79) lies between values typical of granitic (Eu/Eu* ~0.3 to 0.5) and tonalitic sources (Eu/Eu* ~0.9 to 1.0) (e.g. Condie and Wronkiewicz, 1990; Condie, 1993). Th/Sc values (0.60 to 1.78) show a well-defined cluster near upper crustal values suggesting a well-mixed source material (e.g. Taylor and McLennan, 1985; Condie, 1993; McLennan et al., 1993; Cullers, 1994, 2000). The Th/Sc ratio for the bulk of the WSG samples (2 σ) lie within the Neoproterozoic Th/Sc range (McLennan et al., 2003), with considerable overlap in both the stable continental and active tectonic fields. The mafic component is not likely basaltic (e.g. depleted LREE, enriched Cr or Ni contents), but perhaps more similar to tonalite or andesite.

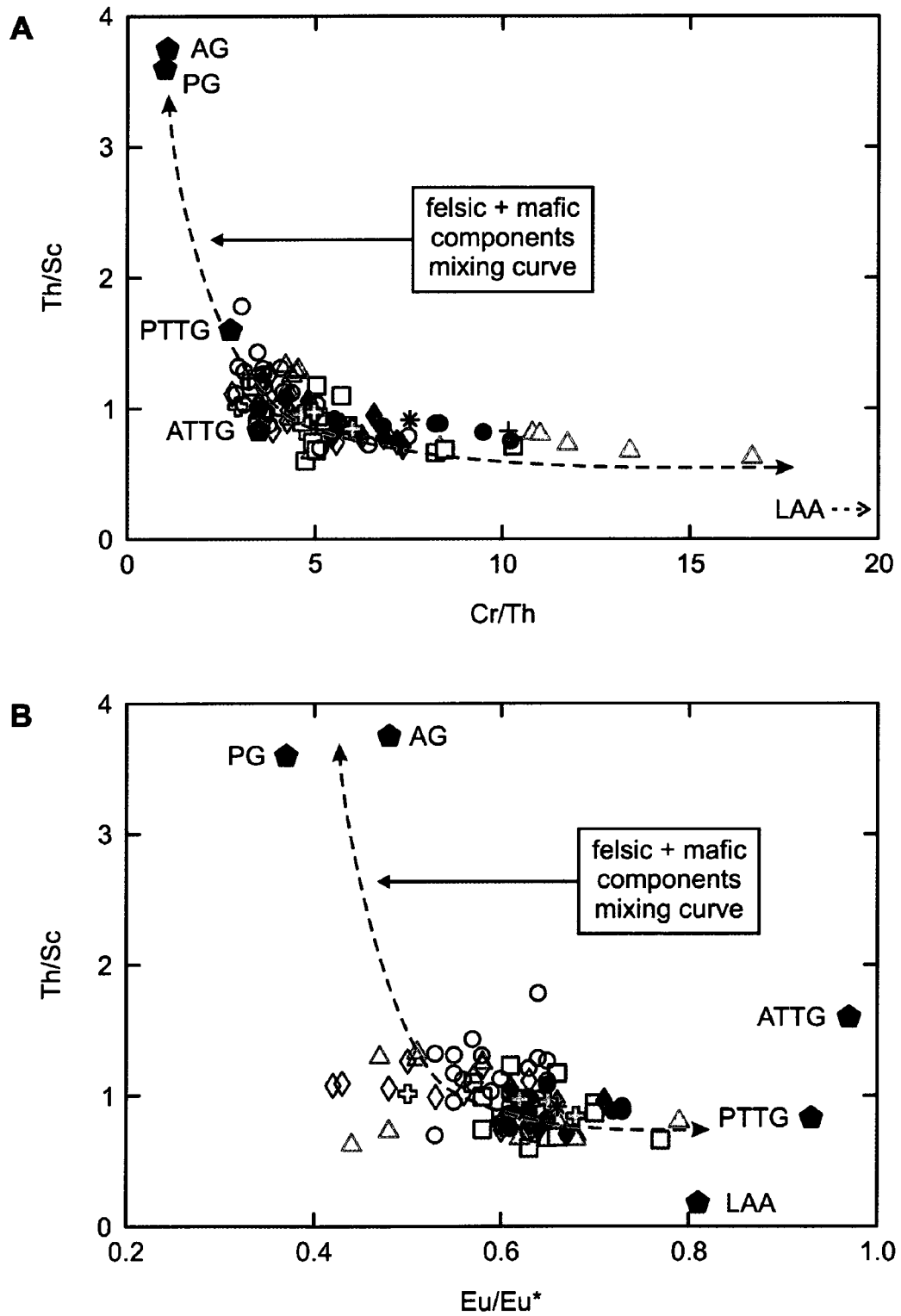


Figure 4.12: Provenience diagrams: A) Plot of Cr/Th vs. Th/Sc. B) Plot of Eu/Eu* vs. Th/Sc. Mixing end members are from Condie (1993). Abbreviations: Archean tonalite-trondhjemite-granodiorite (ATTG); Proterozoic tonalite-trondhjemite (PTTG); Archean granite (AG); Proterozoic granite (PG); and Late Archean andesite (LAA). Legend of symbols is the same as Fig. 4.4.

The WSG displays a geochemical coherence that supports the previous U-Pb detrital zircon analyses from coarse-grained turbidites that identified a primarily homogeneous bimodal pattern consisting of >2.5 Ga or 1.9 to 1.75 Ga with minor contribution from a 2.3 to 1.9 Ga source (Ross and Bowring, 1990; Ross and Parrish, 1991; Smith and Gehrels, 1991; Ross et al, 1997; Gehrels and Ross, 1998; Ross, 2000; Ross and Heaman, 2005; Lemieux et al., 2007). A number of nearby basement domains in southern Alberta offer potential sources for these detrital zircon ages and include: the 1.85 to 1.79 Ga Rimbey magmatic arc, the 2.4 to 2.0 Wabamun and Thorsby domains; and the >2.5 Ga Hearne craton composed of the Medicine Hat, Loverna and Vulcan blocks (Villeneuve et al., 1993). These basement domains are composed predominantly of granite to tonalite rocks and/or high-grade gneiss equivalents, with the exception being the Vulcan block which consists of amphibolite and other metabasic rocks (Villeneuve et al., 1993).

With potential source components identified, it is feasible to conduct simple mass balance mixing models (e.g. Fedo et al, 1996, 1997; Roddaz et al, 2007) in an attempt to constrain the relative proportions to the overall provenance by determining best-fit solutions to closely reproduce the WSG mudstone Cr/Th, Th/Sc, Eu/Eu* and REE profiles from east and west of the SRMT. Unfortunately, the only published geochemical analyses for the Alberta basement are from Burwash and Culbert (1976) whose limited dataset (major elements, select LILE and TTE cited, but values not published) did not include Cr, Th, Sc or the REE. As a consequence, average values of potential source materials are taken from Condie (1993) and include: Archean tonalite-trondhjemite-granodiorite (ATTG); Proterozoic tonalite-trondhjemite (PTTG); Archean granite (AG); Proterozoic granite (PG); and Late Archean andesite (LAA). An attempt was made to be as consistent as possible with the relative proportions of these end-members based on the existing detrital zircon ages (>2.5 Ga ~20%; 2.4 - 2.0 Ga ~10%; 1.9 to 1.7 Ga ~70%) (compiled in Gehrels and Ross, 1998).

Using these defined relative age and lithological constraints, no conclusive matches could be obtained for the average compositions of WSG mudstone units east or west of the SMRT. In both cases, a reasonable model was generated which produces near WSG values for Cr/Th, Eu/Eu* and the HREE. For samples east of the SRMT (WINMIX-east) this involves a mixture of 50% PG + 25% PTTG + 10% ATTG + 10% AG + 5% LAA (Table 4.4, Fig. 4.13A). For samples west of the SRMT (WINMIX-west) it is slightly altered with a mixture of 40% PG + 30% PTTG + 10% ATTG + 10% AG + 10% LAA (Table 4.4, Fig. 4.13B). Most of these proportions can be adjusted by ~5% without seriously affecting the results. In both mixing models, the two chemical signatures that are not reconciled are the LREE (more evident in eastern samples), which are relatively depleted ~1.5 to 2 times, and the Th/Sc ratio which is enriched ~2.5 times the actual WSG values. A plausible explanation for the LREE is an unidentified source with elevated LREE contents or secondary enrichment in the clay fraction by another process (see below). Considering that the WSG shows remarkable consistency in Th/Sc values, and this ratio is interpreted to best represent the composition of the source material (McLennan and Taylor, 1991), this would seem to be the critical value to accurately model. Deviation of the Th/Sc ratio is a product of the significant contribution of PG suggested by the detrital zircon data, which is also required in order to accurately reflect the WSG Eu/Eu* and REE. Attempts to model a similar Th/Sc to the WSG mudstone average using the lithological constraints resulted in significantly higher Eu/Eu* (~0.90), and lower REE contents. Although the potential for a minor contribution of other source material is suggested by newer detrital zircon work (Ross and Heaman, 2005), the granitic source rocks for the WSG could also simply be characterized by a lower Th/Sc ratio or a TTG source with lower Eu/Eu* (~0.80) and higher REE contents than the averages provided in Condie (1993). Geochemical analyses of Alberta basement domains would allow for more robust testing of either of the WINMIX provenance models.

	Windermere Supergroup				Mixing Model Endmembers (Condie, 1993)					Model Results	
	West (<i>n</i> = 34)		East (<i>n</i> = 53)		ATTG	PTTG	AG	PG	LAA	WINMIX	
	Ave.	2 σ	Ave.	2 σ						West	East
La	62.38	24.92	79.87	19.68	30.00	26.00	50.00	48.00	18.00	36.80	39.40
Ce	118.48	51.53	148.73	35.07	56.00	45.00	95.00	115.00	42.00	78.80	85.95
Nd	49.08	18.73	62.36	14.93	22.00	20.00	46.00	54.00	21.00	36.50	39.85
Sm	8.63	3.15	10.14	2.56	3.40	4.50	6.30	8.70	4.60	6.26	6.68
Eu	1.69	0.59	1.66	0.49	1.00	1.30	0.85	1.00	1.20	1.10	1.07
Gd	7.27	2.54	7.65	2.18	2.98	4.09	4.67	8.17	4.54	5.71	6.10
Tb	0.96	0.33	0.98	0.29	0.45	0.63	0.65	1.28	0.73	0.88	0.94
Yb	2.95	0.79	2.92	0.59	1.00	1.50	2.00	3.50	2.10	2.36	2.53
Lu	0.41	0.10	0.40	0.08	0.17	0.23	0.32	0.58	0.33	0.38	0.41
Th/Sc	0.83	0.12	1.06	0.22	1.60	0.83	3.75	3.60	0.18	2.24	2.55
Cr/Th	6.90	2.34	4.50	2.20	2.75	3.50	1.07	1.00	48.57	6.69	4.19
Eu/Eu*	0.66	0.05	0.58	0.06	0.97	0.93	0.48	0.37	0.81	0.65	0.60

WINMIX-West mixing model consists of 10ATTG + 30PTTG + 10AG + 40PG + 10LAA.

WINMIX-East mixing model consists of 10ATTG + 25PTTG + 10AG + 50PG + 5LAA.

Table 4.4: REE, Th/Sc, Cr/Th, and Eu/Eu* for average WSG mudstone (*n* = 87), mixing parameters and model results. Mixing endmembers are from Condie (1993). Abbreviations: Archean tonalite-trondhjemite-granodiorite (ATTG); Proterozoic tonalite-trondhjemite (PTTG); Archean granite (AG); Proterozoic granite (PG); and Late Archean andesite (LAA).

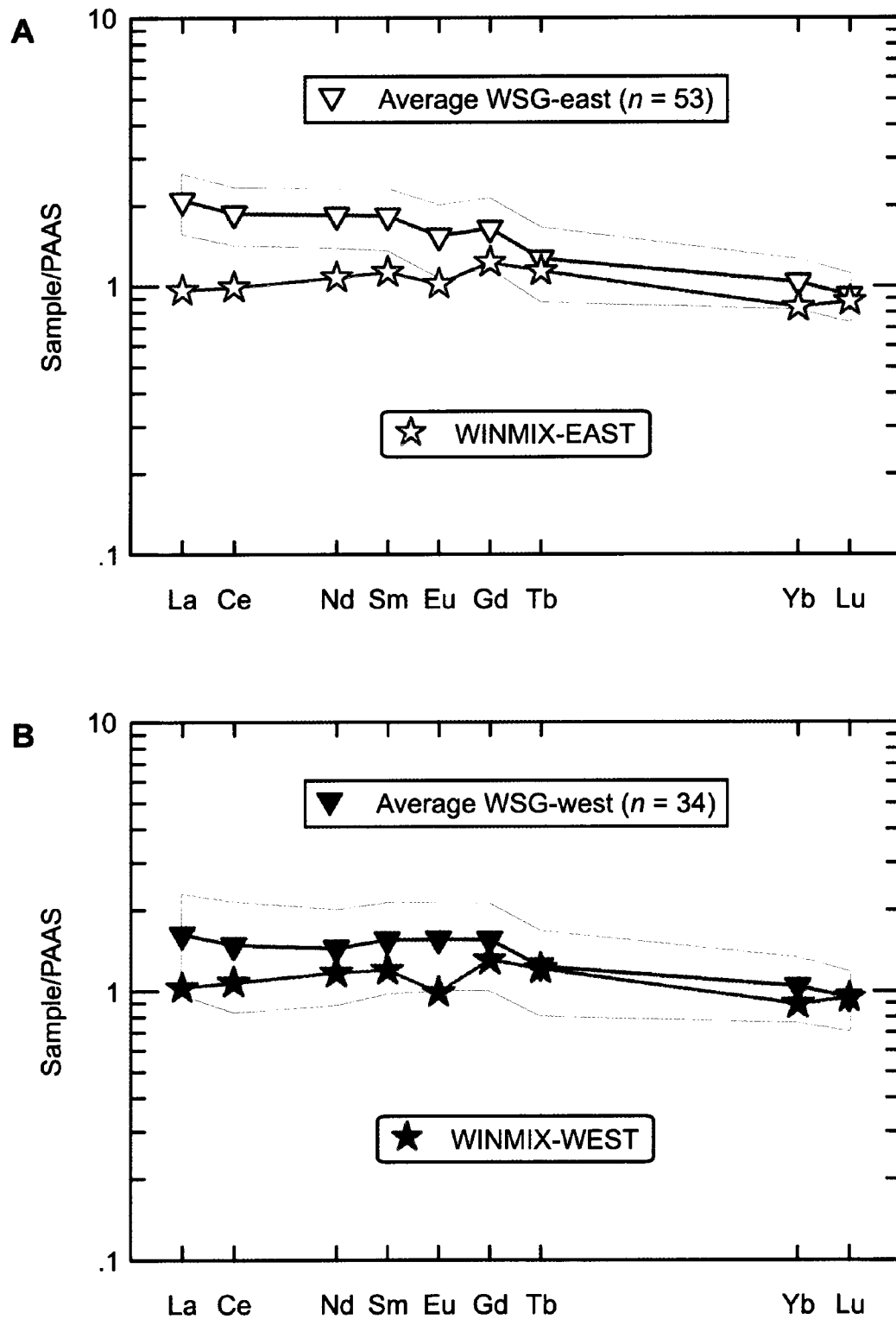


Figure 4.13: REE spider diagrams normalized to Post-Archean Australian Shale (PAAS) (Taylor and McLennan, 1985) showing results of mixing calculations (Table 4.5). A) Average WSG mudstone east of the SRMT. B) Average WSG mudstone west of the SRMT. Shaded regions represent respective average mudstone value $\pm 2\sigma$. End member compositions are from McLennan et al. (1993).

The Th/Sc ratios from WSG strata also concur with previously determined Nd isotopic values that show an upper crust (granodiorite) provenance with a minor contribution from older Archean material (Boghossian et al., 1996). This is consistent with the relative proportions in the simple mixing model conducted in this study and the previous U-Pb detrital zircon work (Ross and Bowring, 1990; Ross and Parrish, 1991; Smith and Gehrels, 1991; Ross et al, 1997; Gehrels and Ross, 1998; Ross, 2000; Ross and Heaman, 2005; Lemieux et al., 2007).

The tectonic environment of the post-rift WSG strata in the southern Canadian Cordillera remains a source of debate between being an intracontinental rift (e.g. Colpron et al, 2002) or passive margin setting (e.g. Ross, 1991; Ross et al, 1995; Ross and Arnott, 2007). This difference is crucial for subsequent redox-sensitive element or stable isotopic proxy studies because it dictates if those interpretations apply to an isolated, intracontinental basin, or global Neoproterozoic open ocean environment. Independently, the WSG mudstone geochemistry does not provide conclusive evidence to rule out either hypothesis. However, the results are fully consistent with the overall size of the Windermere basin, stratal succession thickness, lack of volcanoclastic sedimentary rocks, detrital zircon and paleocurrent data; whereby material of common provenance accumulated in an elongate, generally northwest-flowing turbidite system along an ancient continental passive margin (e.g. Ross, 1991; Ross et al., 1995; Ross and Arnott, 2007). Components of this source material are readily explained by adjacent Precambrian rocks in the subsurface of Alberta (Villeneuve et al., 1993). The WSG mudstone geochemistry shows no new or significant input of mafic volcanic material that usually is present in an intracontinental rift, nor does it suggest that a conjugate western margin of exotic composition is required to explain the chemical signatures (e.g. Sears and Price, 2003; Thompson et al., 2006). Thus, the preferred model for WSG deposition is that of an open ocean, continental passive margin setting (e.g. Ross, 1991), rather than an intra-continental rift (Colpron et al, 2002).

4.6.4 Paleoweathering and metasomatism

Whereas REE, Th, Sc and HFSE are relatively immobile and useful in provenance studies, certain major elements (CaO, Na₂O, K₂O) and LILE (e.g. Rb, Ba, Sr) are more mobile forming soluble cations in aqueous solution. As a result, these elements can provide important information about chemical weathering conditions affecting the source material (e.g. paleoclimate) and subsequent burial diagenesis (e.g. K-metasomatism). Overall, when compared to NASC and PAAS, WSG stratal divisions display elevated values of Al₂O₃, K₂O, Rb, and Ba with the elements all exhibiting strong correlation with one another. The incorporation of these elements into clay minerals coincides with the leaching or removal of SiO₂, Na₂O and Sr which show relative depletions in most WSG samples compared to NASC and PAAS. This relationship suggests the chemical alteration of the feldspars to clay minerals (e.g. kaolinite), which then converted to illite and muscovite. Such characteristics are common in Precambrian sedimentary rocks (e.g. Nesbitt and Young, 1989; Condie, 1993; Fedo et al., 1995, 1996, 1997; Roddaz et al., 2007; Rieu et al., 2007)

The Chemical Index of Alteration (CIA) was first proposed by Nesbitt and Young (1982) and has proven to be an effective tool to quantify the degree of chemical weathering in sedimentary rocks. The CIA is calculated using element molar proportions and is defined as: $CIA = 100 \times [Al_2O_3 / (Al_2O_3 + Na_2O + CaO^* + K_2O)]$; where CaO* represents the CaO content in the silicate fraction only and can be calculated by removing the influence of carbonate and phosphate minerals (e.g. Nesbitt and Young, 1982; Fedo et al., 1995). Petrographic and CO₂ analyses were conducted in order to correct for the Ca in calcite, dolomite or phosphate (e.g. apatite) (Appendix F and I). The index evaluates the extent of chemical weathering of feldspar compared to an unaltered source rock: low CIA values (50 to 60) indicate fresh material with little chemical weathering; and high CIA values (90 to 100) suggest conversion of feldspars to Al-rich clay minerals and removal of mobile cations (Ca, Na, K) from intense chemical weathering (e.g. Nesbitt, 2003 for a

review; Nesbitt and Young, 1982; Fedo et al., 1995). The CIA can then be utilized to decipher paleoclimatic conditions because chemical alteration is favoured in regions with a warm and/or humid climate versus cold and/or arid (e.g. Nesbitt, 2003 and references therein).

A ternary plot (feldspar diagram) of the molar ratios of Al_2O_3 (A), $\text{CaO}^* + \text{Na}_2\text{O}$ (CN) and K_2O (K) provides an effective method of visualizing source rock composition, understanding weathering trends from CIA values, and unraveling potential effects related to potassic metasomatism (e.g. Nesbitt and Young, 1984, 1989; Fedo et al., 1995, 1996, 1997; Nesbitt, 2003). In this diagram, samples should plot along a predicted weathering trend parallel to the A – CN join that then can be projected back towards an inferred composition of the source material. Samples that show a deviation from this trend towards the A – K join are interpreted to have experienced addition of potassium from the formation of illite during K-metasomatism (e.g. Fedo et al., 1995). Corrected values for K-metasomatism are determined by projecting a line from the K apex through the sample to intersect the predicted weathering trend line. A quantitative estimate of the degree of K enrichment can then be calculated from the difference between the pre-metasomatized CIA and current value (e.g. Fedo et al., 1995, 1996, 1997).

CIA values for the WSG ($n = 87$) range from 66 to 81 (WSG average: ~ 75 ; stratal divisions ~ 71 to ~ 76) suggesting a fairly consistent weathering regime for the transported source material (Table 4.2). The WSG samples are plotted in the A – CN – K (molar proportions) compositional ternary diagram (Fig. 4.14) along with the earlier modeled source material (WINMIX-east and WINMIX-west) and end-member igneous components from Condie (1993). The compositional position of idealized minerals is from Fedo et al., (1995). The predicted weathering trend from the source material is indicated by the line with an arrow and the vertical axis left of the ternary diagram corresponds to CIA values.

Many of the WSG samples plot near the overall WINMIX predicted weathering trend (grey shaded box) which lends support to its earlier determination

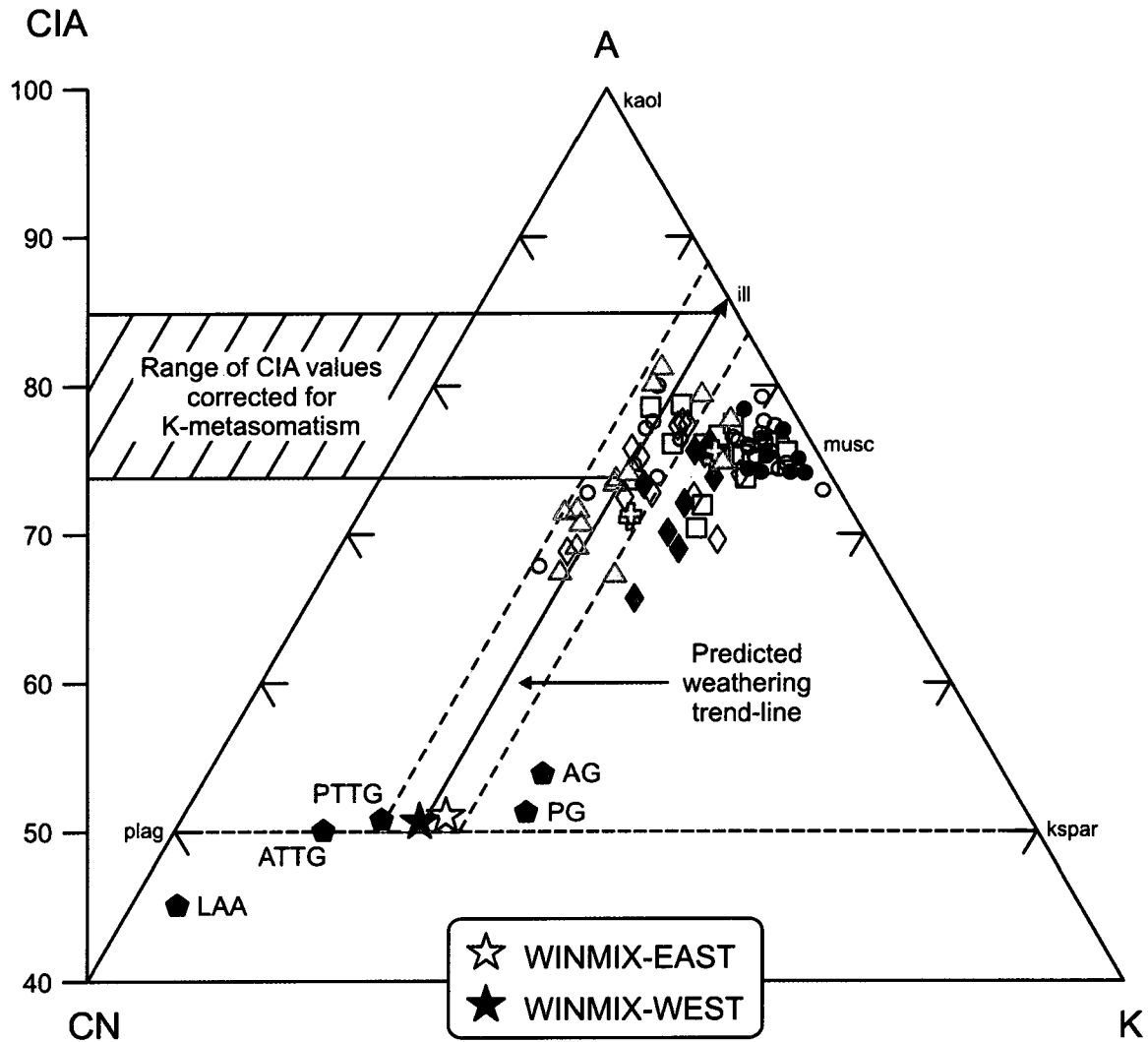


Figure 4.14: A) Molar A - CN - K ternary diagram illustrating CIA (Chemical Index of Alteration) values. Only top 60% of diagram is shown. Potential source components are indicated, including WINMIX determined in this study and igneous end members from Condie (1993). Predicted weathering trend-line from WINMIX is shown as well as range of CIA values corrected for effects of K-metasomatism. A = molar Al_2O_3 ; CN = molar CaO^* (non-carbonate) + molar Na_2O ; K = molar K_2O . Mineral abbreviations include: plag = plagioclase feldspar; Kspar = potassium feldspar; musc = muscovite; ill = illite; kaol = kaolinite. Legend of symbols is the same as Fig. 4.4.

as probable source material (Fig. 4.14). However, a substantial number of the samples plot to the right or below, suggesting secondary alteration. A number of these samples show a good correlation of decreasing CIA values with increasing CaO contents despite correcting for Ca from the carbonate phases in the calculation. Diagenetic carbonate cement likely crystallized at the expense of pre-existing clay minerals resulting in a loss of Na and/or K. The shift of composition right of the line is evidence for post depositional K-enrichment related to illite or muscovite formation (e.g. Fedo et al., 1995, 1996) and explains the elevated K₂O, Rb and Ba contents in the many WSG mudstone units. The effects of K-metasomatism can be corrected to determine paleoweathering intensity (Fedo et al., 1995). However, the potential combined effects of K-metasomatism (shift right) and diagenetic carbonates (shift down, right or left) in certain samples makes it difficult to quantify the relative effects of the distinctive alteration processes.

To determine pre-metasomatized CIA values from WSG strata, lines were projected from the K apex through the samples with the range for each stratal division plotted left of the axis (Fig. 4.14). From WSG strata, the CIA values of the OFF east of the SRMT (69 to 80) and UMG (67 - 74) remain relatively unchanged because they plot within a zone near the weathering trend line. Conversely, K-metasomatism was more prevalent in the other stratigraphic units with pre-metasomatized CIA values for the MKG (77 to 85), MMGB (74 to 82), UKG (81 to 85) and MMGA (68 to 85) and IF (70 to 82). Many of the basin-floor WSG samples (e.g. MKG and UKG) have gained up to 15% K₂O (and perhaps also Rb, Ba) during metasomatism, perhaps related to basinal fluid circulation during rapid deposition and burial. The important deduction from these corrected, pre-metasomatic CIA values is that the intensity of chemical weathering during the deposition of the WSG was variable with units characterized by relatively lower values (e.g. IF, UMG, OFF), but also included periods of intense chemical weathering (CIA >80). Based on the limited paleomagnetic data (Park, 1997) and tectonic reconstructions (Wingate et al., 2002), the near-equatorial position of Laurentia would support

tropical to sub-tropical conditions and accordingly extreme chemical weathering in a wet and/or humid climate.

The intensity of chemical weathering can also be illustrated by using the molar proportions to calculate the Plagioclase Index of Alteration: $PIA = 100 \times [(Al_2O_3 - K_2O)/(Al_2O_3 + Na_2O + CaO^* + K_2O)]$; with the results displayed in a ternary diagram of $Al_2O_3 - K_2O$ (A), CaO^* (C) and Na_2O (N) (e.g. Fedo et al., 1995). The WSG is characterized by PIA values that range from 74 to 98, (average: ~89), wherein values near 100 indicate that almost all plagioclase has been converted to secondary clay minerals (Fedo et al., 1995). The aggressive nature of the weathering is evident in the MKG (average: ~94), MMGB (average ~90), OFP (average: 85), UKG (average: 96), MMGA (average: 91) and IF (average: 88) with these units also showing depletion in Na_2O and Sr. The UMG is an exception with slightly lower PIA values (average: 79) and enrichments in Na_2O and Sr suggesting the preservation of some unweathered plagioclase.

Evidence for periods of extreme chemical weathering from the CIA and PIA values provide a reasonable explanation for commonly high Al_2O_3 and LREE (~1.5 to 5X PAAS values) concentrations in WSG strata. It is interesting to note that the highly aluminous and enriched LREE character of deep-marine Pleistocene mud from the Amazon fan were also interpreted to be the result of extreme chemical weathering in the source area (Kronberg et al., 1986; Nesbitt et al., 1990). Stratal units with the highest corrected CIA values (e.g. UKG, MMGA) coincide with highest LREE enrichments and may explain why the source mixing model could not sufficiently account for their content. The CIA and PIA values of the UMG imply a somewhat less intense weathering regime in the source area during deposition, but are also characterized by enriched LREE (~1.5 to 3X PAAS) suggesting that their chemical signature may be controlled additionally by other factors (e.g. source material mineralogy).

4.6.5 Paleoredox conditions

Following terrestrial weathering, sediment is eventually transported into the deep-marine where it may deposit under a variety of oxygen conditions. If the ambient ocean bottom-water is depleted in O₂, the sediment may become enriched in organic matter and select redox-sensitive transition elements (e.g. Mo, V, Ni, U). In many current models of Neoproterozoic ocean chemistry, persistent deep-ocean anoxia is a common theme (e.g. Canfield, 1998; Hurtgen et al., 2002; Jiang et al., 2007; Canfield et al., 2008). Evidence for episodes of euxinia or upwelling of deep anoxic bottom-water is interpreted predominantly from stable isotopic signatures of shallow-marine carbonates, with many studies focused on the controversial period surrounding the terminal Cryogenian glaciation (e.g. Grotzinger and Knoll, 1995; Hoffman et al., 1998; Hurtgen et al., 2006; Halverson and Hurtgen, 2007). The physical stratigraphic record and complementary evaluation of WSG mudstone paleoredox conditions on the other hand, offers the deep-marine perspective of the terminal Neoproterozoic oceanic sink.

Although there is still debate over the deposition of organic-rich units, the general consensus is that preservation of organic matter is controlled by the interplay of three main factors (e.g. Katz, 2005; Tyson, 2005): increased preservation in anoxic environments; elevated productivity from upwelling or riverine nutrient input; and sedimentation rate, either rapid (increased burial rate) or slow (reduced mineral dilution). Correlation of total organic carbon (TOC) and either content or ratio of redox-sensitive elements has led to the development of proxy signals to assess paleoredox settings and fluctuations in water-column oxygen (e.g. Lewan and Maynard, 1982; Berner and Raiswell, 1983; Hatch and Leventhal, 1992; Wignall, 1994; Crusius et al., 1996; Algeo and Maynard, 2004; Cruse and Lyons, 2004; Jones and Manning, 2004; Rimmer, 2004; Piper and Perkins, 2004; Tribovillard et al., 2004; Algeo and Lyons, 2006; McManus et al., 2006; Lyons and Severmann, 2006; Scott et al., 2008). Most authors present Al-normalized trace element concentrations to correct for dilution effects related to sedimentation (e.g. Arthur et al., 1990; Calvert

and Pedersen, 1993; Morford et al., 2001; Algeo and Maynard, 2004; Cruse and Lyons, 2004; Tribovillard et al., 2004), although it was recently argued that this may lead to unwanted variance in TOC – trace element relationships (Algeo and Lyons, 2006).

Numerous pre-defined geochemical proxy indices have been proposed (e.g. V/Cr, Ni/Co, U/Th, [Cu+Mo]/Zn) with absolute thresholds developed to evaluate oxic, dysoxic and anoxic environments (e.g. Hatch and Leventhal, 1992; Jones and Manning, 1994). However, compared to these studies, the WSG either shows significantly lower elemental concentrations (e.g. TOC, Mo/Al), or generates inconsistent results with most indices indicating oxic conditions. The open deep-marine setting of the WSG may result in a comparatively more dilute chemical signature compared to those reported from inlets, fjords, silled basins or epicratonic seaways with a restricted water mass (e.g. Crusius et al., 1996; Dean et al., 1999; Calvert et al., 2001; Cruse and Lyons, 2003; Lyons et al., 2004; Algeo and Lyons, 2006), which currently form the basis for most anoxia and black shale research. A number of more recent studies now stress the importance of multi-proxy enrichment factors when correlating redox-sensitive trace elements with TOC content to reconstruct paleoenvironmental conditions (e.g. Algeo and Maynard, 2004; Rimmer, 2004).

The TOC contents from WSG mudstone units are relatively low (<0.05 to 1.82%) because of the effect of thermal alteration and low-grade regional metamorphism with primary depositional concentrations likely near four times the current values (Tissot and Welte, 1978; Hayes et al., 1983). In this study, the only redox-sensitive elements or proxies that show positive affinity with TOC are Mo/Al ($\rho = 0.76$), V/Cr ($\rho = 0.54$), Sb/Al ($\rho = 0.51$) and As/Al ($\rho = 0.60$) (Table 4.5). Mo/Al also shows good positive correlation with Sb/Al ($\rho = 0.66$) and V/Cr ($\rho = 0.63$), and weak positive correlation with U/Th ($\rho = 0.39$) (Table 4.5). For the WSG mudstone units, the low Spearman rank order correlation coefficients for TOC and the other potential redox-sensitive elements indicates they are not preferentially concentrated

Redox-proxy	W	TOC	Mo/Al	V/Cr
TOC	0.75	1	0.76	0.54
Mo/Al	0.61	0.76	1	0.63
V/Cr	0.93	0.54	0.63	1
Ni/Co	0.42	-0.01	0.02	0.10
Ni/V	0.94	-0.26	-0.31	-0.55
U/Th	0.83	0.25	0.39	0.18
(Cu+Mo)/Zn	0.93	0.24	0.31	0.04
Fe/Al	0.91	-0.45	-0.28	-0.47
Sb/Al	0.59	0.51	0.66	0.37
V/Al	0.90	0.23	0.52	0.41
U/Al	0.85	0.22	0.35	0.25
Cr/Al	0.92	-0.28	-0.10	-0.54
Co/Al	0.96	-0.11	0.00	-0.32
Ni/Al	0.86	-0.17	-0.04	-0.33
Cu/Al	0.84	0.19	0.19	-0.09
Zn/Al	0.96	0.12	0.08	-0.09
Pb/Al	0.87	0.32	0.43	0.13
As/Al	0.80	0.60	0.42	0.27

Table 4.5: Correlation coefficients between TOC and Mo with potential redox-proxies. Spearman's rank order correlation coefficient (ρ) are used and correlation coefficients with p-values <0.001 are highlighted in bold: positive in red, negative in blue. W = Shapiro-Wilk's test.

in the organic fraction, nor that bottom-water O₂ content was the dominant control on their incorporation into the sediments. This confirms the earlier cluster analysis (Fig. 4.10) that indicated that most of the TTE were associated primarily with detrital heavy or clay minerals. There are also no observable differences if the raw concentrations or Al-normalized values are used for the WSG mudstone units.

In order to calculate the elemental enrichment factor (EF), a liberal cutoff of 0.25% TOC (~1% at deposition) is used to delineate organic-rich ($n = 30$) and non-organic units ($n = 57$) for the purpose of this paper. If a conservative value of 0.5% were applied (~2%, an approximate cutoff for petroleum source rocks), 21 samples would be considered organic-rich (0.50 to 1.82%) with 4 slightly under the cutoff (0.47%). To determine the detrital background chemical signature for the Windermere basin, the non-organic WSG mudstone units ($n = 57$) were used to calculate average elemental values (as opposed to a shale composite such as PAAS). Compared to background WSG, there is a good correlation between relative TOC enrichment (average: ~3X from cutoff value) and the EFs for Mo/Al (average: ~5X) and Sb/Al (average: ~4X), with a more modest EF for V/Cr (average: 1.5X). Within the Windermere basin, Mo (and Sb) content appears to be the best candidate for identifying reducing conditions, with V/Cr also showing potential utility.

Mo is now widely used as a redox proxy because of its associated strong enrichment during deposition of organic-rich mudstone under oxygen-poor conditions (e.g. Algeo and Lyons, 2006 and references therein). Recent investigations focused on the geochemical behaviour of Mo with respect to organic matter (humic substances), Fe-Mn oxyhydroxides, sulfate-reducing bacteria, and Fe-sulfides (e.g. Helz et al., 1996; Erickson and Helz, 2000; Zheng, 2000; Adelson et al., 2001; Vorlicek and Helz, 2002; Vorlicek et al., 2004), which has led to its widespread application as a proxy in high-resolution studies of modern anoxic oceanographic environments and ancient sedimentary successions (e.g. Emerson and Huested, 1991; Jones and Manning, 1994; Crusius et al., 1999; Morford et al., 2001; Piper and Dean, 2002; Werne et al., 2002; Lyons et al., 2003; Algeo and Maynard, 2004; Cruse

and Lyons, 2004; Algeo and Lyons, 2006; McManus et al., 2006; Scott et al., 2008). In deep-marine strata of the Neoproterozoic WSG, Mo is interpreted to be the most sensitive indicator of reducing conditions based on its positive (although moderately scattered) correlation with TOC content and relatively high EF (~5X) compared to WSG background strata. Although the absolute concentration of Mo in WSG strata appears insignificant compared to other black shales (e.g. 100s ppm), the relative co-enrichment of TOC and Mo is suggested as evidence for bottom-water anoxia in the Windermere basin and may represent global Neoproterozoic oceanic conditions. The average Mo/TOC ratio (~5, excluding one anomalously high value) of the WSG organic-rich mudstone units is consistent with other global Neoproterozoic black shale successions, which suggests a Mo-deficient ocean during this period (Scott et al., 2008). A plot of Mo (log scale) vs. TOC (Fig. 4.15A) shows rather well-defined boundaries between background WSG mudstone units which are interpreted to have been deposited during oxic conditions (low TOC, low Mo) and samples co-enriched which are interpreted to have been deposited during anoxic conditions (empirical cutoff at 0.25% TOC and 1 ppm Mo). The diagram also shows that a number of samples are enriched in TOC, but not Mo (and vice-versa). This implies other mechanisms may be active in deposition of organic-rich WSG deep-marine units (e.g. sedimentation rate, upwelling, shelfal transport, paleobathymetric lows) and that perhaps elevated Mo content by itself is not definitive evidence for bottom-water anoxia.

Earlier it was argued that both V and Cr are primarily associated with the detrital heavy or clay mineral fraction. The diagram of Ti vs. V (Fig. 4.16A) shows a good positive correlation of the two elements, but interestingly are a number of samples that plot above the detrital trend line that typically have elevated TOC. Concentration of V in organic matter is associated with denitrification under reducing conditions (e.g. Lewan and Maynard, 1982; Jones and Manning, 1994) and both V and the V/Cr ratio have been used as reliable redox indicators (e.g. Jones and Manning, 1994; Algeo and Maynard, 2004). A plot of Ti vs. V/Cr (Fig. 4.16B)

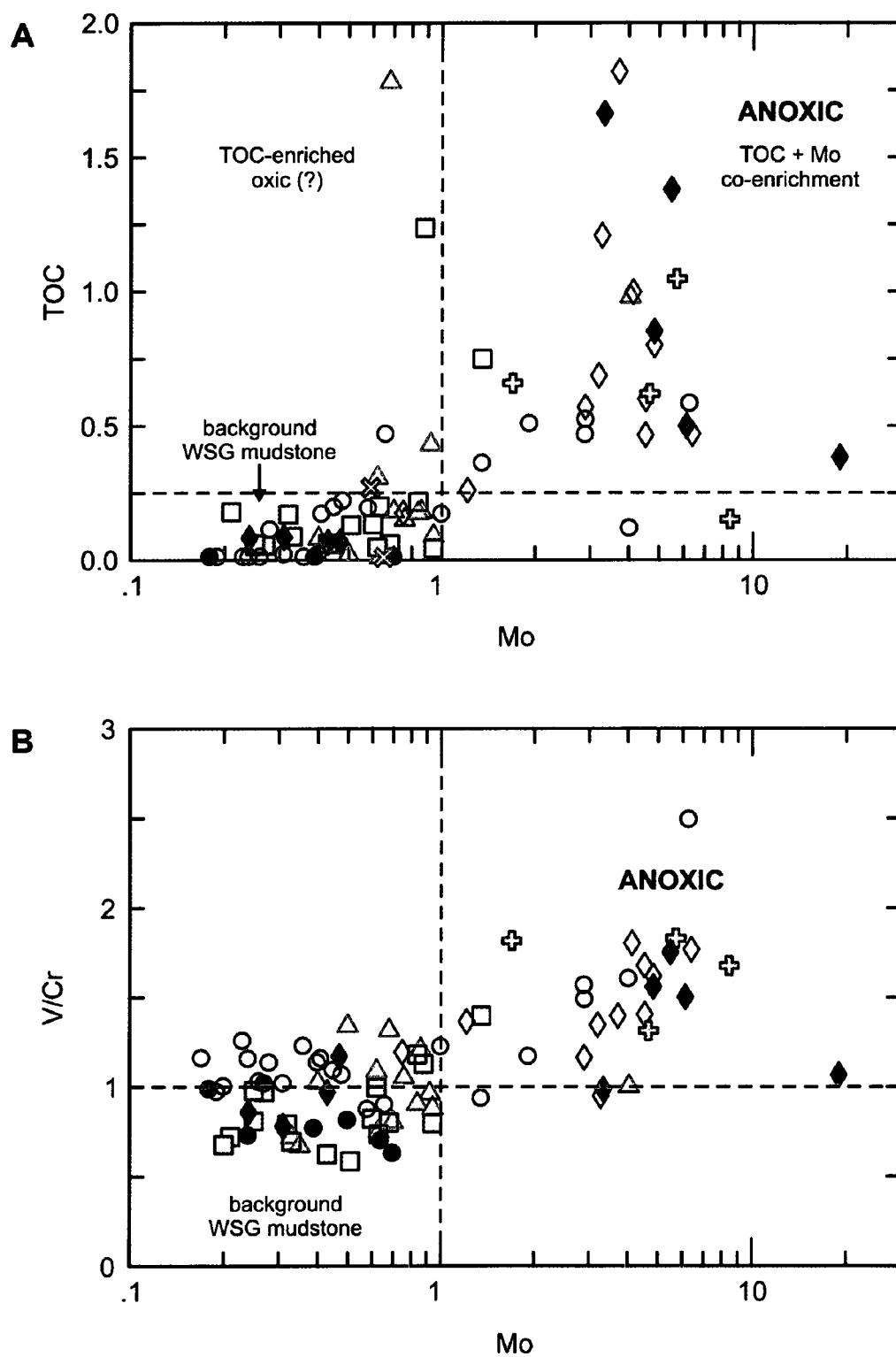


Figure 4.15: Paleoredox diagrams with empirically defined WSG cutoffs for interpreted bottom-water anoxic conditions: A) Plot of Mo (ppm) vs. TOC (wt%). B) Plot of Mo (ppm) vs. V/Cr. Legend of symbols is the same as Fig. 4.4.

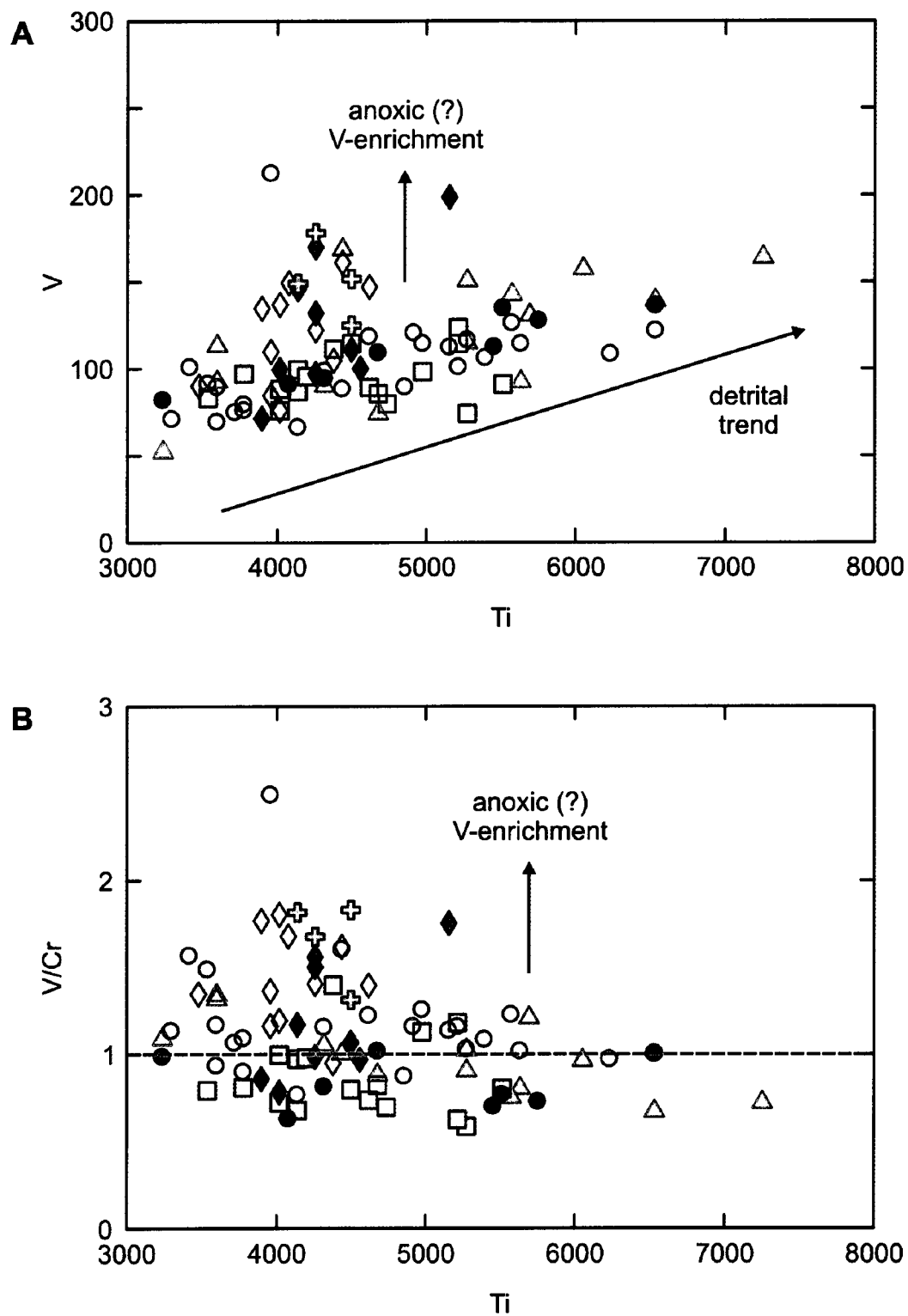


Figure 4.16: Paleoredox diagrams illustrating elevated V contents not associated with detrital mineral fraction. A) Plot of Ti (ppm) vs. V (ppm). B) Plot of Ti (ppm) vs. V/Cr. Legend of symbols is the same as Fig. 4.4.

discriminates most samples whose V content is associated with the organic fraction, rather than the detrital fraction. For the WSG, V/Cr ~1 (non-organic WSG average) is interpreted to represent an approximate boundary representing the transition from oxidizing to reducing conditions, although there is some overlap between organic and non-organic samples. The low EFs and approximate boundary require that V/Cr not be used as the sole indicator of paleoredox conditions, but in conjunction with TOC and Mo (or Mo/Al), with which it shows good affinity (Fig. 4.15B). It is important to note that the WSG V/Cr threshold is significantly lower than those defined by Jones and Manning (1994) for the oxic - dysoxic (V/Cr = 2) and dysoxic - anoxic (V/Cr = 4.25) transitions.

4.6.6 Deep-ocean anoxia

Although subtle, the geochemical indicators in upper bathyal to upper abyssal plain strata of the WSG suggest short-term regional episodes or localized conditions of deep-ocean bottom-water anoxia (or at least relatively O₂ depleted) in a thick succession deposited under fairly oxic conditions. Discrete, but thin mudstone intervals elevated in TOC, Mo and/or V/Cr are present in basin-slope deposits (IF, UMG, MMGA, MMGB) (e.g. Table 4.2, Appendix E; G. M. Ross, unpublished data) but are essentially absent in basin-floor strata (MKG and UKG) (e.g. Table 4.2, Appendix F; Meyer, 2004; G. M. Ross, unpublished data). The exception is the OFP (GSM and WMM) where most of the samples exhibit enrichments in these geochemical proxies interpreted to indicate anoxia when compared to background WSG mudstone units.

The GSM is the middle member of the OFP and forms a regionally extensive, organic-rich mudstone horizon, exposed locally over 35,000 km² of the southern Canadian Cordillera (Chapters 2, 3). The age the GSM is constrained by a Re-Os isochron date of 607.8 ± 4.7 Ma (Kendall et al., 2004) and therefore post-dates the terminal Cryogenian glaciation event (ca. ~635 Ma). This age is thought to be slightly young and represent a minimum timing of GSM deposition based on

regional stratigraphic and isotopic correlations of the OFP to strata in the northern Canadian Cordillera, which are interpreted to represent the transition from terminal Cryogenian glacial to basal Ediacaran post-glacial deposits (e.g. Ross et al., 1995; James et al., 2001; Chapters 3 and 5). The GSM is interpreted to have been deposited along a basin-slope to basin-floor transect during the highstand systems tract that followed a post-glacial eustatic rise, which shutdown the flux of coarse siliciclastic sediment into the Windermere basin (e.g. Ross and Murphy, 1988; Chapter 3). The discharge of large volumes of nutrient-rich glacially charged surface water likely led to an increase in organic productivity. These episodic events superimposed on the rapid rise in sea-level enhanced the potential for anoxia by leading to abrupt short-term water column stratification and development of anoxic bottom waters below a postulated pycnocline. Furthermore, unlike other WSG strata, TOC and chemical indicators of anoxia are consistently enriched in the GSM, irrespective of paleogeographic location (Fig. 4.15, 4.16). The only organic-poor GSM samples are from the southernmost part of the region where local growth faults are interpreted to have increased local sedimentation rate, and as a consequence caused mineral dilution of organic-matter during deposition (Chapter 3).

The UMG is also characterized by organic-rich strata associated with a regional carbonate horizon (e.g. Ross et al., 1995; Ross and Arnott, 2007). Similar to the OFP, this unit is also interpreted to represent highstand conditions (e.g. Ross et al., 1995), but to date has not been studied in detail. Other organic-rich units in the WSG tend to be local in extent, with potential controls being sea-level, transportation of organic-matter from shelfal areas, or deposition in paleobathymetric lows. Recognition of lithological and chemical variations (e.g. Mo/TOC) within these organic-rich units of the WSG when compared to the OFP (GSM and WMM) or UMG may facilitate the development of criteria for identifying controlling factors and relative O₂ depleted conditions (e.g. dysoxic, anoxic, euxinic) that influenced depositional patterns in this Neoproterozoic deep-marine system. Although this work is regional in nature, high-resolution sampling (cm-scale) and

analyses (e.g. Algeo and Maynard, 2004) could be carried out in the better-preserved parts of the WSG (e.g. polished, peri-glacial exposures in Cariboo Mountains) to better resolve bottom-water redox conditions and short-term fluctuations that may have taken place.

Anoxic, organic-rich deposition as a result of deepening following relative sea-level rise might also explain apparent mineral association between the detrital (quartz – plagioclase) and organic fraction (TOC – Mo). Typical WSG strata consist of feldspar-rich immature sediment derived from river systems that bypassed the shelf during lowstand. Conversely, during highstand (e.g. OFP or UMG), most of the fluvial sediment flux was trapped on the proximal shelf/shoreface where it was reworked and winnowed. Thus, at a time of organic-rich deposition, detrital material being transported onto the slope and into the basin would be mineralogically mature, or associated with (highstand) carbonates shed from coeval, upslope shallow-marine platforms.

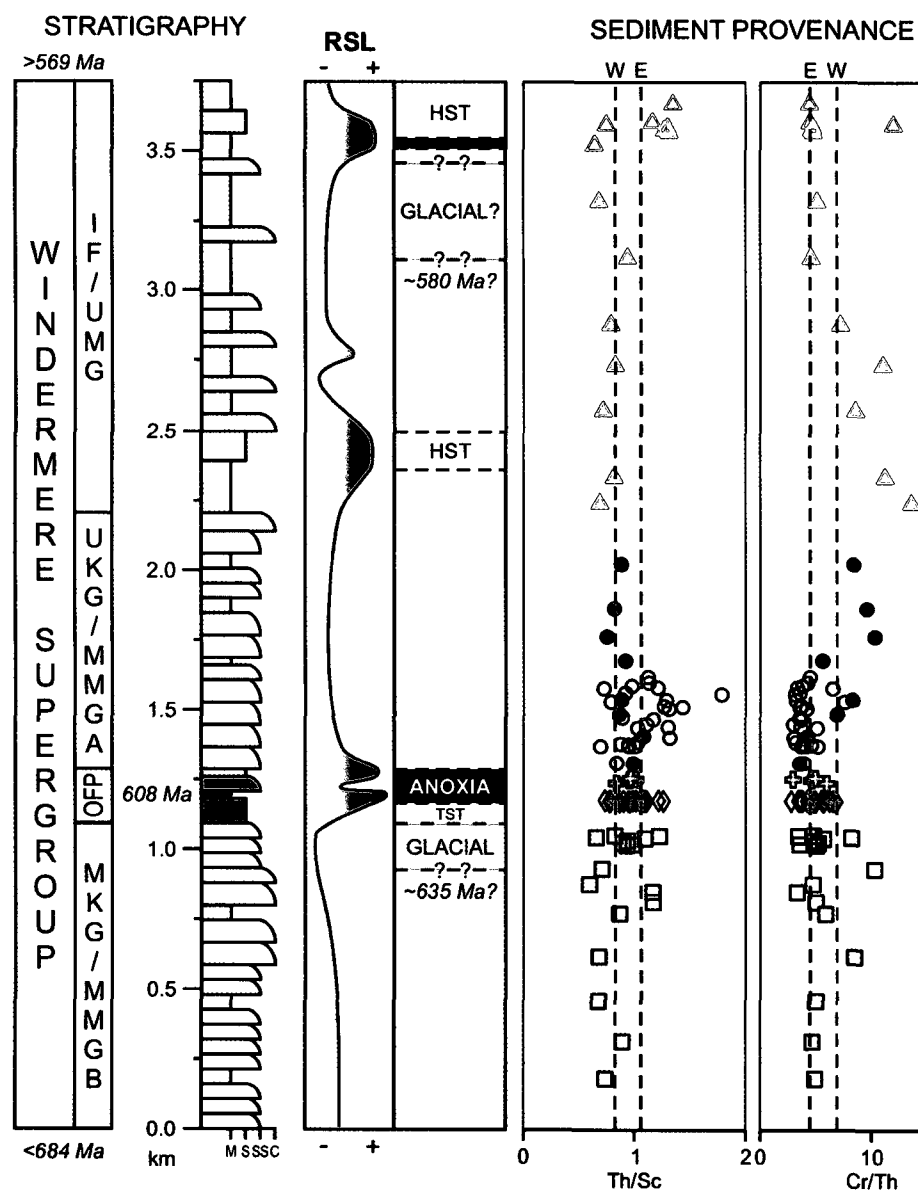
4.6.7 Neoproterozoic WSG geochemical evolution

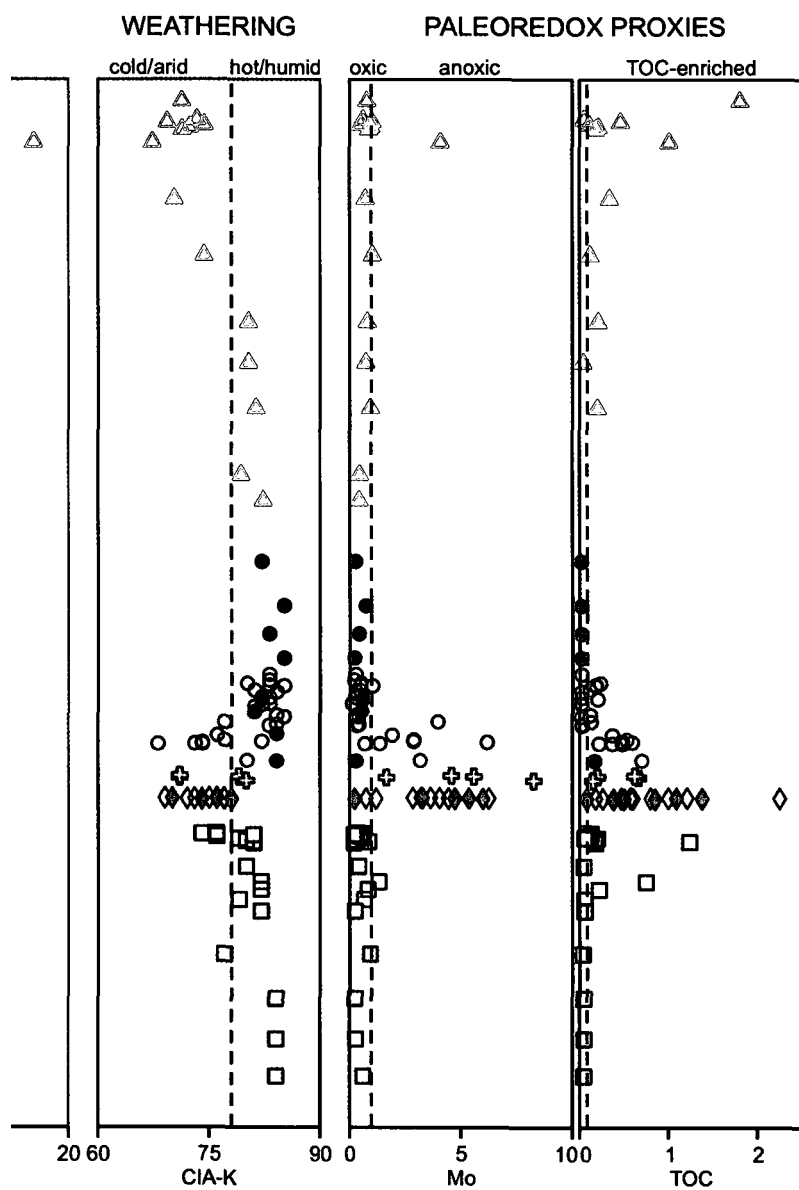
The WSG is interpreted to have accumulated in an open ocean along the continental margin of Laurentia and represents a rare field laboratory to examine the deep-ocean sedimentary sink during the dynamic Cryogenian and Ediacaran periods (e.g. Fairchild and Kennedy, 2007 and references therein). The purpose of the geochemical characterization of the mudstone units is to identify key elemental proxies within the Windermere basin and understand the processes that controlled these chemical signatures. Using these proxies, it is possible to examine the geochemical evolution of the WSG sedimentary pile in order to assess sediment provenance of source material, paleoclimate and paleoredox conditions (e.g. Rieu et al., 2007; Scheffler et al., 2006). In this work, interpretations of the paleo-environmental conditions during deposition of the WSG are limited because of a combination of factors: 1) regional scope of this study, which resulted in a wide sample spacing interval (>100 m per sample from Cariboo Mountains); 2) poor

geochronological control (sampling interval ca. 685 Ma to 570 Ma); and 3) collection of samples from isolated structural panels where only the stratal division was identified, but not precisely positioned within the depositional system. Despite these limitations, most samples collected east of the SRMT (open symbols) were positioned relative to a marker horizon (e.g. OFP); west of the SRMT (closed symbols), in Cariboo Mountains, samples were collected through an uninterrupted, basin-floor to slope composite section constructed from three separate locations (CM1, CM2, and CM3). A generalized evolution of WSG stratigraphy, geochemical profiles of key elemental proxies, their potential controls, and timing of potential Neoproterozoic events is summarized in Figure 4.17.

Overall, the major element and HFSE chemistry suggests that the source of the fine-grained sedimentary rocks of the WSG was well-mixed and relatively homogenous. This interpretation is illustrated by the rather uniform Th/Sc signature throughout the succession (Fig. 4.17) and is consistent with previous Nd isotope (Boghossian et al., 1996) and U-Pb detrital zircon work (Ross and Bowring, 1990; Ross and Parrish, 1991; Smith and Gehrels, 1991; Ross et al, 1997; Gehrels and Ross, 1998; Ross, 2000; Ross and Heaman, 2005; Lemieux et al., 2007). Although the concentrations of the TTE from the stratal units did not display any characteristic enrichments or depletions, a number of them exhibit similar evolutionary profiles in the composite section from the Cariboo Mountains (closed symbols). A geochemical profile of the Cr/Th ratio (Fig. 4.17) is used to demonstrate the trends exhibited by Cr, Co, Ni and Cu (also Fe and Ti to a lesser extent). The Cr/Th ratio shows a gradual trend toward higher values within the MKG, shifts to lower values during deposition of the OFP and gradually returns to higher values through the UKG and basal IF. After deposition of the IF lower carbonate marker, the Cr/Th shows a gradual shift to lower values. These gradual TTE transitions may be related to relative sea-level change where lowered levels possibly modified overall provenance of the source material (e.g. unroofing of a mafic source) transported in basinal environments.

Figure 4.17: Conceptual geochemical evolution model of post-rift WSG strata. Geochemical profiles of Th/Sc and Cr/Th are presented to show WSG sediment provenance. Average values for WSG mudstone east and west of the SRMT are indicated by dashed line in columns showing the ratios Th/Sc (0.83 and 1.06, respectively) and Cr/Th (4.50 and 6.90, respectively). Weathering conditions are represented by the geochemical profile of CIA-K (Chemical Index of Alteration, corrected for K-metasomatism). Dashed line is placed at a CIA-K value of 78, which for the WSG may indicate the transition from hot/humid to cold/arid conditions in hinterland continental settings. Geochemical profiles of Mo (ppm) and TOC (%) are displayed for paleoredox proxies. Dashed line placed at Mo = 1 represents interpreted empirical cutoff in WSG sedimentary rocks for interpreted anoxic conditions. Dashed line placed at TOC = 0.25% is the interpreted cutoff between background, non-organic WSG deposition and organic-rich deposition. Relative timing of deposition is constrained to younger than 684 Ma from correlative rift-related volcanic rocks in Idaho (Lund et al., 2003), and older than 569 Ma based on the timing of volcanic rocks associated with the late Ediacaran rift-event (Colpron et al., 2002). Minimum timing of deposition for the OFP is constrained by an Re-Os whole rock isochron age of 607 ± 4.7 Ma from organic-rich mudstone of the GSM (Kendall et al., 2004). Total stratal thickness is approximate and represents a composite section measured from the three locations (Mount Quanstrom, Eagle Valley, Castle Creek) in the Cariboo Mountains using known marker horizons (Chapter 3; Meyer, 2004; Ross and Arnott, 2007). Also shown are interpreted relative sea-level (RSL) curve, potential timing of glacial events and interpreted development of anoxic deep-ocean conditions. Stratal abbreviations: OFP = Old Fort Point Formation (Whitehorn Mountain Member: red-brown and blue; Geikie Siding Member: black; Temple Lake Member: purple); IF = Isaac Formation, Cariboo Group; UKG = Upper Kaza Group; MKG = Middle Kaza Group; UMG = Upper Miette Group; MMGA = Middle Miette Group above OFP; MMGB = Middle Miette Group below OFP; SRMT = Southern Rocky Mountain Trench. Yellow are sandstone-dominated units, grey are mudstone-dominated units and blue are carbonate-dominated units. Closed symbols are samples collected west of the SRMT, open symbols collected east of the SRMT. Legend of symbols is the same as Fig. 4.4.





Deep-marine strata of the WSG show a number of CIA (corrected for K-metasomatism) shifts that are interpreted to reflect broad changes in paleoclimate and weathering conditions in the continental source areas (Fig. 4.17). Generally, CIA values from the WSG are elevated (>80) which is interpreted to reflect intense chemical weathering related to Laurentia's low-latitude setting at that time (Park, 1997). There are two prominent intervals where CIA values are lowered and are interpreted to reflect periods of reduced chemical weathering (Fig. 4.17). The first interval (upper MKG and MMGB, OFP, lower MMGA) roughly coincides with the timing of the terminal Cryogenian glaciation event and interpreted post-glacial Ediacaran deposition (e.g. Ross et al., 1995; Kendall et al, 2004; Chapter 3). If the second interval (upper IF, UMG) also corresponds to a period of reduced chemical weathering caused by a colder climate, one could speculate that this excursion could represent the Ediacaran glacial ("Gaskiers" episode) to post-glacial transition, but there is no current geochronological constraint to support this hypothesis. Both of these lowered CIA intervals correspond with periods of transgression coincident with transport and deposition of carbonate in the Windermere basin (Ross et al., 1995; Chapter 3). Although based on only two observations, this consistent relationship suggests a possible link between relative sea-level change and variations in CIA values, and therefore climatic conditions. In both instances the trend towards lower CIA values begins during lowstand and persists through the ensuing transgressive phase. The onset of the trend toward lower CIA values is interpreted to reflect less intense chemical weathering caused by a climatic cooling (glaciation) and deposition of less chemically weathered sediment during the subsequent rise of sea-level associated with continental glacial melting. This suggests there may be a temporal lag between the initiation of continental changes in climate, and hence weathering, and its related geochemical expression in deep-marine environments. Another interval of lower CIA values (1 sample) is observed in the MKG - MMGB prior to the interpreted terminal Cryogenian glaciation. Although the relative shift from lower to higher CIA with a return to lower CIA

may suggest an interruption during the overall glacial episode (e.g. glacial – interglacial glacial) (e.g. Rieu et al., 2007) the sample spacing precludes any definitive interpretation.

Although many models of Neoproterozoic oceanic chemistry propose persistent deep-ocean bottom-water anoxia, their interpretations are based primarily on evidence from the shallow-marine rock record and/or stable isotopic proxies. The WSG is an uninterrupted, thick succession of deep-marine siliciclastic sedimentary rocks whose physical and chemical features suggest deposition under background oxic conditions with periodic episodes of anoxia of an unknown but relatively short duration, which appear to coincide to major events of sea-level rise (Fig. 4.17). The strongest evidence for deep-ocean bottom-water anoxia in the WSG succession is suggested by the co-enrichment of Mo and TOC in strata of the post-glacial highstand OFP (and locally the overlying MMGA) (Fig. 4.15A). Strata in the UMG strata are also locally organic-rich, but only one sample shows elevated Mo content, and this unit certainly warrants further study (Fig. 4.17).

The geochemical data from the WSG mudstone units clearly do not support some of the current Neoproterozoic paleo-oceanographic models. The first is the constant theme in a number of the competing hypotheses surrounding the terminal Cryogenian glacial episode whereby they propose development of a syn-glacial, euxinic ocean (e.g. Grotzinger and Knoll, 1995; Hoffman et al, 1998; Hoffman and Schrag, 2002; Hurtgen et al., 2006; Halverson and Hurtgen, 2007). The physical observations and mudstone geochemistry from stratal units (MMGB, MKG) interpreted to be deep-marine equivalents of the glaciogenic diamictite units of the Vreeland Formation (McMechan, 2000) clearly contrast with these models as they show no evidence from the established redox-proxies for prolonged and/or regionally extensive deep-ocean anoxia, although local reducing conditions (dysoxic?) may have been present during certain periods based on the distinctive green colour of some MKG basinal deposits.

The second is that the mudstone geochemical data from the deep-marine WSG strata (>50 Myr) are also inconsistent with other studies which propose frequent and/or long-term bottom-water anoxia during the Neoproterozoic (e.g. Jiang et al., 2007; Canfield et al., 2008), prior to well-oxygenated conditions at around 580 Ma. For example, the study of Canfield et al. (2008), bases their argument primarily on Fe-speciation results whereby ratio values of $\text{FeHR}/\text{FeT} > 0.38$ (modern cut-off) indicate anoxic conditions. Although there appears to be a conflict in hypotheses, interestingly, the data presented by Canfield et al. (2008, supplementary data) from WSG samples in the Cariboo Mountains is in fact remarkably consistent with the results of the mudstone geochemistry presented above. Relative to the $\text{FeHR}/\text{FeT} = 0.38$ value: select samples from the OFP are above that value indicating anoxia, the UKG is consistently below indicating deep-water oxic conditions except near the UKG – IF contact; and samples from the IF are commonly below, but quite variable (Canfield et al. 2008, supplementary data). Overall Fe concentrations are relatively enriched in the WSG ranging from approximately 5 to 9 wt%, which may indicate the deep-ocean was enriched in reduced iron, but widespread bottom-water anoxia was not a common feature as proposed by Canfield et al (2008). In fact, the OFP which is characterized by other redox-proxies (e.g. Mo, V, TOC) suggestive of bottom-water anoxia has relatively low Fe content (5 to 6 wt%) compared to other deep-marine WSG stratal units.

4.7 CONCLUSIONS

Geochemical analyses of mudstone units of the Neoproterozoic WSG complement existing sedimentologic and stratigraphic studies conducted on this thick siliciclastic sedimentary succession. These data come from the perspective of the deep-marine siliciclastic sink and thus, provide an alternate viewpoint and interpretation of Neoproterozoic oceanic chemistry when compared to other studies from predominantly shallow-marine successions. A number of conclusions about

the WSG are made regarding provenance, tectonic setting, weathering regimes, and paleoredox conditions:

- 1) As a whole, WSG strata display relatively consistent major-element chemistry with higher contents of Al_2O_3 and K_2O , and lower SiO_2 compared to mudstone standards. With the possible exception of MgO , geochemical compositions were not significantly modified by low-grade regional metamorphism.
- 2) Cluster analysis suggests three main mineralogical groups for the elemental chemistry: clay/mica, heavy detrital minerals and quartz-plagioclase-organics. Elements or elemental ratios (e.g. Ti, Nb) associated with the heavy mineral fraction may have utility in discriminating paleogeographic setting because of preferential sorting during sediment gravity-flow transport.
- 3) Stratigraphically consistent Th/Sc, Cr/Th, Eu anomalies and REE profiles suggest a well-homogenized provenance for all stratal units. Two approximate mixing models of source material for WSG fine-grained sedimentary rocks east and west of the SRMT were generated using Archean and Proterozoic igneous components based on the relative proportions of probable Alberta basement domains indicated by U-Pb detrital zircon work. The WSG mudstone geochemical signatures show no major influx of exotic or sediment of differing composition, which is more consistent with deposition in an open ocean, passive margin setting (Ross, 1991; Ross et al, 1995; Ross and Arnott, 2007), rather than an intra-continental rift (Colpron et al, 2002).
- 4) Relative enrichments in K_2O , Rb, and Ba values suggest addition of these elements, likely from post-depositional K-metasomatism. Calculated pre-metasomatism CIA values (67 to 85) suggest changes in paleoclimate in hinterland continental settings, including periods of intense chemical

weathering prior to transport and deposition in deep-water environments. PIA values and enriched LREE also suggest a high degree of chemical weathering in the source area for most stratal units.

- 5) Previously defined thresholds for evaluating redox conditions are not viewed as applicable for the deep-marine WSG. The consistent positive covariance and significant enrichment factors in TOC, Mo, V and V/Cr are interpreted to suggest that these proxies are the most sensitive for identifying periods bottom-water anoxia in the Windermere basin and potentially global Neoproterozoic deep ocean conditions.
- 6) Despite a broad sampling over a poorly constrained time interval (~100 Ma), the WSG exhibits observable stratal shifts in paleoclimatic and redox proxies that appear to correlate with established global Neoproterozoic environmental changes. Most importantly, these geochemical signals also suggest that regionally widespread bottom-water anoxia was a short-term, periodic phenomena, that developed during post-glacial highstand deposits; not during the preceding glacial episode, as proposed by many of the current models for the Cryogenian to Ediacaran transition, nor as a consistent, long-term feature indicative of Neoproterozoic deep ocean conditions.



uOttawa

L'Université canadienne
Canada's university

CHAPTER 5: Carbonate paragenesis and isotope geochemistry of the Old Fort Point Formation, Windermere Supergroup, southern Canadian Cordillera: the deep-marine perspective of post-glacial Ediacaran environmental change.

5.1 INTRODUCTION

The globally recognized stratigraphic association of Neoproterozoic low-latitude glacigenic diamictite sharply overlain by thin, unusual carbonate deposits remains a controversial enigma with competing paleo-climatic and paleo-oceanographic models (see recent review in Fairchild and Kennedy, 2007 and references therein). Transgressive post-glacial cap carbonate strata are characterized by a basal dolostone (Kennedy, 1996; Shields, 2005; Hoffman et al., 2007), which locally is overlain by limestone (Hoffman et al., 1998; James et al., 2001; Nogueira et al., 2003; Hoffman et al., 2007). Cap dolostones are generally thin (<5 m), composed of microcrystalline dolomite and characterized by an unusual, but remarkably uniform suite of features including: peloidal textures, tepee-like antiform structures, sheet cracks, vertical tube-like structures within stromatolites and cemented syn-sedimentary deformation structures (e.g. Cloud et al., 1974; Deynoux et al., 1976; Aitken et al., 1991; Kennedy, 1996; Kennedy et al., 1998, 2001; James et al., 2001; Leather et al., 2002; Hoffman and Schrag, 2003; Jiang et al., 2003; de Alvarenga et al., 2004; Porter et al., 2004; Halverson et al., 2004, 2005; Allen and Hoffman, 2005; Corsetti and Grotzinger, 2005; Gammon et al., 2005; Shields, 2005; Jiang et al., 2006; Hoffman et al., 2007; Shields et al., 2007). Post-glacial limestones are locally characterized by neomorphosed aragonite fans regarded by many authors as evidence for seafloor precipitation (e.g. James et al., 2001; Hoffman et al., 1998; 2007; Nogueira et al., 2003; Lorentz et al., 2004). The contact between the two

is commonly marked by the presence of barite (Walter and Bauld, 1983; Kennedy, 1996; Kennedy et al., 2001; Hoffman and Schrag, 2002; Jiang et al., 2003, 2006; Shields, 2005; Shields et al., 2004, 2007; Hoffman et al., 2007), and in some cases shows evidence of soft-sediment deformation (Nogueira et al., 2003) or subaerial exposure (James et al., 2001).

Cap carbonate successions consistently show negative $\delta^{13}\text{C}$ signatures, and have been interpreted by many authors to reflect a correlatable secular change in Neoproterozoic seawater chemistry associated with the preceding glacial event (e.g. Hoffman et al., 1998; Hoffman and Schrag, 2002; Halverson et al., 2005). Although most authors agree on a global event of increased carbonate alkalinity, specific mechanisms remain controversial and a number of models have been proposed: 1) snowball Earth hypothesis (e.g. Kirschvink, 1992; Hoffman et al., 1998; Hoffman and Schrag, 2002; Higgins and Schrag, 2003; Hoffman et al., 2007); 2) oceanic stratification and upwelling (Grotzinger and Knoll, 1995; Knoll et al., 1996; Kaufman et al., 1997; Ridgeway et al., 2003; Shields, 2005; Giddings and Wallace, 2009); 3) gas hydrate destabilization (Kennedy et al., 2001; Jiang et al., 2003, 2006; Kennedy et al., 2008) and 4) microbial mediated dolomite precipitation (Nedelec et al., 2007; Font et al., 2006; Elie et al., 2007). Most of these studies interpret profound changes in Neoproterozoic climatic and oceanic conditions based on the coincident association of glacial deposits and large shifts in $\delta^{13}\text{C}$ isotope chemostratigraphy (see recent review by Fairchild and Kennedy, 2007, and references therein). However, only a small number of studies have examined in detail the associated small-scale textural features to unravel the depositional and diagenetic history of the strata (e.g. Kennedy, 1996; James et al., 2001; Jiang et al., 2003, 2006; Nogueira et al., 2003; Allen and Hoffman, 2005; Gammon et al., 2005).

In the southern Canadian Cordillera, Neoproterozoic strata are preserved within the thick (~9 km) stratigraphic succession of the Windermere Supergroup (WSG), dominated by siliciclastic meta-sedimentary rocks deposited in deep-water slope to basin-floor settings (e.g. Ross et al., 1989, 1995; Ross and Arnett, 2007).

These bathyal to upper abyssal environments (Chapter 2) offer a rare opportunity to study the uninterrupted stratigraphic and chemical evolution of the terminal Neoproterozoic. Within this stratal succession is the Old Fort Point Formation (OFP), a distinctive, mixed siliciclastic and carbonate marker horizon whose minimum timing of deposition has been dated at 607.8 ± 4.7 Ma (Kendall et al., 2004) (Fig. 5.2). Basal strata of the Ediacaran OFP are predominantly turbidites that accumulated during transgression (Ross and Murphy, 1988; Ross et al., 1995; Chapter 3) as a result of melting related to the terminal Cryogenian glacial episode at ca. 635 Ma (Hoffman et al., 2004; Condon et al., 2005). The OFP is broadly correlative with cap carbonate strata overlying glacial diamictite exposed in the northern Canadian Cordillera (Ross et al., 1995). This paper describes the types, textural features, and diagenetic processes of the OFP carbonate units, in addition to presenting new geochemical and stable isotopic data from the OFP. The purpose of these data is threefold: 1) to identify the significance of the carbonate phases and determine which, if any, component is a faithful record of coeval seawater biogeochemistry; 2) to provide improved regional stratigraphic correlations with better studied strata in the northern Canadian Cordillera; and 3) as a rare bathyal to upper abyssal Ediacaran post-glacial carbonate succession it hosts a stratigraphic record that provides an alternate perspective into global oceanic environmental change during this dynamic period in Earth's history.

5.2 REGIONAL GEOLOGY AND TECTONIC SETTING

The Neoproterozoic Windermere Supergroup (WSG) is extensively exposed over an area of 35,000 km² in the southern Canadian Cordillera, and consists of a thick succession (~9 km) of primarily deep-marine meta-sedimentary rocks (Fig. 5.1). The WSG records the rifting and the break-up of the supercontinent Rodinia and subsequent post-rift thermal subsidence (Stewart, 1972; Ross, 1991) (Fig. 5.2). The local timing of the rifting is constrained by U-Pb zircon ages of ca. 740 to 728

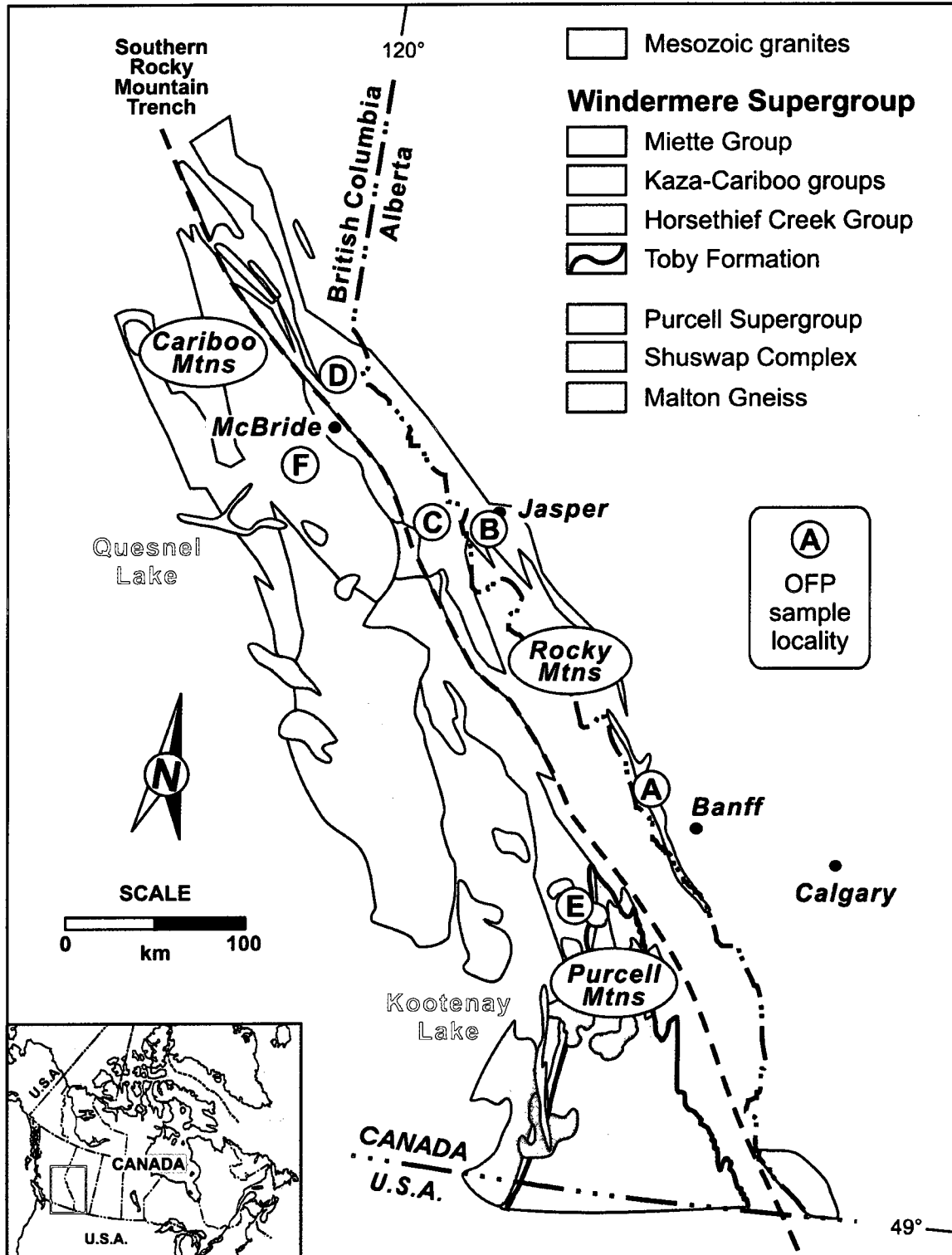


Figure 5.1: Simplified regional geological map of the WSG and study locations in the southern Canadian Cordillera, western Canada (modified from Ross and Murphy, 1988; Ross, 1991). OFP sample localities: A - Lake Louise, Banff National Park (LL); B - Jasper National Park (JP); C - Mount Robson Provincial Park (MR); D - McKale River (MK); E - Frances Creek, Purcell Mountains (PM); F - Cariboo Mountains (CM).

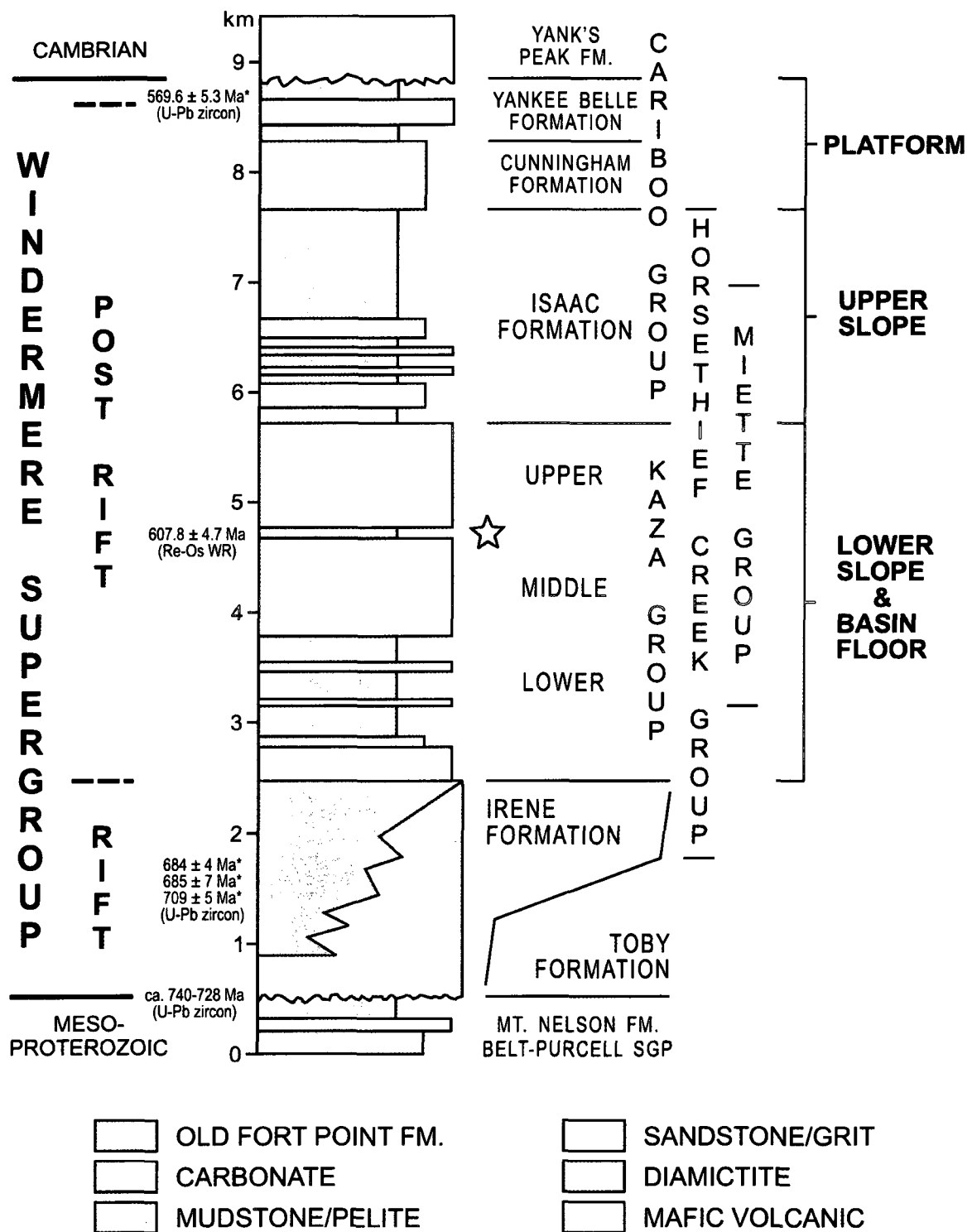


Figure 5.2: Stratigraphic column for the WSG from the Cariboo-Purcell-Rocky Mountains in the southern Canadian Cordillera (modified from Ross et al. 1995). Rift and post-rift strata, paleogeographic environment and relative stratigraphic position of the OFP are shown. Ages shown are discussed in the text and are from McDonough and Parrish (1991), Lund et al. (2003), Kendall et al. (2004) and Colpron et al. (2002). Asterisk indicates the age is from correlative strata to the column.

Ma obtained from basement rocks in the Canadian Cordillera (Evenchick et al. 1984; Parrish and Scamell 1988; McDonough and Parrish, 1991). Basal strata of the WSG accumulated synchronously with the active rifting phases and were controlled by syn-sedimentary faulting that tends to limit their regional extent (Aalto, 1971; Root, 1987; Warren, 1997). These deposits include glacial diamictite of the Toby Formation and associated volcanic rocks of the Irene Formation (Aalto, 1971; Root, 1987). The timing of rift-related volcanism is postulated to be from ca. 709 to 684 Ma based on potential correlatives located elsewhere in North America (Ferri et al., 1999; Lund et al., 2003; Fanning and Link, 2004). Moreover, the range of ages suggests a protracted rifting event (Fanning and Link, 2004).

Currently, there is some debate about the nature of the post-rift setting of the basin as to whether it was a passive continental margin (e.g. Ross, 1991; Ross et al., 1995) or an approximately 2500 km-long intracontinental rift system (Colpron et al., 2002). The preferred model is that of a passive margin with a substantial open ocean based on: consistent regional turbidite paleocurrent data towards the west-northwest (e.g. Ross and Arnott, 2007 and references therein); a predominantly bimodal (>2.5 Ga or 1.9 to 1.75 Ga) U-Pb detrital zircon pattern (Ross and Bowring, 1990; Ross and Parrish, 1991; Ross and Heaman, 2005; Lemieux et al, 2007); and homogeneous whole-rock geochemistry signatures from mudstone units (Chapter 4) implying common provenance from adjacent basement domains in southern Alberta; contourites in Mackenzie Mountains suggesting open ocean circulation (Dalyrymple and Narbonne, 1996); absence of extension-related volcanic rocks and volcanoclastic rocks in the post-rift strata; and current lack of the evidence for the conterminous western margin to the basin (although possibly obscured by Cordilleran deformation).

Rift-related units are overlain conformably by a regionally widespread, ~5-km thick sedimentary succession of monotonous, immature turbiditic strata that accumulated during post-rift thermal relaxation (e.g. Ross et al., 1989; 1995; Ross and Arnott, 2007). Nomenclature of these strata is variable and a number of region-

specific names exist throughout the southern Canadian Cordillera (Horsethief Creek Group, Kaza and Cariboo groups, Miette Group) (Fig. 5.2). Within the fossil-poor, turbiditic strata of the WSG, a number of lithologically distinctive, regional marker units have been recognized and used to establish an internal stratigraphic framework (e.g. Ross et al., 1989, 1995; Ross and Arnott, 2007). The Old Fort Point Formation (OFP) is the lowest of these stratigraphic marker horizons and is easily differentiated from the typical turbidites of the WSG post-rift succession (Ross and Murphy, 1988; Ross et al., 1995; Chapter 3) (Fig. 5.2). Basinal turbidite deposits are overlain by a kilometre-scale upward-shoaling trend to mudstone-dominated upper slope units and shelf platform carbonates (e.g. Ross et al. 1989; Ross et al., 1995; Ross and Arnott, 2007). The termination of WSG deposition is marked by a subtle regional unconformity that is succeeded by deposits of a latest Neoproterozoic to Cambrian rift-drift succession (e.g. Devlin and Bond, 1988; Kubli, 1990; Warren, 1997; Colpron et al., 2002). Felsic volcanic rocks associated with the second rift episode are well-constrained at 569.6 ± 5.3 Ma (Colpron et al., 2002).

Strata of the WSG have undergone regional metamorphism and are currently exposed in a series of thrust sheets associated with the eastern Cordillera orogen. Despite widespread uplift and deformation, areas of sub-greenschist (western Main Ranges of the Rocky Mountains) to greenschist (northern Cariboo Mountains, eastern Purcell Mountains) grade metamorphism exist, where exceptional primary sedimentary textures and structures are well-preserved.

5.3 STRATIGRAPHY AND SEDIMENTOLOGY

The Old Fort Point Formation (OFP) ranges from 60 to 450 m thick and is a mixed siliciclastic and carbonate succession consisting of basin-slope to basin-floor deposits in upper bathyal to upper abyssal (water depths approximately 500 m to 3000 m) environments (Chapter 2). During OFP sedimentation, paleogeographic environments of deposition are interpreted to be: mid- to lower slope settings at

Lake Louise (LL), Jasper (JP), and Frances Creek in the Purcell Mountains (PM); base of slope at Mount Robson (MR) and McKale River (MK); and basin-floor in the Cariboo Mountains (CM) (Chapter 3). The OFP conformably overlies, and is overlain by fine- and coarse-grained arkosic turbidites of the WSG. It comprises three distinctive lithological members that in ascending stratigraphic order are: 1) Temple Lake Member (TLM); 2) Geikie Siding Member (GSM); and 3) Whitehorn Mountain Member (WMM) (for details see Chapters 2 and 3). The following is a brief description of each member.

The TLM ranges from 50 to 125 m thick and because of its variable colour (purple, green, red-brown) is the most visually distinctive member of the OFP (Fig. 5.3A to F). The thin-bedded TLM usually consists of siltstone-dominated strata that grade upward into rhythmic limestone-siltstone couplets (average 2 to 3 cm thick) with an overall stratal thickness of 6 to 24 m (average around 15 m thick). Limestone and siltstone units of the TLM are consistently organic-poor with TOC contents <0.25% (Appendix K). Thin-bedded strata of the TLM consistently exhibit traction sedimentary structures and are interpreted to be low concentration turbidites (e.g. Bouma, 1962; Stow and Shanmugam, 1980). Associated with the fine-grained turbiditic strata are local breccia units with TLM-derived clasts interpreted as slump, slide or debris flow deposits.

Gradationally overlying the TLM is the GSM, which is 2 to 15 m thick and made up mostly of organic-rich mudstone with isolated beds of dark-grey coloured, organic-rich limestone (TOC up to ~4%) or sandstone. The dominant depositional mechanism for the GSM is suspension fallout of hemipelagic or pelagic material with subordinate low concentration turbidity currents. Both the TLM and GSM are regionally widespread implying basin-wide, line-source accumulation.

Unlike the lower two members, the WMM is highly variable in thickness (<0.5 to 165 m) and lithology. Its basal contact is usually sharp, commonly associated with significant erosion in basin-slope settings and its strata consist of a wide range of fine- and coarse-grained, siliciclastic and carbonate deposits such as:

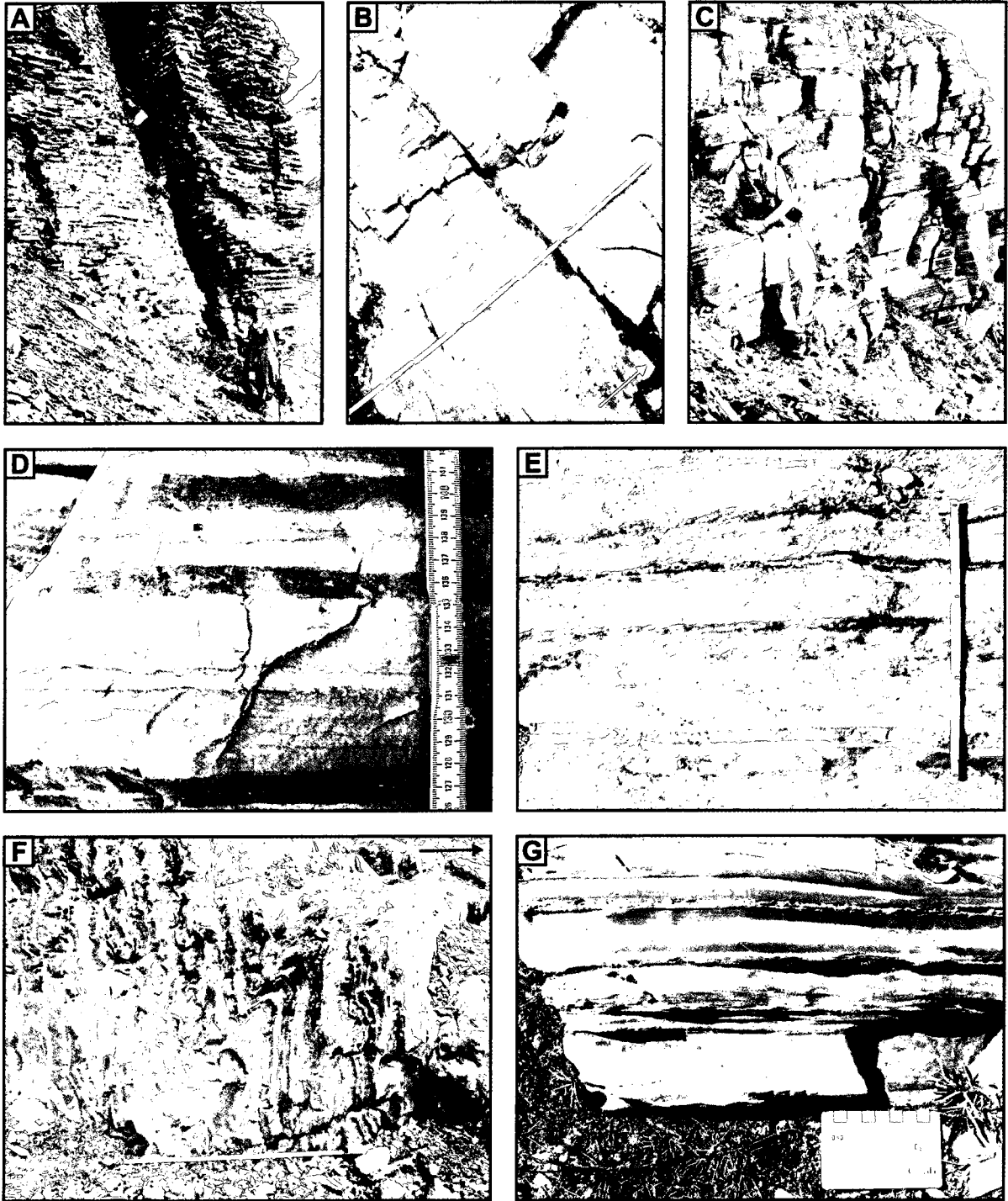


Figure 5.3: A) to F) Photos of distinctive TLM limestone-siltstone rhythmites from the southern Canadian Cordillera. A) LL1: purple siltstone and pink limestone. B) JP1: green siltstone and pink to grey limestone. Ruler is 100 cm. C) MR1: red-brown siltstone and white limestone. D) MR1: stratified Tbcd turbidites with pyrite. Ruler is 16 cm. E) CM1: grey siltstone and white to dark grey limestone. Ruler is 50 cm. F) PM1: red-brown siltstone and dark grey limestone. Ruler is 50 cm. G) Photo of WMM dark grey limestone interbedded with quartz-rich siliciclastics. Arrows indicate stratigraphic upward direction.

diamictite, breccia, conglomerate, mudstone, siltstone, sandstone, calcareous arenite, arenaceous limestone and limestone (TOC up to 5%). Deposition of the WMM occurred in submarine canyons that developed on the slope and acted as conduits to direct sediment-gravity flows (e.g. turbidity currents, debris flows) downslope and onto the basin-floor. The upper part of the WMM consists of texturally and mineralogically mature quartzose clastic rocks and limestone implying derivation from a mixed siliciclastic-carbonate upslope sediment staging area (Fig. 5.3G).

Organic-rich mudstone of the GSM has been dated at 607.8 ± 4.7 Ma (Kendall et al., 2004) placing it in the Ediacaran Period (Knoll et al., 2004, 2006). The OFP is interpreted to have principally accumulated during a eustatic rise related to glacial melting with the GSM representing a deep-water condensed section (Ross and Murphy, 1988; Ross et al., 1995; Chapter 3). Moreover, it is interpreted to be a post-glacial deep-water succession that correlates with cap carbonate strata overlying glaciogenic diamictite exposed in the Canadian Cordillera (e.g. Aitken, 1991a, b; Narbonne et al., 1994; Ross et al., 1995; McMechan, 2000; James et al., 2001; Hoffman and Halverson, submitted). This broad correlative link is based primarily on regional stratigraphic relationships and the consistent presence of carbonates with distinctive bladed calcite crystals (Ross et al. 1995; Chapter 3). Although there are no absolute age constraints from the glacial to post-glacial strata in the Mackenzie Mountains, northern Canadian Cordillera, the succession is globally correlated to ca. 635 Ma Cryogenian to Ediacaran strata based on the physical and isotopic similarities (e.g. James et al., 2001; Hoffman et al., 2007; Hoffman and Halverson, submitted). Because the OFP is inferred to be correlative to units in the Mackenzie Mountains, the ~608 Ma data is thought to represent a minimum timing deposition, rather than an absolute age constraint. There are no published paleogeographic constraints for the OFP, but a low-latitude position is suggested based on paleomagnetic data obtained from Neoproterozoic sedimentary rocks in the Mackenzie Mountains, Northwest Territories (Park, 1997), and that most tectonic

reconstructions place Laurentia near the equator at this time (e.g. Moores, 1991; Dalziel, 1991; Karlstrom et al., 1999; Wingate et al., 2002).

5.4 SAMPLING AND ANALYTICAL METHODS

This research is based on fieldwork conducted on the OFP in six separate regions of Alberta and British Columbia in the southern Canadian Cordillera (Fig. 5.1). Measured sections with accompanying sedimentologic and stratigraphic characteristics of the OFP and its three constituent members have been presented in detail elsewhere (Chapter 3). This study focuses on the physical, chemical and stable isotopic ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$) characteristics of the carbonate units, with most of the data derived from samples of the lower two members (TLM and GSM). A total of 125 representative petrographic thin sections were examined after staining with a combined Alizarin Red-S and potassium ferricyanide solution (Dickson, 1966). Additional stable isotopic analyses from the OFP of $\delta^{13}\text{C}$ from organic residue and $\delta^{34}\text{S}$ from pyrite were also obtained.

Quantitative chemical analyses of Ca, Mg, Fe, Mn, Sr and Si were performed on 26 carbon-coated, polished thin sections using an automated 4 spectrometer Camebax MBX electron microprobe by wavelength dispersive x-ray analysis (WDX) at Carleton University. The operating conditions for the carbonates were set at an accelerating potential of 15 kV, beam current of 15 nA and a beam diameter of approximately 10 μm to minimize beam damage to the sample. Peak counting time for each analyzed element was set at 20 to 40 seconds. Raw data were converted to elemental weight % by the Cameca PAP matrix correction program. Calibration standards were a suite of well-characterized natural minerals (USNM) with detection limits for each element as follows: Ca 0.02 wt%; Mg 0.015 wt%; Fe 0.03 wt%; Mn 0.04 wt%; Sr 0.03 wt%; and Si 0.02 wt%. Digital back scatter electron (BSE) images were collected with a Lamont 4-element solid state BSE detector.

All stable isotopic analyses in this study were conducted at the G. G. Hatch Stable Isotope Laboratory, Department of Earth Sciences, University of Ottawa. Sample powders selected for carbon and oxygen isotopic analyses were microdrilled from thin section stubs or derived from small chip fragments of unweathered, fresh material pulverized in a ceramic ring mill. Depending on the percentage of detrital silicate component, powders of calcite and dolomite ranging from 0.5 to 10 mg were reacted for 24 hours with 0.1 mL of anhydrous 100% phosphoric acid in an exetainer flushed and filled with helium off-line. Calcite samples were reacted at 25.0°C and dolomite at 50.0°C. The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values were analyzed online using an automated Thermo Finnigan Gasbench continuous flow sampler that delivered exetainer headspace CO_2 directly to a Thermo Finnigan DeltaPlus XP isotope ratio mass-spectrometer (IRMS). Carbon and oxygen isotope values were calibrated using the international NBS19 standard and the compositions reported use the standard ‰ notation in units of ‰ relative to the PDB standard. Analytical precision (2σ) for the data is $\pm 0.1\text{‰}$ with duplicate $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analyses generally within $<0.1\text{‰}$.

For organic carbon, fresh, unweathered chip fragments were pulverized in a ceramic ring mill and treated with HCl to remove carbonate prior to $\delta^{13}\text{C}$ isotopic analyses for organic carbon. Sample powders from 1 to 50 mg (based on %C) were weighed out into tin capsules. The isotopic composition of organic carbon is determined by the analysis of CO_2 produced by flash combustion at 1800°C on an Elementar VarioEL III elemental analyzer (EA) followed by gas chromatograph separation and on-line analysis by continuous-flow with a Thermo Finnigan DeltaPlus Advantage IRMS via a ConFlo II interface. Analytical precision (2σ) for the data is $\pm 0.20\text{‰}$ with duplicate $\delta^{13}\text{C}$ analyses within $<0.1\text{‰}$.

Hand-picked, pure pyrite separates (single and multi-crystal) were selected for sulfur isotopic analyses. Pyrite was pulverized with an agate mortar and pestle and cleaned in dilute nitric acid in between samples to avoid contamination. Approximately 0.2 mg of weighed sample was mixed with an equal amount of

tungsten oxide (WO₃), placed in a tin capsule and flash combusted at 1800°C to release SO₂ gas. SO₂ was separated by the “purge and trap” method on the VarioEL III EA, and subsequently carried with helium for the isotopic ratio measurements using a Thermo Finnigan DeltaPlus IRMS. Sulfur isotopic compositions are reported using standard δ notation in units of ‰ relative CDT (Canyon Diablo Troilite) standard. Analytical precision (2 σ) for the data is ± 0.20 ‰ with duplicate $\delta^{34}\text{S}$ analyses generally within <0.5 ‰.

5.5 PETROGRAPHY AND GEOCHEMISTRY

Based on petrographic and geochemical work the OFP contains a number of regionally identifiable calcite and dolomite phases that define a consistent regional carbonate paragenetic framework. The different mineral phases demonstrate that detrital, diagenetic and metamorphic carbonates are within the OFP.

Electron microprobe chemical analyses of all OFP carbonate phases are located in Appendix J with a summary of the chemical compositions presented in Table 5.1. Elemental compositions of the carbonate phases are displayed in an Mg – Ca – Fe ternary diagram (Fig. 5.4) with additional elemental cross-plots of calcite (Fig. 5.5A to E) and dolomite (Fig. 5.5F to H). Overall, calcite phases ($n = 285$) in OFP strata show low and consistent Mg (range: 0.14 to 3.90 mol%); with variable Fe (range: b.d. to 3.20 mol%), and Mn (range: b.d. to 2.60 mol%) concentrations. Both Fe and Mn reflect diagenetic influences. Sr contents are generally low (<1000 ppm), although local or stratal enrichments are recorded (up to 4397 ppm).

5.5.1 Calcite 1 (CC1)

Calcite 1 (CC1) is the earliest calcite phase in the limestone units of the OFP. It is the primary detrital component observed in all three members of the OFP, and represents resedimented material sourced from a more upslope location. It is observed in calcite-rich turbidites of the TLM and WMM, in addition to the

Phase	CC1 (n = 55)		CC2 - TLM (n = 80)		CC2 - WMM (n = 9)		CC3 (n = 85)		CC4 (n = 38)	
	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Element										
CaCO ₃	96.14	99.15	93.07	98.52	94.34	96.30	93.79	99.52	96.64	99.23
FeCO ₃	b.d.	0.70	0.06	2.38	1.43	3.20	0.04	2.53	0.14	1.64
MnCO ₃	b.d.	0.81	0.06	1.60	b.d.	0.51	0.05	2.47	0.15	0.72
MgCO ₃	0.64	3.48	0.43	3.90	1.44	1.86	0.14	2.25	0.29	1.91
Sr (ppm)	b.d.	507	b.d.	1607	2621	4313	b.d.	2283	b.d.	4397

Phase	DOL1 (n = 7)		DOL2 (n = 59)		ANK (n = 5)		BLD CC (n = 8)		BLD CCm (n = 10)	
	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Element										
CaCO ₃	49.61	55.63	48.63	55.33	50.78	51.58	96.52	98.04	94.85	97.36
FeCO ₃	0.13	2.15	5.36	19.26	26.42	38.80	0.00	0.46	0.40	1.54
MnCO ₃	b.d.	0.61	0.26	4.32	0.56	0.96	0.00	0.23	1.22	2.60
MgCO ₃	42.97	49.78	28.51	41.91	9.32	21.52	1.75	3.27	0.83	2.10
Sr (ppm)	b.d.	85	b.d.	1099	b.d.	b.d.	b.d.	592	b.d.	254

Table 5.1: Minimum (min.) and maximum (max.) values for carbonate phases of the OFP from electron microprobe analyses. n = number of analyses; b.d. = below detection limit.

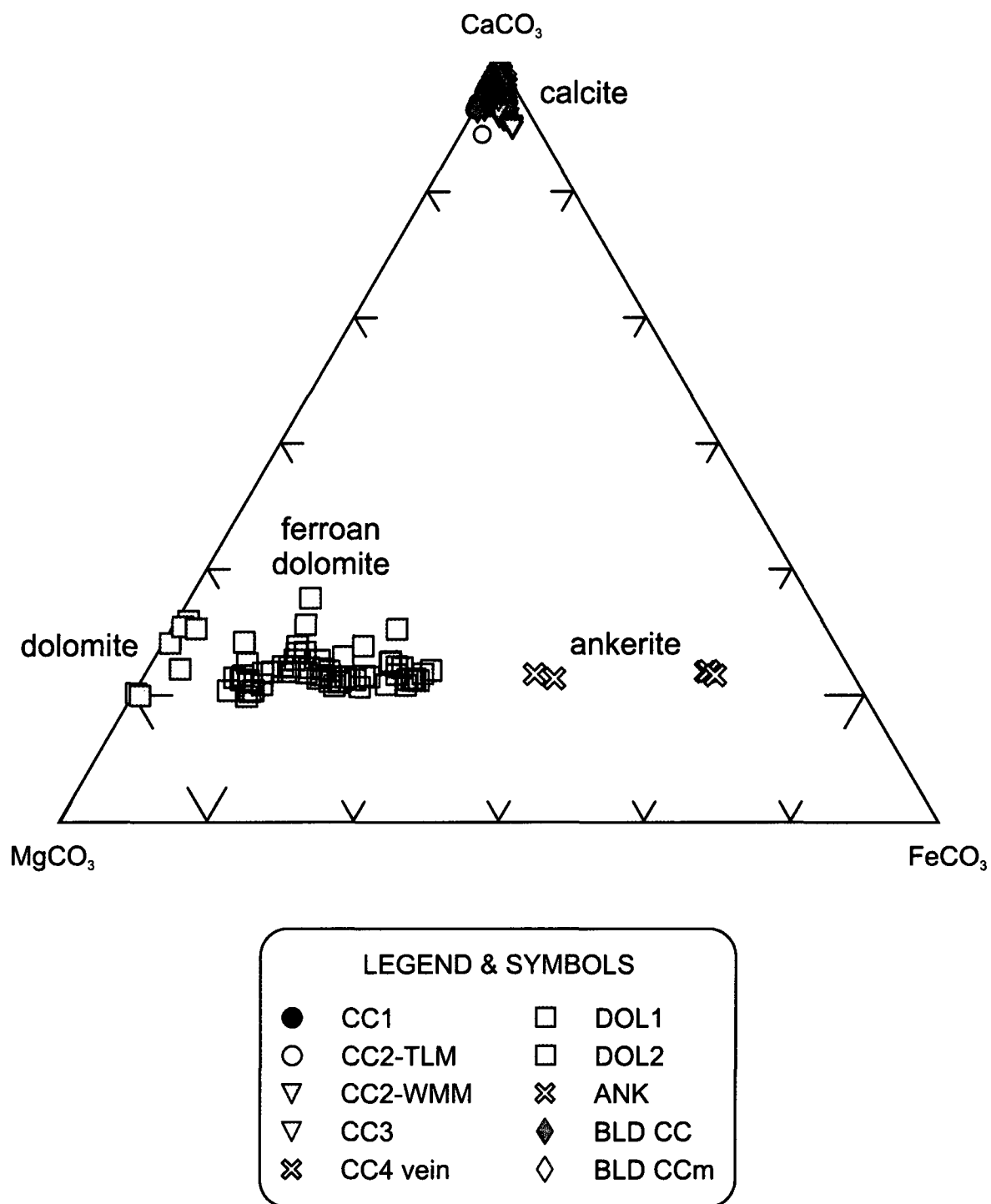


Figure 5.4: Ternary diagram illustrating mineralogical compositions in MgCO_3 - CaCO_3 - FeCO_3 space of OFP carbonate phases analyzed on the electron microprobe. Note that only the upper 60% of the diagram is displayed.

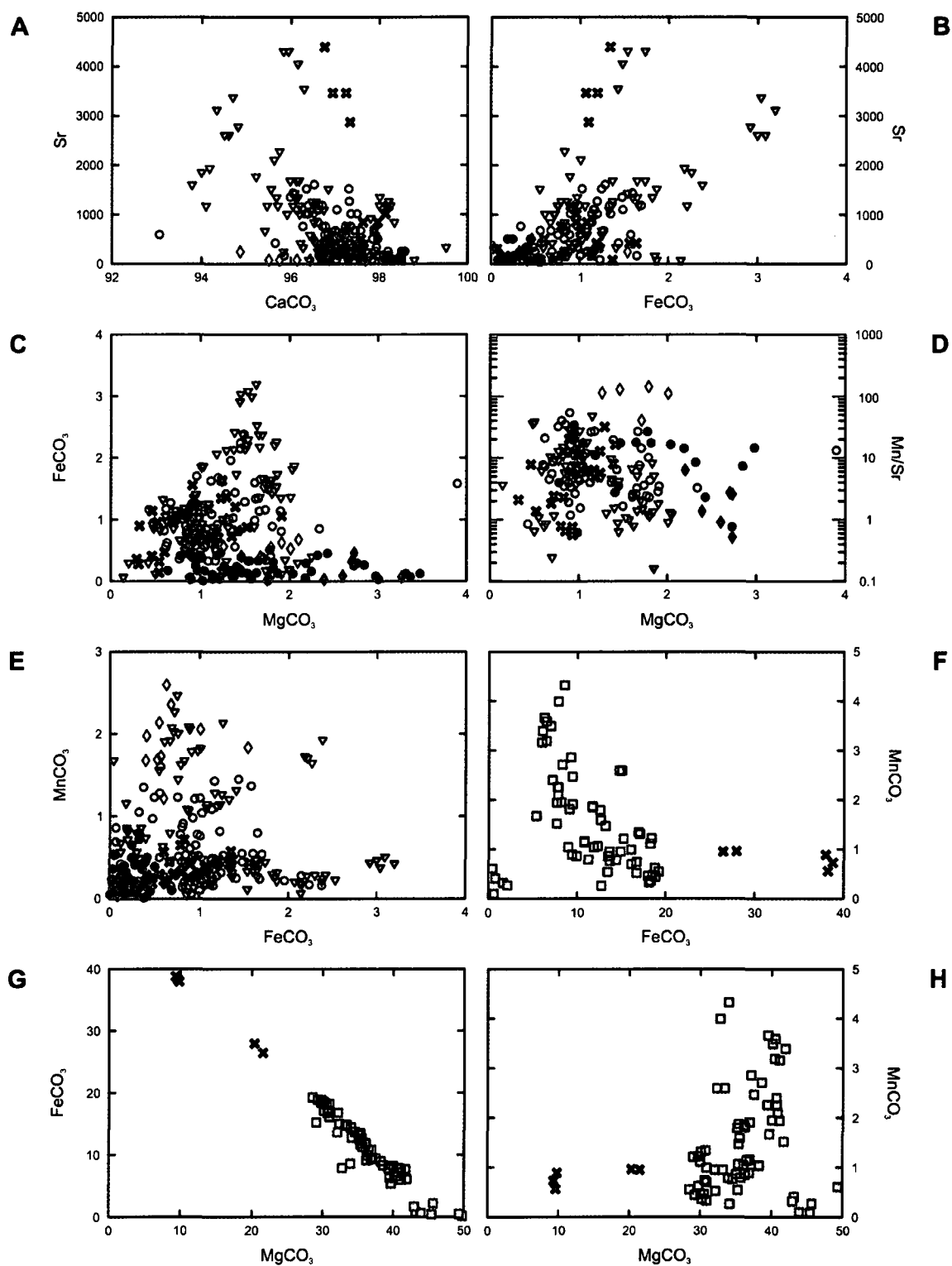


Figure 5.5: A) to E) Elemental cross-plots of calcite phases. A) CaCO₃ vs. Sr. B) FeCO₃ vs. Sr. C) MgCO₃ vs. FeCO₃. D) MgCO₃ vs. Mn/Sr. E) FeCO₃ vs. MnCO₃. F) to H) Elemental cross-plots of dolomite and ankerite phases. F) FeCO₃ vs. MnCO₃. G) MgCO₃ vs. FeCO₃. H) MgCO₃ vs. MnCO₃. Legend is the same as in Figure 5.4.

suspension deposits in all three members. CC1 is non-ferroan and consistently associated with calcite 2 (CC2) (Fig. 5.6A to F). However, in BSE images from purple-coloured TLM limestone rhythmite strata at low metamorphic grade (LL, JP), CC1 can be differentiated from CC2 (Fig. 5.7A and B). In these sections, the two have a mottled texture reflecting their different chemical composition. CC1 is sub-rounded, darker patches of silt-sized microsparite (usually >5 to 20 μm). Generally, it has indistinct crystal boundaries and is relatively inclusion-rich containing detrital minerals, hematite (purple units) or pyrite (green, red-brown, grey or black units). With increasing stratigraphic height (upper TLM, GSM and WMM), CC1 is pervasively recrystallized to pseudospar CC2, and is only identifiable by BSE as “dark spots” (Fig. 5.7C to H).

Chemical analyses of the darker zones on the BSE ($n = 55$) show that CC1 (closed red circles) is generally characterized by low trace-element concentrations: MgCO_3 from 0.64 to 3.48 mol%; FeCO_3 from b.d. to 0.70 mol%; MnCO_3 from b.d. to 0.81 mol%; and Sr from b.d. to 507 ppm. Samples with elevated Fe and Mn contents may have resulted from contamination by detrital minerals (e.g. chlorite) or CC2 because of the required beam width (10 μm).

5.5.2 Calcite 2 (CC2)

Calcite 2 (CC2) forms a mosaic of irregular, anhedral crystals of recrystallized sparite (20 to 60 μm) with noticeably fewer inclusions compared to CC1 (Fig. 5.7C to H). Local inclusions (1 to <10 μm) of pyrite or hematite are present. In general, CC2 has indistinct boundaries, shows no zoning and has a poikilotopic texture which envelopes CC1; however, these CC1-CC2 boundaries are poorly defined as opposed to distinctive overgrowth zoning. Local TLM breccia units (i.e. slump, slide or debris flow deposits) contain cohesive limestone clasts composed of CC1 and CC2, suggesting that CC2 cementation was early, and prior to the collapse and resedimentation episode. Recrystallization of CC1 by CC2 becomes more pervasive upward in the TLM, with complete diagenetic recrystallization in dark, organic-rich

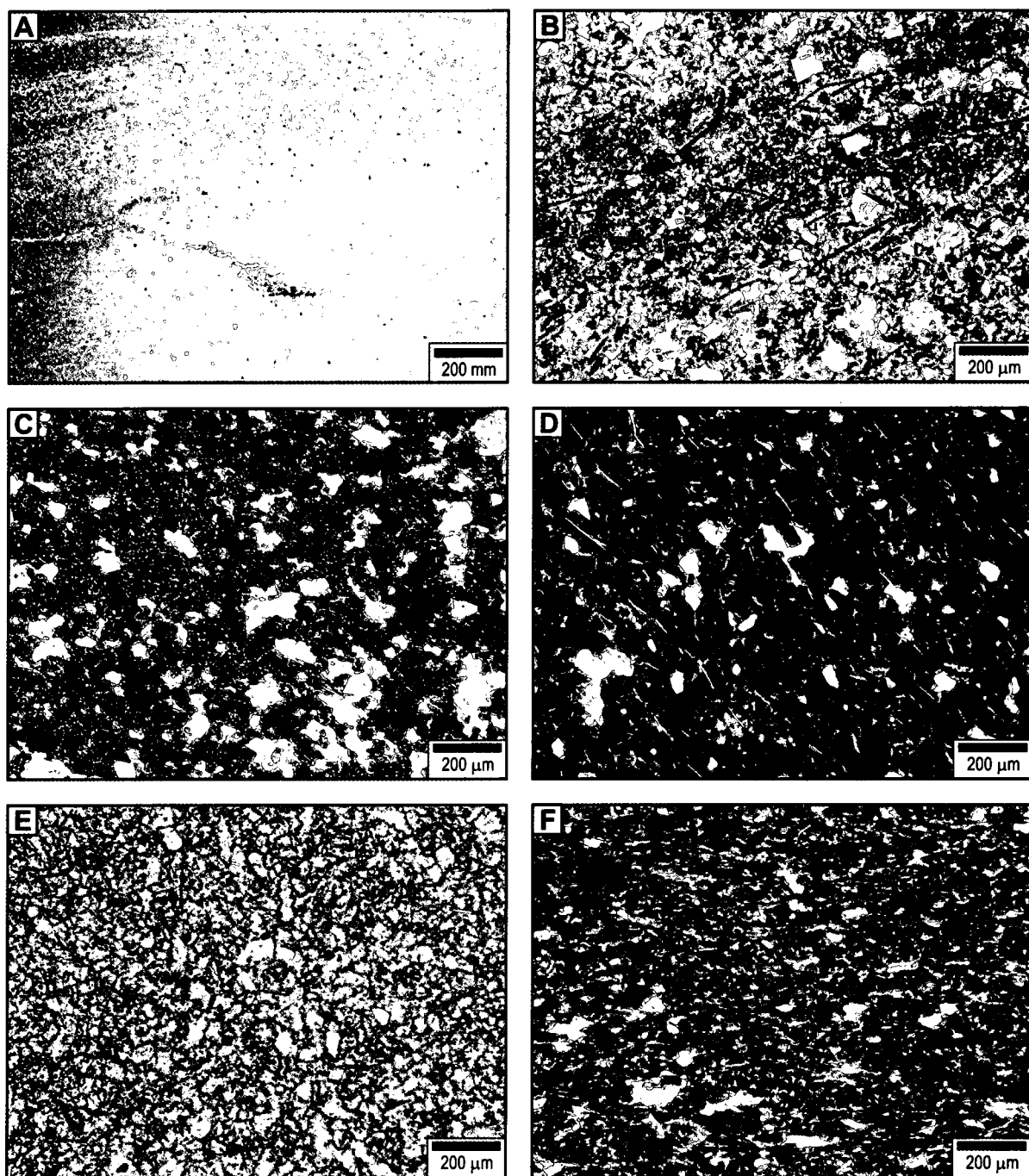


Figure 5.6: A) to F) Representative stained thin sections photomicrographs of CC1 and CC2. Pink to red coloured staining indicated iron-poor calcite phases and purple to royal blue staining indicates iron-rich calcite phases. A) LL5: TLM. B) LL1: TLM. C) JP1: TLM. D) MR1: TLM. E) JP1: GSM. F) CM1: GSM.

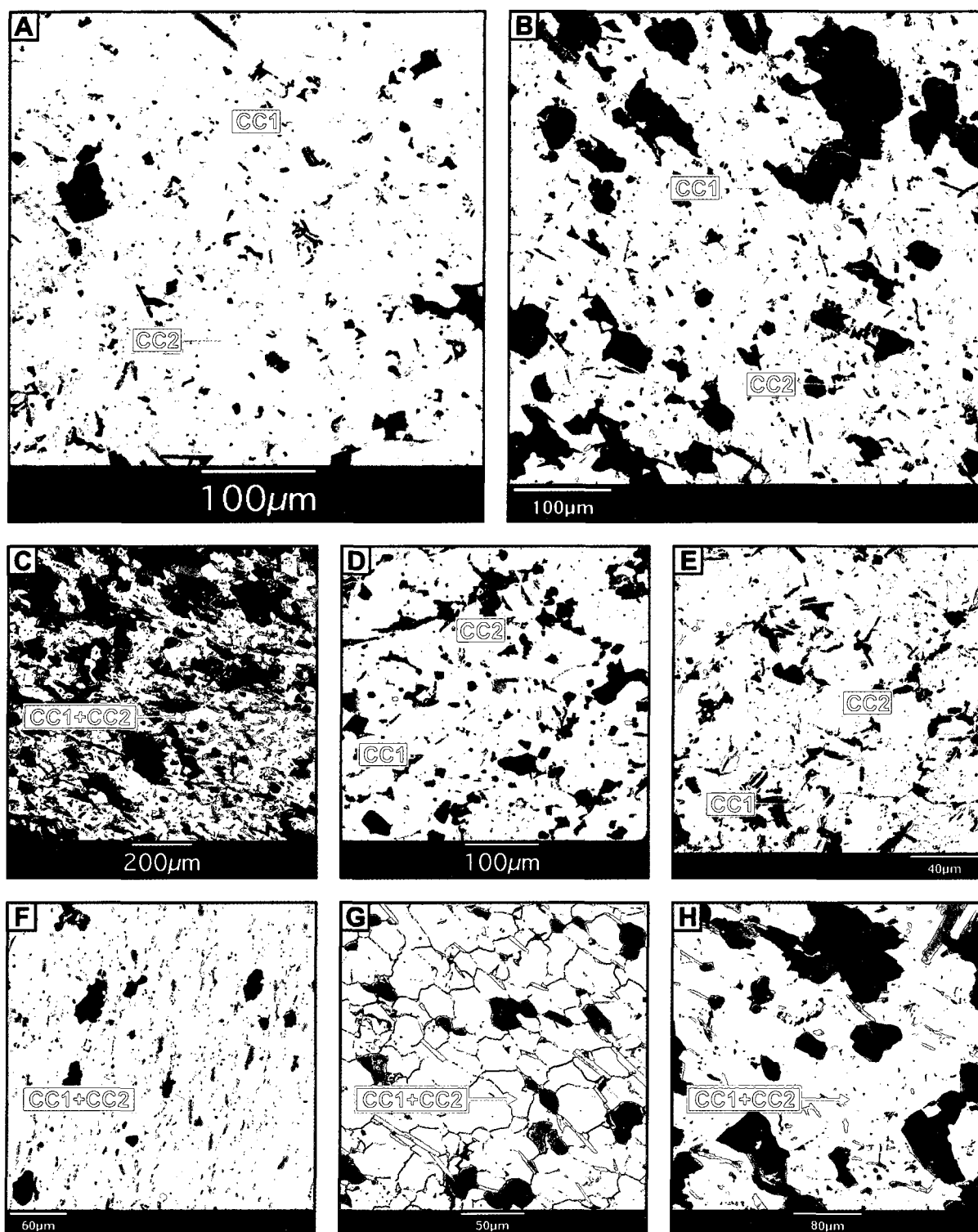


Figure 5.7: A) to H) Representative backscatter electron (BSE) images of carbonate phases CC1 (dark) and CC2 (light) from limestone units of the OFP. A) LL1: TLM. B) JP1: TLM. C) MR1: TLM. D) LL1: GSM. E) JP1: GSM. F) MK1: WMM. G) CM1: TLM. H) CM1: WMM. Note the increasing degree of recrystallization (diagenetic) with increasing stratigraphic height (TLM → GSM → WMM) and metamorphic grade (east to west: LL → JP → MR → MK → CM)

limestone units of the WMM (CC2-WMM) where the two phases form a sparite framework (30 to 90 μm). Also within the lower portions of the TLM, CC1 + CC2 become pervasively recrystallized with increasing metamorphic grade towards the west.

Chemical analyses of the TLM limestone rhythmites ($n = 80$) show that CC2 (open red circles) is characterized by low and consistent Mg (range: 0.43 to 3.90 mol%) whereas it is relatively enriched compared to CC1 in Fe (range: 0.06 to 2.38 mol%) and Mn (range: 0.06 to 1.60 mol%). CC2 also exhibits locally elevated Sr contents up to 1607 ppm. In the WMM limestone beds ($n = 9$), the recrystallized CC1 + CC2 (open red upside-down triangles) show a narrow range of Mg (range: 1.44 to 1.86 mol%) and low Mn (range: b.d. to 0.51 mol%). However, Fe (range: 1.43 to 3.20 mol%) and Sr (range: 2621 to 4313 ppm) contents are enriched compared to the TLM CC2. In comparison to CC1, CC2 displays a number of distinctive trends with respect to its trace-elements: enrichment of MnCO_3 ; co-enrichment of MnCO_3 and FeCO_3 ; or enrichment of FeCO_3 (Fig. 5.5E). FeCO_3 and Sr also appear to exhibit co-enrichment trends (Fig. 5.5B).

5.5.3 Calcite 3 (CC3)

Calcite 3 (CC3) is a non-ferroan to ferroan cement phase, and is ubiquitous within siliciclastic units of the OFP (Fig. 5.8A to C). It is absent in the basal parts of the TLM and certain immature fine-grained units in the WMM, but is the dominant cement phase throughout the remainder of the succession, commonly in the coarser-grained units (breccia and conglomerate). It is composed of irregular, anhedral crystals that range from 20 to 200 μm and form a poikilotopic texture. The morphology and degree of cementation is directly influenced by the detrital grain-size of the siliciclastic unit. In some BSE images, CC3 is non-ferroan in the centre of the crystal and becomes more ferroan outward (Fig. 5.9A and B). The non-ferroan, darker patches on the BSE may be recrystallized CC1. CC3 has minor detrital mineral inclusions, in addition to local inclusions (1 to <100 μm) of diagenetic barite,

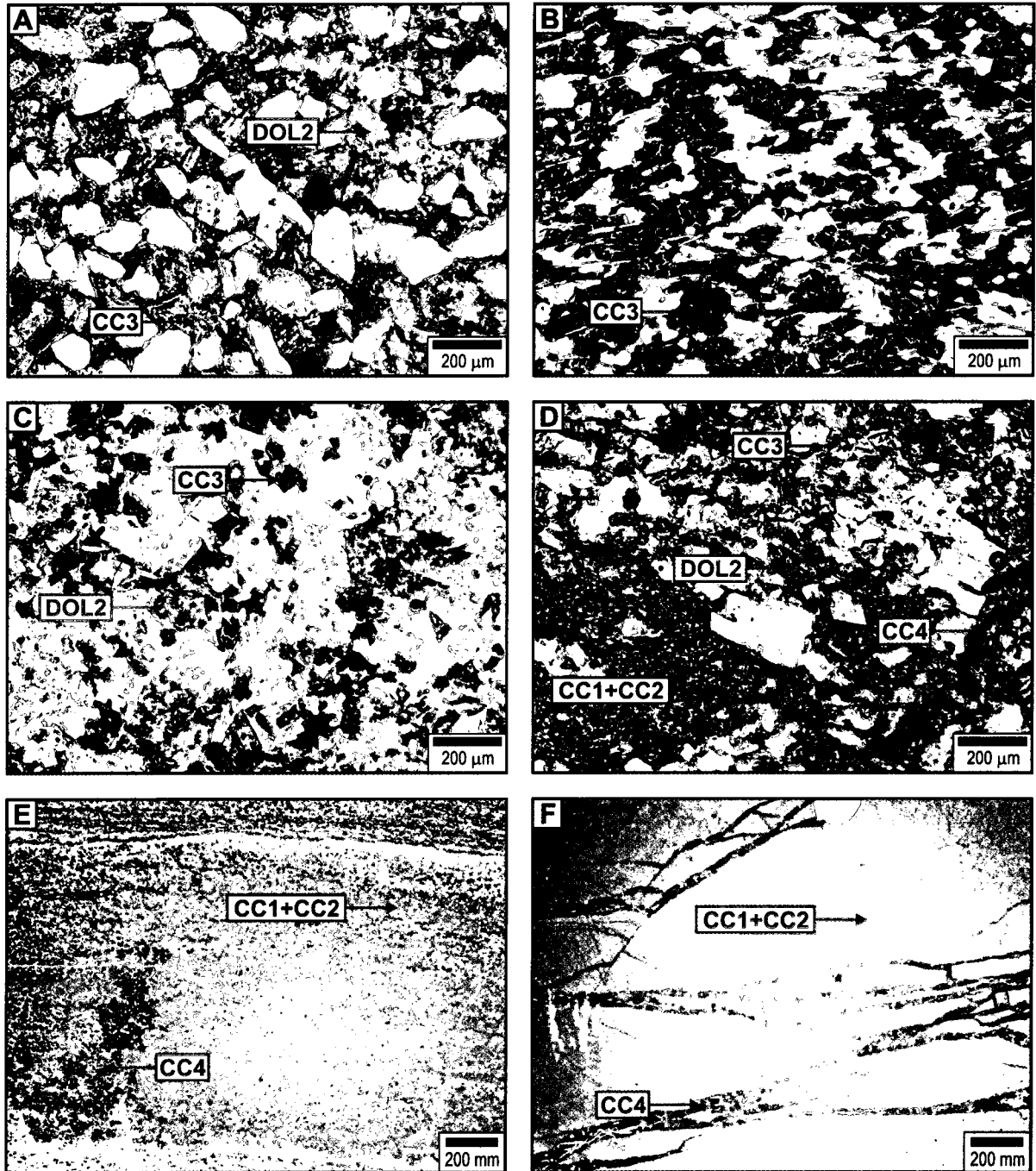


Figure 5.8: A) to C) Representative stained thin section photomicrographs of carbonate cement phase CC3. Pink to red coloured staining indicated iron-poor calcite phases, purple to royal blue staining indicates iron-rich calcite phases, no staining indicates iron-poor dolomite and light blue to turquoise staining indicates iron-rich dolomite. A) LL5: TLM. B) CM1: TLM. C) LL1: TLM, note replacement of DOL2 by CC3. D) to F) Representative stained thin section photos of cross-cutting vein CC4. D) LL1: TLM, CC4 cuts across clasts of CC1 + CC2 and breccia matrix where DOL2 is replaced by CC3. E) LL1: TLM. F) LL1: TLM.

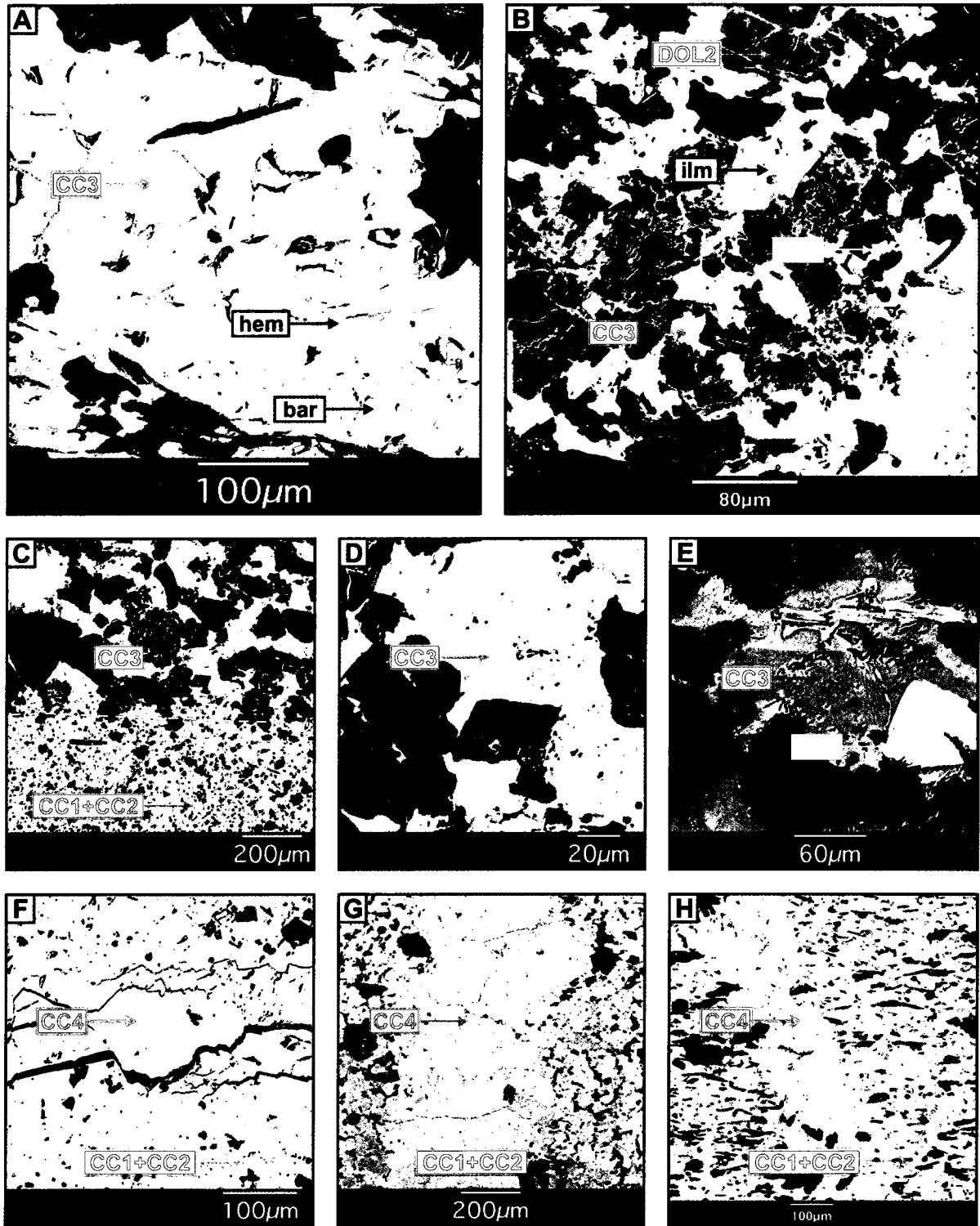


Figure 5.9: A) to E) Representative BSE images of CC3. A) LL1: TLM, diagenetic barite and hematite present. B) LL1: TLM, replacement of DOL2 by CC3 and corrosion of former ilmenite grain. C) LL5: TLM, contact between mud- to silt-sized calcite-rich suspension fallout bed (CC1 + CC2) and overlying very fine sand-sized siliciclastic bed deposited by tractional processes and cemented by CC3. D) and E) LL5: TLM, CC3 zonation. F) to H) Representative BSE images of cross-cutting vein CC4 phase. F) LL1: TLM. G) LL1: GSM. H) CM1: GSM.

pyrite or hematite (also filamentous hematite, see Fig. 5.11H). CC3 is commonly observed replacing dolomite 2 (DOL2) and the two are the principal cements in siliciclastic strata. In these strata, CC3 has also corroded the margins of detrital quartz, feldspar and heavy mineral grains.

Trace-element concentrations of CC3 ($n = 85$) (closed red upside-down triangles) are similar to CC2: MgCO_3 from 0.14 to 2.25 mol%, FeCO_3 from 0.04 to 2.53 mol%; MnCO_3 from 0.05 to 2.47 mol%; and Sr contents up to 2283 ppm. Similar to CC2, CC3 exhibits MnCO_3 , MnCO_3 and FeCO_3 or FeCO_3 enrichment trends as well as two separate trends between FeCO_3 and Sr.

5.5.4 Calcite 4 (CC4)

Calcite 4 (CC4) is a relatively late-stage, generally ferroan vein phase, which cross-cuts CC1 + CC2, CC3 and DOL2 (Fig. 5.8D to F). It comprises a mosaic of anhedral to subhedral crystals of sparite (75 to 500 μm) that form a moderately sharp boundary with the surrounding material (Fig. 5.9F to H). It is also relatively inclusion-free, although rare hematite is observed.

Chemical analyses of CC4 veins ($n = 38$) (open purple inclined cross) show that it is similar to both CC2 and CC3 phases: MgCO_3 from 0.29 to 1.91 mol%; FeCO_3 from 0.14 to 1.64 mol%; MnCO_3 from 0.15 to 0.72 mol%; and Sr locally up to 4397 ppm.

5.5.5 Dolomite 1 (DOL1)

Only in BSE images of two polished thin sections was a non-ferroan dolomite 1 (DOL1) phase identified in OFP siltstone (Fig. 5.11A). Crystals are euhedral to subhedral, 20 to 40 μm , with abundant detrital inclusions that form the core for well-zoned overgrowths with distinct boundaries of dolomite 2 (DOL2). The relatively intact rhombohedral shape of DOL1 may indicate that is a detrital rather than early cement phase, but its rare presence makes it difficult to interpret with certainty.

Chemical analyses of DOL1 ($n = 7$) (closed blue square) show that it is nearly stoichiometric with an average Mg/Ca ratio of 0.87 (range: 0.78 to 0.99) and low trace-element concentrations of FeCO_3 (range: 0.13 to 2.15 mol%), MnCO_3 (range: b.d to 0.61 mol%) and Sr (range: b.d. to 85 ppm).

5.5.6 Dolomite 2 (DOL 2)

Dolomite 2 (DOL2) is a ferroan dolomite mainly in immature siliciclastic strata of the OFP, but also uncommonly in impure TLM limestone strata (Fig. 5.10A to F). It is an intergranular diagenetic cement that ranges from 20 to 200 μm depending on the grain-size and pore-space of the host rock. Crystals are typically subhedral, although well developed euhedral rhombs are frequently preserved. Chemical zoning is common with alternating Fe-poor and Fe-rich layers. DOL2 is observed as overgrowths on DOL1, and is replaced by CC3 where the two are found together. Inclusions of detrital minerals, hematite or pyrite are common.

DOL2 ($n = 59$) (closed blue squares) is characterized by a relatively wide range of MgCO_3 from 28.51 to 41.91 mol%, FeCO_3 from 5.36 to 19.26 mol% and MnCO_3 from 0.26 to 4.32 mol%. Sr contents are up to 1099 ppm. FeCO_3 displays good negative correlation with both MgCO_3 ($\rho = 0.962$) and MnCO_3 ($\rho = 0.743$) implying Mg and Mn replacement by Fe.

5.5.7 Ankerite (ANK)

Where observed in BSE images, ankerite (ANK) is as a series of late-stage overgrowths on coarser ferroan DOL2 crystals in OFP siliciclastic units. It is in remnant porosity not filled by the main diagenetic cements such as DOL2 or CC3.

Chemical analyses ($n = 5$) (open blue inclined cross) show that it is characterized by: MgCO_3 from 9.32 to 21.52 mol%; FeCO_3 from 26.42 to 38.80 mol%; and MnCO_3 from 0.56 to 0.96 mol%.

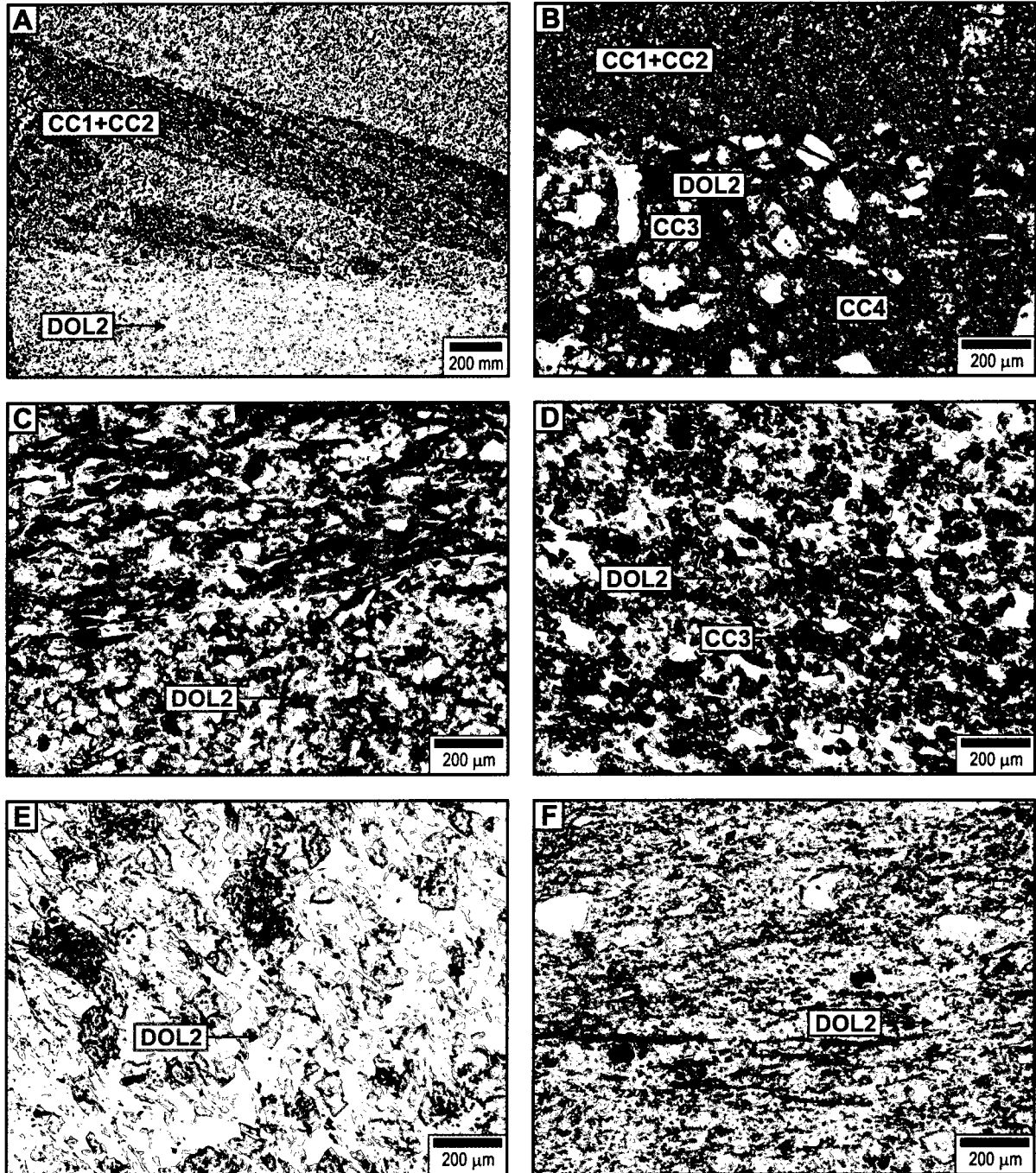


Figure 5.10: A) to F) Representative stained thin section photomicrographs of dolomite (DOL2) from the OFP. Pink to red coloured staining indicated iron-poor calcite phases, purple to royal blue staining indicates iron-rich calcite phases, no staining indicates iron-poor dolomite and light blue to turquoise staining indicates iron-rich dolomite. A) JP1: TLM, DOL2 cementation in siliciclastic-dominated parts of turbidite beds (both lower and ripple-stratified upper bed). B) LL1: TLM, DOL2 is replaced by CC3 between clasts of CC1 + CC2. C) LL5: TLM, DOL2 crystal size and degree of cementation is controlled by grain-size of siliciclastic matrix. D) MR1: TLM, DOL2 replaced by CC3. E) CM1: TLM. F) LL4: WMM.

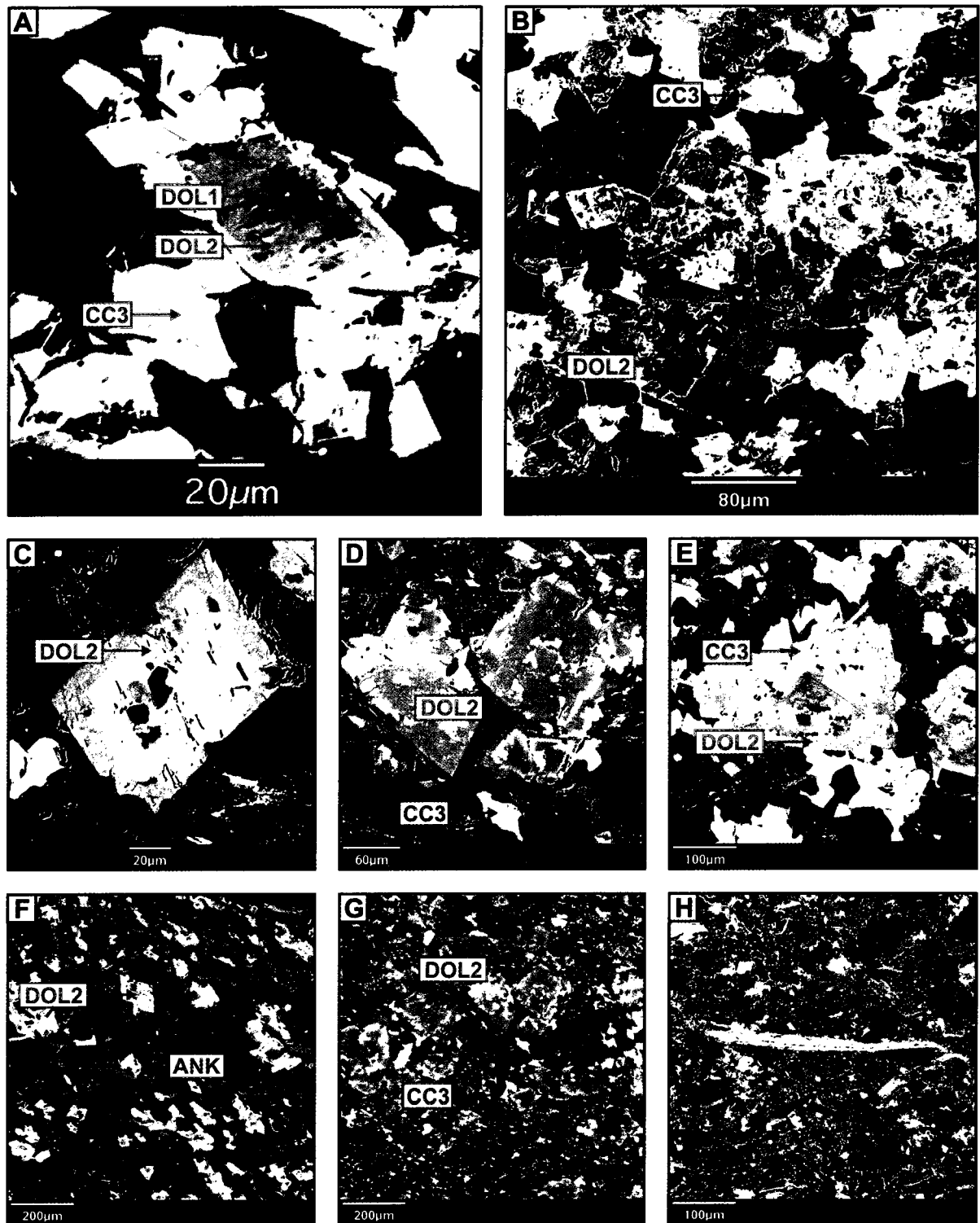


Figure 5.11: A) to G) Representative BSE images of dolomite phases from the OFP. A) MR1: TLM, DOL1 core replaced by DOL2, which is then replaced by CC3. B) LL1: TLM, replacement of DOL2 by CC3. C) JP1: TLM, euhedral DOL2 displaying zonation. D) - E) JP1: TLM, DOL2 replacement by CC3. F) MR1: TLM, ANK rims encompassing DOL2 crystals. G) LL5: TLM, DOL2 replacement by CC3. H) LL5: TLM, large filament of diagenetic hematite.

5.5.8 Clasts of bladed-calcite crystal limestone (BLD CC)

Within WMM breccia and conglomerate units are clasts of locally derived OFP strata and shallow-marine carbonate (SMC) lithologies eroded from an upslope source. Clasts include ooid limestone, swaley cross-stratified micritic dolostone, microbial-laminated dolostone, sandy dolostone and rare bladed-calcite crystal limestone (Fig. 5.12A) similar to that observed in the post-glacial Hayhook Formation, Mackenzie Mountains (e.g. Aitken, 1991; James et al., 2001) and other Neoproterozoic successions (e.g. Hoffman and Schrag, 2002; Lorentz et al., 2004). Crystals in the Hayhook Formation are interpreted to be neomorphosed aragonite that originally precipitated at or just below the seafloor and grew upward in the water column; or as syn-sedimentary replacement of stromatolites (James et al., 2001).

Within the clasts of the WMM, the bladed-calcite crystals are elongate, 1 to 4 mm long by about 1 mm wide, have an easily identifiable basal structure, and are in laminae as small palisades or as a poorly developed mm-scale “fan” (Fig. 5.12B to D). Each blade consists of a mosaic of anhedral sparite (20 to 100 μm), but unfortunately, no obvious relict textures such as hexagonal shapes indicative of neomorphosed aragonite were observed (e.g. Sandberg, 1985). BSE images show a mottled crystal texture from an inclusion-rich non-ferroan phase (darker), which is irregularly rimmed along its margins by a calcite phase enriched in heavier trace-elements (lighter) (Fig. 5.12E to G). The basal structure of the bladed-calcite crystals are distinctively situated slightly below the surface of the bed on which it grew, suggesting that crystal growth likely initiated just below the sediment-water interface. Each lamina of crystal growth created subtle sea-floor topography and coincided with episodes of negligible deposition. Blades are separated by an infill of silt-sized detritus of quartz, mica and heavy accessory minerals interpreted to have settled from suspension and accumulated between the blades growing on the seafloor. Subsequently, crystal growth was terminated by burial beneath a calcite-rich turbidite remarkably similar in texture and mineralogy to limestone of the

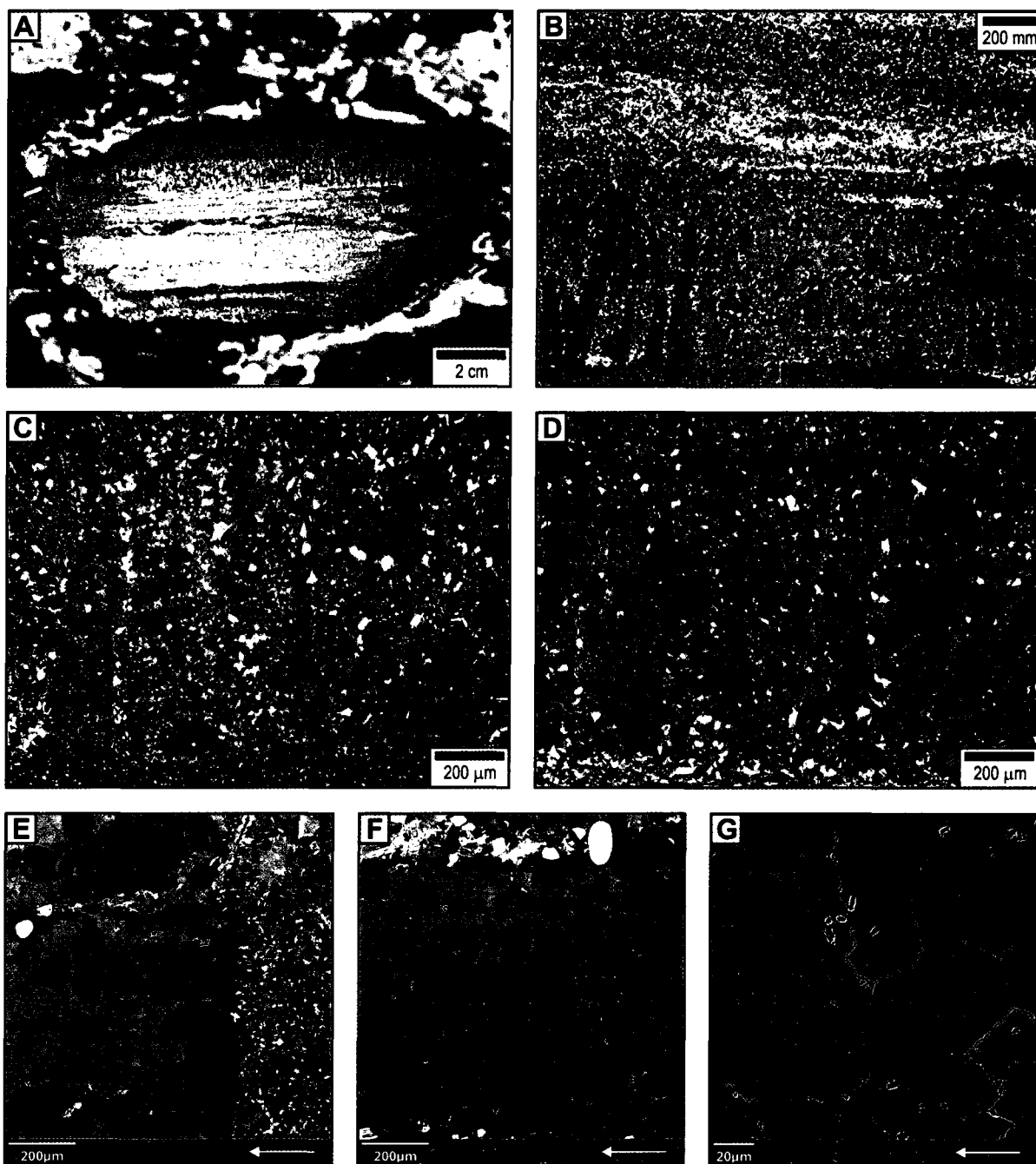


Figure 5.12: Representative images from clasts of bladed-calcite crystal limestone in WMM breccia at LL4. A) Clast in outcrop. Photo courtesy of G. M. Ross. B) to D) Stained thin section photomicrographs showing bladed and “fan” morphology with infilling of siliciclastic detritus between the blades. Pink to red coloured staining indicated iron-poor calcite phases. E) to G) BSE images showing mottled texture within bladed calcite crystals. Arrows indicate stratigraphic-upward direction in BSE images.

TLM. Similar to siltstone beds of the TLM limestone rhythmites, a later ferroan calcite phase (CC3 equivalent) infilled the remnant porosity cementing the sediment.

Chemically, ($n = 8$) bladed-calcite crystals (BLD CC, closed purple diamonds) are characterized by a relatively higher MgCO_3 from 1.75 to 3.27 mol% compared to other OFP calcite phases, with low Fe (range: b.d to 0.46 mol%) and Mn (range: b.d. to 0.23 mol%). Sr contents are low and range from b.d. to 592 ppm, which contrasts some of the fans in the Hayhook Formation where Sr concentration is elevated (3300 to 3700 ppm) (James et al., 2001). Analyses ($n = 10$) of the margins (BLD CCm, open purple diamonds) of the crystals show relative enrichments in FeCO_3 (range: 0.40 to 1.54 mol%) and MnCO_3 (range: 1.22 to 2.60 mol%).

5.6 STABLE ISOTOPE RESULTS

Stable isotope data are presented in Tables 5.2, 5.3, 5.4 and 5.5. The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotopic compositions are from 303 new carbonate samples from this study and an additional 45 previously unpublished analyses (G. M. Ross, unpublished data) from the OFP (Table 5.2) and other WSG strata (Table 5.3). A total of 65 new samples of mudstone, siltstone and carbonate were analyzed for $\delta^{13}\text{C}$ from organic residue with an additional 17 previously unpublished analyses (G. M. Ross, unpublished data) from the OFP (Table 5.3). Additional $\delta^{13}\text{C}$ analyses of organic residue from other units in the WSG (G. M. Ross, unpublished data) are located in Appendix K. The $\delta^{34}\text{S}$ pyrite results include 65 new analyses and 20 previously published analyses (Ross et al., 1995) from the OFP (Table 5.4). At all locations, strata of the OFP experienced varying degrees of low-grade regional metamorphism. Thus, it is critical to evaluate each isotopic system to determine the degree of metamorphic modification, and then make an assessment of the depositional versus diagenetic carbonate phases.

Sample	Lct.	Unit	Phase	$\delta^{13}\text{C}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{PDB}}$
MDS04-052	LL1	TLM	CC1+CC2	-11.96	-15.92
MDS04-053	LL1	TLM	CC1+CC2	-11.92	-15.95
MDS04-054-1	LL1	TLM	CC1+CC2	-11.86	-15.83
MDS04-055	LL1	TLM	CC1+CC2	-11.59	-16.19
MDS04-056	LL1	TLM	CC1+CC2	-11.51	-16.12
MDS04-057	LL1	TLM	CC1+CC2	-11.05	-16.16
MDS04-058	LL1	TLM	CC1+CC2	-10.80	-16.14
MDS04-059	LL1	TLM	CC1+CC2	-10.60	-15.95
MDS04-060A	LL1	TLM	CC1+CC2	-10.39	-16.08
MDS04-061	LL1	TLM	CC1+CC2	-10.23	-16.46
MDS04-062	LL1	TLM	CC1+CC2	-10.02	-16.08
MDS04-063	LL1	TLM	CC1+CC2	-9.97	-16.03
MDS04-064	LL1	TLM	CC1+CC2	-10.20	-16.08
MDS04-066	LL1	TLM	CC1+CC2	-9.37	-16.63
MDS04-067	LL1	TLM	CC1+CC2	-9.05	-16.32
MDS04-068	LL1	TLM	CC1+CC2	-9.43	-15.65
MDS04-069	LL1	TLM	CC1+CC2	-9.72	-15.46
MDS04-070A	LL1	TLM	CC1+CC2	-9.50	-15.44
MDS04-071	LL1	TLM	CC1+CC2	-9.24	-15.70
MDS04-072	LL1	TLM	CC1+CC2	-9.06	-15.80
MDS04-073	LL1	TLM	CC1+CC2	-9.08	-15.83
MDS04-074	LL1	TLM	CC1+CC2	-9.35	-15.85
MDS04-075	LL1	TLM	CC1+CC2	-8.89	-16.09
MDS04-076	LL1	TLM	CC1+CC2	-9.10	-15.76
MDS04-077	LL1	TLM	CC1+CC2	-9.64	-16.05
MDS04-078	LL1	TLM	CC1+CC2	-9.08	-15.56
MDS04-079	LL1	TLM	CC1+CC2	-8.83	-15.85
MDS04-080	LL1	TLM	CC1+CC2	-8.99	-15.90
MDS04-081	LL1	TLM	CC1+CC2	-8.71	-15.74
MDS04-082	LL1	TLM	CC1+CC2	-8.74	-15.71
MDS04-083	LL1	TLM	CC1+CC2	-9.11	-17.63
MDS04-084-1	LL1	TLM	CC1+CC2	-8.62	-15.79
MDS04-084-2	LL1	TLM	CC1+CC2	-8.64	-15.70
MDS04-085	LL1	TLM	CC1+CC2	-8.58	-15.63
MDS04-086	LL1	TLM	CC1+CC2	-8.49	-15.69
MDS04-087	LL1	TLM	CC1+CC2	-8.55	-15.51
MDS04-088	LL1	TLM	CC1+CC2	-8.32	-15.79
MDS04-090	LL1	TLM	CC1+CC2	-8.31	-15.52
MDS04-091-1	LL1	TLM	CC1+CC2	-8.22	-15.63
MDS04-092	LL1	TLM	CC1+CC2	-8.20	-15.49
MDS04-094	LL1	TLM	CC1+CC2	-8.12	-15.37

Table 5.2: Results of carbon and oxygen isotopic analyses of OFP carbonate. Samples denoted by an asterisk (*) are previously unpublished data from G. M. Ross.

Sample	Lct.	Unit	Phase	$\delta^{13}\text{C}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{PDB}}$
MDS04-095	LL1	TLM	CC1+CC2	-8.02	-15.50
MDS04-096	LL1	TLM	CC1+CC2	-7.95	-15.44
MDS04-097	LL1	TLM	CC1+CC2	-7.96	-15.34
MDS04-098	LL1	TLM	CC1+CC2	-8.04	-15.38
MDS04-099	LL1	TLM	CC1+CC2	-8.30	-15.34
MDS04-100	LL1	TLM	CC1+CC2	-7.92	-15.28
MDS04-101	LL1	TLM	CC1+CC2	-7.99	-15.43
MDS04-102	LL1	TLM	CC1+CC2	-7.80	-15.27
MDS04-103-1	LL1	TLM	CC1+CC2	-7.64	-15.19
MDS04-104	LL1	TLM	CC1+CC2	-7.69	-15.14
MDS04-106	LL1	TLM	CC1+CC2	-8.02	-15.61
MDS04-107	LL1	TLM	CC1+CC2	-9.39	-15.87
MDS04-108	LL1	TLM	CC1+CC2	-9.84	-16.01
MDS04-065	LL1	TLM	CC3	-8.69	-15.85
MDS04-089	LL1	TLM	CC3	-8.11	-15.78
MDS04-105	LL1	TLM	CC3	-6.68	-17.17
MDS04-054-2	LL1	TLM	CC4	-11.37	-15.53
MDS04-091-2	LL1	TLM	CC4	-8.17	-17.85
MDS04-103-2	LL1	TLM	CC4	-8.04	-13.29
MDS04-049A	LL1	TLM	DOL2	-12.48	-15.15
MDS04-122	LL5	TLM	CC1+CC2	-11.75	-15.14
MDS04-132A	LL5	TLM	CC1+CC2	-9.46	-15.17
MDS04-132B	LL5	TLM	CC1+CC2	-9.38	-15.21
MDS04-135	LL5	TLM	CC1+CC2	-9.51	-14.45
MDS04-136A	LL5	TLM	CC1+CC2	-9.17	-14.51
MDS04-136B	LL5	TLM	CC1+CC2	-8.61	-14.50
MDS04-137	LL5	TLM	CC1+CC2	-8.54	-14.66
MDS04-138	LL5	TLM	CC1+CC2	-8.88	-14.82
MDS04-139A	LL5	TLM	CC1+CC2	-9.14	-14.70
MDS04-140A	LL5	TLM	CC1+CC2	-8.56	-14.68
MDS04-141	LL5	TLM	CC1+CC2	-9.01	-14.75
MDS04-142	LL5	TLM	CC1+CC2	-8.56	-14.76
MDS04-143	LL5	TLM	CC1+CC2	-8.48	-14.78
MDS04-144	LL5	TLM	CC1+CC2	-8.31	-14.82
MDS04-145	LL5	TLM	CC1+CC2	-8.65	-14.75
MDS04-146	LL5	TLM	CC1+CC2	-8.62	-14.71
MDS04-147	LL5	TLM	CC1+CC2	-8.50	-14.71
MDS04-148	LL5	TLM	CC1+CC2	-8.44	-14.74
MDS04-149	LL5	TLM	CC1+CC2	-8.49	-14.60
MDS04-150	LL5	TLM	CC1+CC2	-8.22	-14.63
MDS04-151	LL5	TLM	CC1+CC2	-8.30	-14.63
MDS04-153	LL5	TLM	CC1+CC2	-8.09	-14.74
MDS04-154	LL5	TLM	CC1+CC2	-8.12	-14.50
MDS04-155-1	LL5	TLM	CC1+CC2	-8.20	-14.51
MDS04-156A	LL5	TLM	CC1+CC2	-8.05	-14.65
MDS04-157	LL5	TLM	CC1+CC2	-7.90	-14.52
MDS04-158	LL5	TLM	CC1+CC2	-8.55	-14.52
MDS04-159	LL5	TLM	CC1+CC2	-8.08	-14.47
MDS04-160	LL5	TLM	CC1+CC2	-8.65	-14.39
MDS04-162	LL5	TLM	CC1+CC2	-8.73	-14.42
MDS04-163	LL5	TLM	CC1+CC2	-8.63	-14.39
MDS04-123	LL5	TLM	CC3	-11.86	-15.25
MDS04-125	LL5	TLM	CC3	-12.05	-15.36
MDS04-126	LL5	TLM	CC3	-11.35	-15.35
MDS04-127	LL5	TLM	CC3	-11.42	-15.25

Table 5.2 (cont.) Results of carbon and oxygen isotopic analyses of OFP carbonate. Samples denoted by an asterisk (*) are previously unpublished data from G. M. Ross.

Sample	Lct.	Unit	Phase	$\delta^{13}\text{C}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{PDB}}$
MDS04-128	LL5	TLM	CC3	-11.17	-15.36
MDS04-129	LL5	TLM	CC3	-10.85	-15.26
MDS04-130	LL5	TLM	CC3	-10.76	-15.23
MDS04-131	LL5	TLM	CC3	-10.09	-15.24
MDS04-134	LL5	TLM	CC3	-11.49	-19.09
MDS04-152	LL5	TLM	CC3	-7.99	-15.80
MDS04-155-2	LL5	TLM	CC3	-8.64	-14.65
MDS04-121	LL5	TLM	DOL2	-9.92	-16.11
MDS04-124	LL5	TLM	DOL2	-12.05	-16.20
MDS04-133	LL5	TLM	DOL2	-9.97	-16.23
MDS04-004	JP1	TLM	CC1+CC2	-8.28	-16.14
RAR-01-25I*	JP1	TLM	CC1+CC2	-9.49	-15.49
RAR-01-25J*	JP1	TLM	CC1+CC2	-9.44	-15.58
RAR-01-25K*	JP1	TLM	CC1+CC2	-9.64	-14.50
RAR-01-25L*	JP1	TLM	CC1+CC2	-9.80	-14.22
RAR-01-25M*	JP1	TLM	CC1+CC2	-8.93	-15.27
RAR-01-25N*	JP1	TLM	CC1+CC2	-8.61	-15.57
RAR-01-25O*	JP1	TLM	CC1+CC2	-8.23	-15.36
RAR-01-25P*	JP1	TLM	CC1+CC2	-8.11	-15.45
RAR-01-25Q*	JP1	TLM	CC1+CC2	-8.01	-15.48
RAR-01-25R*	JP1	TLM	CC1+CC2	-7.75	-15.67
RAR-01-25S*	JP1	TLM	CC1+CC2	-7.44	-15.39
RAR-01-25T*	JP1	TLM	CC1+CC2	-7.77	-16.78
RAR-01-25U*	JP1	TLM	CC1+CC2	-7.07	-15.52
RAR-01-25V*	JP1	TLM	CC1+CC2	-6.98	-15.32
RAR-01-25W*	JP1	TLM	CC1+CC2	-6.88	-15.52
RAR-01-25X*	JP1	TLM	CC1+CC2	-6.74	-15.62
MDS04-003	JP1	TLM	CC3	-10.41	-19.50
MDS04-002	JP1	TLM	DOL2	-11.80	-15.62
RAR-01-25A*	JP1	TLM	DOL2	-9.62	-13.88
RAR-01-25B*	JP1	TLM	DOL2	-9.66	-13.82
RAR-01-25C*	JP1	TLM	DOL2	-9.87	-13.87
RAR-01-25D*	JP1	TLM	DOL2	-9.57	-13.85
RAR-01-25E*	JP1	TLM	DOL2	-10.16	-13.90
RAR-01-25F*	JP1	TLM	DOL2	-10.29	-14.46
RAR-01-25G*	JP1	TLM	DOL2	-9.91	-14.38
RAR-01-25H*	JP1	TLM	DOL2	-9.93	-15.21
MDS04-019	JP4	TLM	CC1+CC2	-9.95	-16.20
MDS04-020	JP4	TLM	CC1+CC2	-7.95	-16.20
MDS04-194	MR1	TLM	CC1+CC2	-10.76	-16.60
MDS04-195	MR1	TLM	CC1+CC2	-10.70	-16.34
MDS04-196	MR1	TLM	CC1+CC2	-10.50	-16.61
MDS04-197	MR1	TLM	CC1+CC2	-10.26	-16.80
MDS04-198	MR1	TLM	CC1+CC2	-9.93	-16.38
MDS04-199	MR1	TLM	CC1+CC2	-9.90	-16.90
MDS04-200	MR1	TLM	CC1+CC2	-9.78	-16.80
MDS04-201	MR1	TLM	CC1+CC2	-9.76	-16.76
MDS04-203	MR1	TLM	CC1+CC2	-9.46	-16.74
MDS04-204	MR1	TLM	CC1+CC2	-9.32	-16.84
MDS04-205	MR1	TLM	CC1+CC2	-9.24	-16.76
MDS04-206	MR1	TLM	CC1+CC2	-9.00	-16.82
MDS04-207	MR1	TLM	CC1+CC2	-8.80	-16.96
MDS04-188B	MR1	TLM	DOL2	-10.96	-16.25
MDS04-202	MR1	TLM	DOL2	-10.36	-17.20
MDS05-125	MR2	TLM	CC3	-9.55	-16.98

Table 5.2 (cont.) Results of carbon and oxygen isotopic analyses of OFP carbonate. Samples denoted by an asterisk (*) are previously unpublished data from G. M. Ross.

Sample	Lct.	Unit	Phase	$\delta^{13}\text{C}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{PDB}}$
MDS05-126	MR2	TLM	CC1+CC2	-9.60	-16.88
MDS05-127	MR2	TLM	CC1+CC2	-7.90	-16.83
MDS05-057	PM1	TLM	CC1+CC2	-2.80	-16.94
MDS05-058	PM1	TLM	CC1+CC2	-0.76	-16.28
MDS05-059	PM1	TLM	CC1+CC2	2.22	-16.40
MDS05-060	PM1	TLM	CC1+CC2	6.66	-16.15
MDS05-061	PM1	TLM	CC1+CC2	2.68	-16.30
MDS05-062	PM1	TLM	CC1+CC2	3.49	-16.38
MDS05-063	PM1	TLM	CC1+CC2	3.49	-16.28
MDS05-064	PM1	TLM	CC1+CC2	1.86	-15.60
MDS05-054	PM1	TLM	DOL2	-0.83	-17.10
MDS05-055	PM1	TLM	DOL2	1.95	-17.01
MDS03-010	CM1	TLM	CC1+CC2	-10.38	-18.04
MDS03-011	CM1	TLM	CC1+CC2	-10.42	-17.89
MDS03-012	CM1	TLM	CC1+CC2	-10.46	-17.91
MDS04-220	CM1	TLM	CC1+CC2	-10.61	-17.97
MDS04-221	CM1	TLM	CC1+CC2	-10.65	-17.89
MDS04-222	CM1	TLM	CC1+CC2	-10.51	-18.01
MDS04-223	CM1	TLM	CC1+CC2	-10.54	-17.95
MDS04-225	CM1	TLM	CC1+CC2	-10.48	-17.77
MDS04-226	CM1	TLM	CC1+CC2	-10.36	-17.85
MDS04-227	CM1	TLM	CC1+CC2	-10.01	-17.72
MDS04-229	CM1	TLM	CC1+CC2	-10.07	-18.03
MDS04-230	CM1	TLM	CC1+CC2	-10.13	-17.91
MDS04-231	CM1	TLM	CC1+CC2	-10.00	-17.84
MDS04-232	CM1	TLM	CC1+CC2	-10.15	-17.85
MDS05-020	CM2	TLM	CC1+CC2	-10.12	-17.93
MDS03-008	CM1	TLM	CC3	-10.81	-17.79
MDS03-009A	CM1	TLM	CC3	-10.76	-17.92
MDS03-004	CM1	TLM	DOL2	-12.90	-17.74
MDS03-006	CM1	TLM	DOL2	-12.63	-17.73
MDS04-215	CM1	TLM	DOL2	-12.14	-19.92
MDS04-216	CM1	TLM	DOL2	-13.82	-18.15
MDS04-217	CM1	TLM	DOL2	-13.54	-17.82
MDS04-218	CM1	TLM	DOL2	-11.23	-18.85
MDS04-109	LL1	GSM	CC1+CC2	-10.14	-16.05
MDS04-110	LL1	GSM	CC1+CC2	-10.26	-15.98
MDS04-164	LL5	GSM	CC1+CC2	-9.54	-14.43
MDS04-165	LL5	GSM	CC1+CC2	-10.13	-14.44
MDS04-006	JP1	GSM	CC1+CC2	-8.44	-16.28
MDS04-009	JP1	GSM	CC1+CC2	-7.26	-16.35
RAR-01-25Y*	JP1	GSM	CC1+CC2	-6.50	-15.74
RAR-01-25Z*	JP1	GSM	CC1+CC2	-8.81	-14.64
MDS05-075	PM1	GSM	CC3	-11.52	-16.19
MDS03-014	CM1	GSM	CC1+CC2	-8.33	-17.88
MDS03-014-1	CM1	GSM	CC1+CC2	-9.70	-17.73
MDS03-014-2	CM1	GSM	CC1+CC2	-9.55	-17.65
MDS03-014-3	CM1	GSM	CC1+CC2	-8.62	-17.59
MDS03-015	CM1	GSM	CC1+CC2	-9.06	-17.92
MDS03-017	CM1	GSM	CC1+CC2	-8.37	-17.95
MDS03-018	CM1	GSM	CC1+CC2	-8.35	-17.95
MDS03-021A	CM1	GSM	CC1+CC2	-8.39	-17.92
MDS03-021B	CM1	GSM	CC1+CC2	-8.46	-18.06
MDS03-021C	CM1	GSM	CC1+CC2	-7.99	-18.04
MDS03-020	CM1	GSM	CC3	-9.31	-17.09

Table 5.2 (cont.) Results of carbon and oxygen isotopic analyses of OFP carbonate. Samples denoted by an asterisk (*) are previously unpublished data from G. M. Ross.

Sample	Lct.	Unit	Phase	$\delta^{13}\text{C}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{PDB}}$
MDS03-022	CM1	GSM	CC3	-8.33	-17.82
MDS04-233	CM1	GSM	CC1+CC2	-9.05	-18.02
MDS04-234A	CM1	GSM	CC1+CC2	-9.29	-17.97
MDS04-235	CM1	GSM	CC1+CC2	-5.48	-17.92
MDS05-022	CM2	GSM	CC1+CC2	-9.08	-18.06
MDS05-024	CM2	GSM	CC1+CC2	-8.80	-17.90
MDS04-034	LL4	WMM	CC3	-9.82	-15.32
MDS04-035	LL4	WMM	DOL2	-9.87	-14.90
MDS04-036	LL4	WMM	DOL2	-11.45	-15.20
MDS04-018	JP3	WMM	DOL2	-13.18	-15.16
MDS05-136	MK1	WMM	CC2-WMM	-3.89	-16.94
MDS05-137	MK1	WMM	CC2-WMM	-5.33	-18.22
MDS05-138	MK1	WMM	CC2-WMM	-4.84	-17.98
MDS05-139	MK1	WMM	CC2-WMM	-5.12	-17.73
MDS05-140	MK1	WMM	CC2-WMM	-5.37	-17.29
MDS05-141	MK1	WMM	CC2-WMM	-4.31	-17.15
MDS05-143	MK1	WMM	CC2-WMM	-5.16	-17.13
MDS05-144	MK1	WMM	CC2-WMM	-3.84	-17.18
MDS05-146	MK1	WMM	CC2-WMM	-3.62	-18.12
MDS05-147	MK1	WMM	CC2-WMM	-3.55	-17.63
MDS05-148	MK1	WMM	CC2-WMM	-3.74	-17.94
MDS05-149	MK1	WMM	CC2-WMM	-3.17	-18.59
MDS05-151	MK1	WMM	CC2-WMM	-1.74	-17.44
MDS05-133A	MK1	WMM	CC3	-7.38	-18.77
MDS05-094	PM1	WMM	CC2-WMM	-6.56	-15.16
MDS05-095	PM1	WMM	CC2-WMM	-6.18	-15.22
MDS05-096A	PM1	WMM	CC2-WMM	-5.53	-14.89
MDS05-097	PM1	WMM	CC2-WMM	-5.52	-14.06
MDS05-098	PM1	WMM	CC2-WMM	-5.21	-14.17
MDS05-100	PM1	WMM	CC2-WMM	-7.21	-14.82
MDS05-101	PM1	WMM	CC2-WMM	-5.81	-16.19
MDS05-102	PM1	WMM	CC2-WMM	-4.33	-11.95
MDS05-103A	PM1	WMM	CC2-WMM	-3.46	-9.90
MDS05-103B	PM1	WMM	CC2-WMM	-3.13	-9.89
MDS05-103C	PM1	WMM	CC2-WMM	-6.69	-11.14
MDS05-103D	PM1	WMM	CC2-WMM	-4.84	-11.37
MDS05-105	PM1	WMM	CC2-WMM	-1.50	-10.80
MDS05-106	PM1	WMM	CC2-WMM	-1.87	-12.92
MDS05-107A	PM1	WMM	CC2-WMM	-2.04	-12.56
MDS05-107B	PM1	WMM	CC2-WMM	-1.42	-11.75
MDS05-109	PM1	WMM	CC2-WMM	-0.41	-13.37
MDS05-110	PM1	WMM	CC2-WMM	-1.63	-13.63
MDS05-080	PM1	WMM	CC3	-8.89	-16.76
MDS05-081	PM1	WMM	CC3	-11.28	-16.85
MDS05-086	PM1	WMM	CC3	-11.86	-16.36
MDS05-088	PM1	WMM	CC3	-12.08	-16.51
MDS05-089	PM1	WMM	CC3	-12.34	-16.28
MDS05-091	PM1	WMM	CC3	-11.53	-16.12
MDS05-093	PM1	WMM	CC3	-11.46	-15.91
MDS03-023	CM1	WMM	CC2-WMM	-6.99	-18.02
MDS03-028	CM1	WMM	CC2-WMM	1.34	-18.00
MDS03-029	CM1	WMM	CC2-WMM	-2.32	-18.08
MDS04-237	CM1	WMM	CC2-WMM	-6.85	-18.04
MDS04-238	CM1	WMM	CC2-WMM	-7.28	-18.16
MDS04-239	CM1	WMM	CC2-WMM	-6.38	-18.01

Table 5.2 (cont.) Results of carbon and oxygen isotopic analyses of OFP carbonate. Samples denoted by an asterisk (*) are previously unpublished data from G. M. Ross.

Sample	Lct.	Unit	Phase	$\delta^{13}\text{C}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{PDB}}$
MDS04-241	CM1	WMM	CC2-WMM	-1.96	-18.01
MDS04-242	CM1	WMM	CC2-WMM	-7.36	-18.46
MDS04-246	CM1	WMM	CC2-WMM	-3.50	-18.32
MDS04-249A	CM1	WMM	CC2-WMM	-2.90	-18.43
MDS04-249B	CM1	WMM	CC2-WMM	-2.73	-18.26
MDS03-024	CM1	WMM	CC3	-6.36	-18.02
MDS03-025	CM1	WMM	CC3	-5.15	-18.18
MDS04-240	CM1	WMM	CC3	-7.15	-18.19
MDS04-243	CM1	WMM	CC3	-6.82	-18.84
MDS04-244	CM1	WMM	CC3	-6.59	-18.24
MDS04-245	CM1	WMM	CC3	-4.59	-18.31
MDS04-248	CM1	WMM	CC3	-2.31	-18.27
MDS04-026	LL4	WMM clast	CC1+CC2	-10.12	-15.53
MDS04-027	LL4	WMM clast	CC1+CC2	-8.88	-16.96
MDS04-028C	LL4	WMM clast	CC1+CC2	-10.01	-15.56
MDS04-032A	LL4	WMM clast	CC1+CC2	-8.27	-15.20
MDS04-032B	LL4	WMM clast	CC1+CC2	-9.36	-15.36
MDS04-033A	LL4	WMM clast	CC1+CC2	-8.83	-15.24
MDS04-033B	LL4	WMM clast	CC1+CC2	-9.10	-15.21
MDS04-046A	LL4	WMM clast	CC1+CC2	-7.63	-14.77
MDS04-046B	LL4	WMM clast	CC2-WMM	-9.81	-14.81
MDS04-046C	LL4	WMM clast	CC2-WMM	-11.35	-14.93
MDS04-046D	LL4	WMM clast	CC2-WMM	-8.95	-14.92
MDS04-047A	LL4	WMM clast	CC2-WMM	-8.49	-14.89
MDS04-047B	LL4	WMM clast	CC2-WMM	-9.45	-14.86
MDS04-028E-1	LL4	WMM clast	BLD CC	-9.28	-15.16
MDS04-028E-2	LL4	WMM clast	CC1+CC2	-10.17	-15.33
LL-A*	LL4	WMM clast	CC1+CC2	-8.9	-14.6
LL-B-1	LL4	WMM clast	BLD CC	-7.93	-14.84
LL-B-1*	LL4	WMM clast	BLD CC	-8.5	-14.5
LL-B-2	LL4	WMM clast	CC1+CC2	-8.76	-14.94
LL-B-2*	LL4	WMM clast	CC1+CC2	-8.3	-14.4
LL-C*	LL4	WMM clast	CC1+CC2	-9.0	-14.2
LL-D*	LL4	WMM clast	CC1+CC2	-8.7	-14.5
LL-E*	LL4	WMM clast	CC1+CC2	-8.1	-14.6
LL-F*	LL4	WMM clast	CC1+CC2	-8.8	-14.7
MDS04-028A	LL4	WMM clast	DOL-SMC	-0.96	-5.07
MDS04-028D	LL4	WMM clast	DOL-SMC	4.57	-3.06
MDS04-012-1	JP1	WMM clast	CC2-WMM	-1.98	-15.57
MDS04-012-2	JP1	WMM clast	CC2-WMM	-5.48	-15.70
MDS04-017A	JP3	WMM clast	DOL2	-5.90	-7.38
MDS04-017B	JP3	WMM clast	DOL2	-11.70	-15.42
MDS04-017C	JP3	WMM clast	DOL2	-11.04	-15.58
MDS05-130A	MR2	WMM clast	CC2-WMM	-5.47	-16.94
MDS05-130B	MR2	WMM clast	CC2-WMM	-6.49	-16.79
MDS05-130C	MR2	WMM clast	DOL-SMC	-7.22	-17.17
MDS05-133C	MK1	WMM clast	CC2-WMM	-3.09	-18.70
C-71-E*	MK1	WMM clast	CC2-WMM	-5.8	-20.7
S-87-35*	MK1	WMM clast	CC2-WMM	-9.7	-17.0
MDS05-133E	MK1	WMM clast	CC-SMC	-1.23	-14.18
MDS05-133B	MK1	WMM clast	DOL-SMC	-4.58	-18.12
MDS05-133D	MK1	WMM clast	DOL-SMC	-3.55	-17.57
MDS05-111A	PM1	WMM clast	CC2-WMM	-1.16	-16.28
MDS05-111B	PM1	WMM clast	CC2-WMM	0.02	-16.18
MDS05-113	PM1	WMM clast	CC2-WMM	-2.44	-16.70

Table 5.2 (cont.) Results of carbon and oxygen isotopic analyses of OFP carbonate. Samples denoted by an asterisk (*) are previously unpublished data from G. M. Ross.

Sample	Lct.	Unit	Phase	$\delta^{13}\text{C}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{PDB}}$
RAR-R01-120C*	LL2	MMGB	CC	-1.31	-12.80
RAR-R01-120G*	LL2	MMGB	CC	-2.54	-14.66
MDS04-022-1	LL2	MMGB-clast	CC-SMC	9.23	-13.96
MDS04-022-2	LL2	MMGB-clast	DOL-SMC	6.00	-15.24
MDS04-113A	LL5	MMGB-clast	DOL-SMC	-6.82	-10.92
MDS04-170	LL5	MMGA	CC-nodule	-8.54	-13.46
RAR03-01A	CM1	UKG	CC	-5.79	-18.11
RAR03-01B	CM1	UKG	CC	-2.17	-17.97
RAR03-01C	CM1	UKG	CC	-2.05	-17.96
RAR03-01D	CM1	UKG	CC	-1.49	-17.96
RAR03-01E	CM1	UKG	CC	-6.82	-17.05
RAR03-01F	CM1	UKG	CC	-2.82	-17.98
RAR03-01G	CM1	UKG	CC	-0.83	-18.00
RAR03-01H	CM1	UKG	CC	-0.62	-17.88
RAR03-01I	CM1	UKG	CC	-1.41	-18.08
RAR-R014-T*	CM3	IF	CC	-1.07	-15.55
RAR-R014-X.2*	CM3	IF	CC	-1.18	-15.28
RAR-R014-LL.2*	CM3	IF clast	DOL-SMC	-2.14	-12.57
RAR-R014-LL.3*	CM3	IF clast	DOL-SMC	-10.34	-14.53
RAR-R014-LL.4*	CM3	IF clast	DOL-SMC	-6.52	-12.99
RAR-R071-B*	CM3	IF	CC	0.58	-15.27
RAR-R071-D*	CM3	IF	CC	1.20	-16.63
RAR-R071-E*	CM3	IF	CC	1.97	-15.16
RAR-R071-F*	CM3	IF	CC	1.69	-16.17
RAR-R071-G*	CM3	IF	CC	2.00	-15.78
RAR-R071-H*	CM3	IF	CC	2.41	-15.51
RAR-R071-I*	CM3	IF	CC	3.28	-15.15
RAR-R071-J*	CM3	IF	CC	3.52	-15.06
RAR-R071-L*	CM3	IF	CC	3.52	-15.26
RAR-R071-O*	CM3	IF	CC	3.81	-15.43
RAR-R071-Q*	CM3	IF	CC	3.19	-15.21
RAR-R071-R*	CM3	IF	CC	3.70	-15.22
RAR-R071-T*	CM3	IF	CC	2.26	-15.32
RAR-R071-U*	CM3	IF	CC	2.54	-15.36
RAR-R071-W*	CM3	IF	CC	2.22	-16.04
RAR-R071-X*	CM3	IF	CC	1.82	-15.75
RAR-R071-Z*	CM3	IF	CC	1.69	-15.20
RAR-R071-DD*	CM3	IF	CC	1.36	-15.10
RAR-R071-EE*	CM3	IF	CC	-0.45	-15.18
RAR-R071-FF*	CM3	IF	CC	-1.24	-15.58
RAR-R071-GG*	CM3	IF	CC	0.66	-16.10
RAR-R071-HH*	CM3	IF	CC	-3.24	-15.73
RAR-R084-B*	CM3	IF	CC	-2.23	-12.00

Table 5.3: Results of carbon and oxygen isotopic analyses of other WSG carbonates. Samples denoted by an asterisk (*) are previously unpublished data from G. M. Ross. Monk = Monkman Pass area, B.C.; VF = Vreeland Formation; FF = Framstead Formation; SMC = shallow-marine carbonate.

Sample	Lct.	Unit	Phase	$\delta^{13}\text{C}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{PDB}}$
RAR-R01-12A*	MR3	UMG	CC	0.29	-14.36
RAR-R01-12B*	MR3	UMG	CC	2.23	-14.35
RAR-R01-12C*	MR3	UMG	CC	1.79	-14.50
RAR-R01-12D*	MR3	UMG	CC	1.72	-14.11
RAR-R01-12E*	MR3	UMG	CC	2.53	-14.01
RAR-R01-12H*	MR3	UMG	CC	-1.50	-13.71
RAR-R01-12I-2*	MR3	UMG	CC	-1.48	-12.35
RAR-R01-12J*	MR3	UMG	CC	0.23	-13.80
RAR-R01-12K*	MR3	UMG	CC	-0.04	-13.61
RAR-R01-12L*	MR3	UMG	CC	-0.30	-13.57
RAR-R01-12M*	MR3	UMG	CC	0.21	-13.69
RAR-R01-12N*	MR3	UMG	CC	0.79	-13.78
RAR-R01-12O*	MR3	UMG	CC	2.53	-13.64
RAR-R01-12Q*	MR3	UMG	CC	2.94	-13.48
RAR-R01-12R*	MR3	UMG	CC	3.33	-13.68
RAR-R01-12T*	MR3	UMG	CC	2.03	-13.27
RAR-R01-12U*	MR3	UMG	CC	3.15	-13.48
RAR-R01-12V*	MR3	UMG	CC	3.13	-13.21
RAR-R01-12W*	MR3	UMG	CC	2.28	-13.19
RAR-R01-12Z*	MR3	UMG	CC	2.66	-13.19
RAR-R01-12AA*	MR3	UMG	CC	2.67	-13.20
RAR-R01-12BB*	MR3	UMG	CC	2.90	-13.41
RAR-90-W16A	Monk	VF	CC	-2.79	-13.90
RAR-90-W16A*	Monk	VF	CC	-3.6	-15.2
RAR-90-W16B	Monk	VF	CC	-1.94	-13.52
RAR-90-W16B*	Monk	VF	CC	-2.3	-14.0
RAR-90-W16C	Monk	VF	CC	-3.16	-13.84
RAR-90-W16C*	Monk	VF	CC	-2.8	-13.6
RAR-90-W17A-1*	Monk	FF clast	DOL-SMC	-4.3	-9.4
RAR-90-W17A-2*	Monk	FF clast	DOL-deformed	-19.5	-6.6
RAR-90-W17A-3*	Monk	FF clast	DOL-saddle	-2.6	-7.0
RAR-90-W17B	Monk	FF clast	DOL-SMC	-5.89	-12.56
RAR-90-W17B*	Monk	FF clast	DOL-SMC	-5.4	-11.1
RAR-90-W17C-1	Monk	FF clast	DOL-saddle	-15.98	-10.90
RAR-90-W17C-1*	Monk	FF clast	DOL-saddle	-17.1	-7.9
RAR-90-W17C-2	Monk	FF clast	DOL-saddle	-2.92	-10.22
RAR-90-W17C-2*	Monk	FF clast	DOL-saddle	-2.2	-8.6
RAR-90-W17C-3	Monk	FF clast	DOL-SMC	-4.62	-12.75
RAR-90-W17C-3*	Monk	FF clast	DOL-SMC	-4.8	-11.2
MDS05-056	PM1	qtz vein	ANK	-3.62	-15.98

Table 5.3 (cont.): Results of carbon and oxygen isotopic analyses of other WSG carbonates. Samples denoted by an asterisk (*) are previously unpublished data from G. M. Ross. Monk = Monkman Pass area, B.C.; VF = Vreeland Formation; FF = Framstead Formation; SMC = shallow-marine carbonate.

Sample Name	Lct.	Unit	$\delta^{13}\text{C}_{\text{org}}$	Sample Name	Lct.	Unit	$\delta^{13}\text{C}_{\text{org}}$
MDS04-048	LL1	TLM	-27.39	MDS04-028	LL4	WMM	-26.42
MDS04-051	LL1	TLM	-27.34	MDS04-029	LL4	WMM	-27.08
MDS04-089	LL1	TLM	-27.80	MDS04-030	LL4	WMM	-27.74
MDS04-103	LL1	TLM	-26.45	MDS04-031	LL4	WMM	-27.59
MDS04-105	LL1	TLM	-28.44	MDS04-037	LL4	WMM	-27.62
MDS04-065	LL1	TLM	-27.23	MDS04-039	LL4	WMM	-27.76
MDS04-117	LL5	TLM	-27.71	MDS04-041	LL4	WMM	-28.16
MDS04-118	LL5	TLM	-27.24	MDS04-042	LL4	WMM	-29.35
MDS04-119	LL5	TLM	-27.34	RAR-01-30*	JP1	WMM	-25.71
MDS04-152	LL5	TLM	-28.38	RAR-01-25KK*	JP1	WMM	-27.90
MDS04-157	LL5	TLM	-26.88	MDS04-014	JP3	WMM	-28.56
MDS04-001	JP1	TLM	-26.72	MDS04-015	JP3	WMM	-27.32
MDS04-003	JP1	TLM	-26.95	RAR-01-25II*	JP1	WMM	-25.70
RAR-01-22*	JP1	TLM	-25.48	RAR-01-25JJ*	JP1	WMM	-23.80
RAR-01-24*	JP1	TLM	-26.21	RAR-01-25HH*	JP1	WMM	-23.20
RAR-01-27*	JP1	TLM	-25.74	MDS05-134	MK1	WMM	-20.18
RAR-01-28*	JP1	TLM	-26.12	MDS05-135	MK1	WMM	-20.27
MDS04-188B	MR1	TLM	-26.94	MDS05-136	MK1	WMM	-19.11
MDS04-109	LL1	GSM	-27.66	MDS05-142	MK1	WMM	-20.06
MDS04-111	LL1	GSM	-31.70	MDS05-143	MK1	WMM	-18.60
MDS04-112	LL1	GSM	-31.21	MDS05-147	MK1	WMM	-17.39
MDS05-154	LL1	GSM	-32.42	MDS05-150A	MK1	WMM	-17.56
MDS05-007	LL5	GSM	-30.22	MDS05-150B	MK1	WMM	-24.68
MDS05-008	LL5	GSM	-33.25	MDS05-083	PM1C	WMM	-26.16
MDS05-009	LL5	GSM	-31.36	MDS05-084	PM1C	WMM	-26.26
MDS05-010	LL5	GSM	-30.42	MDS05-087	PM1C	WMM	-26.40
MDS05-012	LL6	GSM	-31.58	MDS05-090	PM1C	WMM	-26.27
MDS05-013	LL6	GSM	-31.89	MDS05-092	PM1C	WMM	-25.89
MDS05-014	LL6	GSM	-32.26	MDS05-096B	PM1C	WMM	-19.25
MDS04-006	JP1	GSM	-28.80	MDS05-099	PM1C	WMM	-19.73
MDS04-009	JP1	GSM	-27.43	MDS05-104	PM1C	WMM	-17.86
MDS04-011	JP1	GSM	-31.08	MDS05-111B	PM1C	WMM	-18.34
RAR-01-25AA*	JP1	GSM	-32.30	MDS05-112	PM1C	WMM	-14.94
RAR-01-25BB*	JP1	GSM	-31.80				
RAR-01-25CC*	JP1	GSM	-31.40				
RAR-01-25DD*	JP1	GSM	-27.40				
RAR-01-25EE*	JP1	GSM	-27.43				
RAR-01-29*	JP1	GSM	-31.22				
RAR-01-25FF*	JP1	GSM	-30.20				
RAR-01-25GG*	JP1	GSM	-29.50				
MDS04-208	MR1	GSM	-24.72				
MDS04-209	MR1	GSM	-24.67				
MDS05-128A	MR2	GSM	-20.71				
MDS05-128B	MR2	GSM	-21.14				
MDS03-016	CM1	GSM	-23.44				
MDS04-234B	CM1	GSM	-22.41				
MDS03-018	CM1	GSM	-21.22				
MDS03-019	CM1	GSM	-21.83				
MDS04-236	CM1	GSM	-22.03				

Table 5.4: Results of carbon isotopic analyses from organic residue in strata of the OFP. Samples denoted by an asterisk (*) are previously unpublished data from G. M. Ross.

Sample Name	Lct.	Unit	$\delta^{34}\text{S}_{\text{py}}$	Sample Name	Lct.	Unit	$\delta^{34}\text{S}_{\text{py}}$
MDS04-139A	LL5	TLM	-13.83	MDS04-008	JP1	GSM	0.31
MDS04-142	LL5	TLM	-13.91	JS06-019	PM2	GSM	-29.16
MDS04-145	LL5	TLM	-6.42	A288*	CM1	GSM	-19.1
MDS04-163	LL5	TLM	7.49	G86-41*	CM1	GSM	-22.7
MDS04-004	JP1	TLM	28.38	G86-79*	CM1	GSM	-25.2
MDS04-005	JP1	TLM	17.29	G86-86*	CM1	GSM	-23.5
MDS04-020	JP4	TLM	14.48	S87-29*	CM1	GSM	-25.8
MDS04-178	MR1	TLM	23.70	S-87-30*	CM1	GSM	-25.3
MDS04-179	MR1	TLM	20.82	S-87-31A*	CM1	GSM	-27.7
MDS04-180	MR1	TLM	15.92	S87-32*	CM1	GSM	-27.0
MDS04-181	MR1	TLM	17.72	MDS05-021	CM2	GSM	-26.95
MDS04-184	MR1	TLM	13.58	MDS05-023	CM2	GSM	-26.97
MDS04-185	MR1	TLM	13.75	MDS05-129-1	MR2	WMM	-1.60
MDS04-189	MR1	TLM	11.08	MDS05-129-2	MR2	WMM	-1.67
MDS04-190	MR1	TLM	12.00	MDS05-129-3	MR2	WMM	-1.60
MDS04-191A	MR1	TLM	11.26	MDS05-129-4	MR2	WMM	-1.28
MDS04-191B-1	MR1	TLM	14.60	MDS05-082	PM1	WMM	-14.59
MDS04-191B-2	MR1	TLM	14.30	MDS05-083-1	PM1	WMM	-15.55
MDS04-191B-3	MR1	TLM	14.30	MDS05-083-2	PM1	WMM	-15.78
MDS04-191B-4	MR1	TLM	14.34	MDS05-084	PM1	WMM	-29.09
MDS04-191B-5	MR1	TLM	14.25	MDS05-087	PM1	WMM	-29.56
MDS04-192	MR1	TLM	11.26	MDS05-090-1	PM1	WMM	-27.76
MDS04-193	MR1	TLM	12.93	MDS05-090-2	PM1	WMM	-27.68
MDS04-194-1	MR1	TLM	14.81	MDS05-090-3	PM1	WMM	-27.86
MDS04-194-2	MR1	TLM	15.15	MDS05-090-4	PM1	WMM	-27.82
MDS04-205	MR1	TLM	22.78	MDS05-090-5	PM1	WMM	-27.81
MDS05-123	MR2	TLM	15.00	MDS05-092-1	PM1	WMM	-27.12
MDS05-124	MR2	TLM	14.00	MDS05-092-2	PM1	WMM	-27.28
MDS05-125	MR2	TLM	13.70	MDS05-093	PM1	WMM	-27.41
MDS05-051	PM1	TLM	-11.41	MDS04-247	CM1	WMM	-4.02
MDS05-053	PM1	TLM	-16.49	A294*	CM1	WMM	5.1
MDS05-065	PM1	TLM	-8.25	A297-FF*	CM1	WMM	-25.4
MDS05-066-1	PM1	TLM	-7.91	A297-GG*	CM1	WMM	-22.2
MDS05-066-2	PM1	TLM	-9.93	A297-HH*	CM1	WMM	-20.0
MDS04-224	CM1	TLM	-31.28	A297-II*	CM1	WMM	-5.2
MDS04-228	CM1	TLM	-30.36	A297-JJ*	CM1	WMM	-3.7
G86-37*	CM1	TLM	9.4	MDS05-001	LL2	MMGB	25.17
G86-73*	CM1	TLM	-29.8	MDS05-002	LL2	MMGB	24.41
G86-114*	CM1	TLM	-29.2	MDS05-046	PM1	HTC	18.34
S87-33*	CM1	TLM	-30.9	MDS05-047	PM1	HTC	9.15
S87-34A-B*	CM1	TLM	-31.9	MDS05-049	PM1	HTC	13.36
S87-35*	CM1	TLM	-31.6	MDS05-114-1	PM1	HTC	-3.95
				MDS05-114-2	PM1	HTC	-3.81

Table 5.5: Results of sulfur isotopic analyses from pyrites in strata of the OFP and WSG. Samples denoted by an asterisk (*) are from Table 1 in Ross et al. (1995).

5.6.1 Carbonate: $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$

Due to their neomorphosed, recrystallized aspect, CC1 + CC2 are inseparable and thus, stable isotopic analyses of limestone units unavoidably reflect a mixture of the detrital grains (CC1) and the earliest enveloping cement (CC2). The $\delta^{13}\text{C}$ values of CC1 + CC2 ($n = 182$) in the TLM and GSM at most locations are consistently negative ranging from -11.96 to -5.48‰ (Table 5.2; Figs. 5.13 to 5.15) and comparable to other post-glacial, basal Ediacaran successions (e.g. Halverson et al., 2005). Locally, the TLM also shows an excellent correlation from sections only a few kilometers apart. For example, in the Lake Louise area, $\delta^{13}\text{C}$ values from two different locations (LL1 and LL5) stratigraphically-upward increase by 4 to 5‰ from approximately -12 to -7‰ (Figs. 5.14). Also at this location, $\delta^{13}\text{C}$ isotopic analyses ($n = 3$) of bladed-calcite crystals from clasts (-9.28 to -7.93‰) and the overlying limestone turbidite bed (-10.17 to -8.30‰) are similar to the TLM. In an east to west, equivalent to slope to basin transect (Jasper to Cariboo Mountains), the TLM (and GSM) show a consistent, stratigraphically-upward positive 3‰ shift in $\delta^{13}\text{C}$ values (Fig. 5.13). Correlative TLM limestone strata interpreted to have been deposited in deep-water (i.e. basinal settings in the west) are about 1 to 2‰ more negative than their shallower water counterparts (Fig. 5.13), are therein consistent with trends observed in other Neoproterozoic strata (e.g. Kennedy, 1996; James et al., 2001; Shen et al., 2005; Giddings and Wallace, 2009). This trend is not always consistent within the TLM and there is regional variation in the absolute $\delta^{13}\text{C}$ values. For example, >200 km to the south of this transect (palinspastically unrestored), Lake Louise is interpreted to represent a mid-slope paleogeographic setting compared to the lower slope setting at Jasper. These two locations are generally similar based on sedimentologic and stratigraphic considerations (e.g. purple to green transition) and overall isotopic trends with the interpreted paleogeographic difference primarily based on more frequent mass movement deposits at Lake Louise (i.e. increased slope gradient) (Chapter 3). Although sedimentary rocks at the Lake Louise location is interpreted to have been deposited

Figure 5.13: Simplified stratigraphic columns of the OFP, correlated cross-section and stable isotopic profiles ($\delta^{13}\text{C}_{\text{org}}$; carbonate $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) of the three members of the OFP. Cross-section is in an east to west direction, along a paleogeographic slope to basin-floor transect and uses the top of the GSM as a datum. Sections from Jasper National Park and Mount Robson area are composite sections for display purposes and include analyses from more than one locality. The carbonate $\delta^{13}\text{C}$ profile through the TLM (and GSM in the Cariboo Mountains) consistently shows a stratigraphically-upward 3‰ shift towards more positive values. The TLM also displays a negative ~1.5‰ shift from lower slope to basin floor depositional environments. In the Jasper region, the negative ~2.5‰ shift in the GSM corresponds to a prominent negative shift in the $\delta^{13}\text{C}_{\text{org}}$ values. The WMM in the Cariboo Mountains exhibits a stratigraphically-upward 4 to 5‰ shift towards near-zero $\delta^{13}\text{C}$ values in limestone units. Conversely, the carbonate $\delta^{18}\text{O}$ values appear homogenized at each geographic region, with increasing negative values corresponding to the increase in metamorphic grade from east to west.

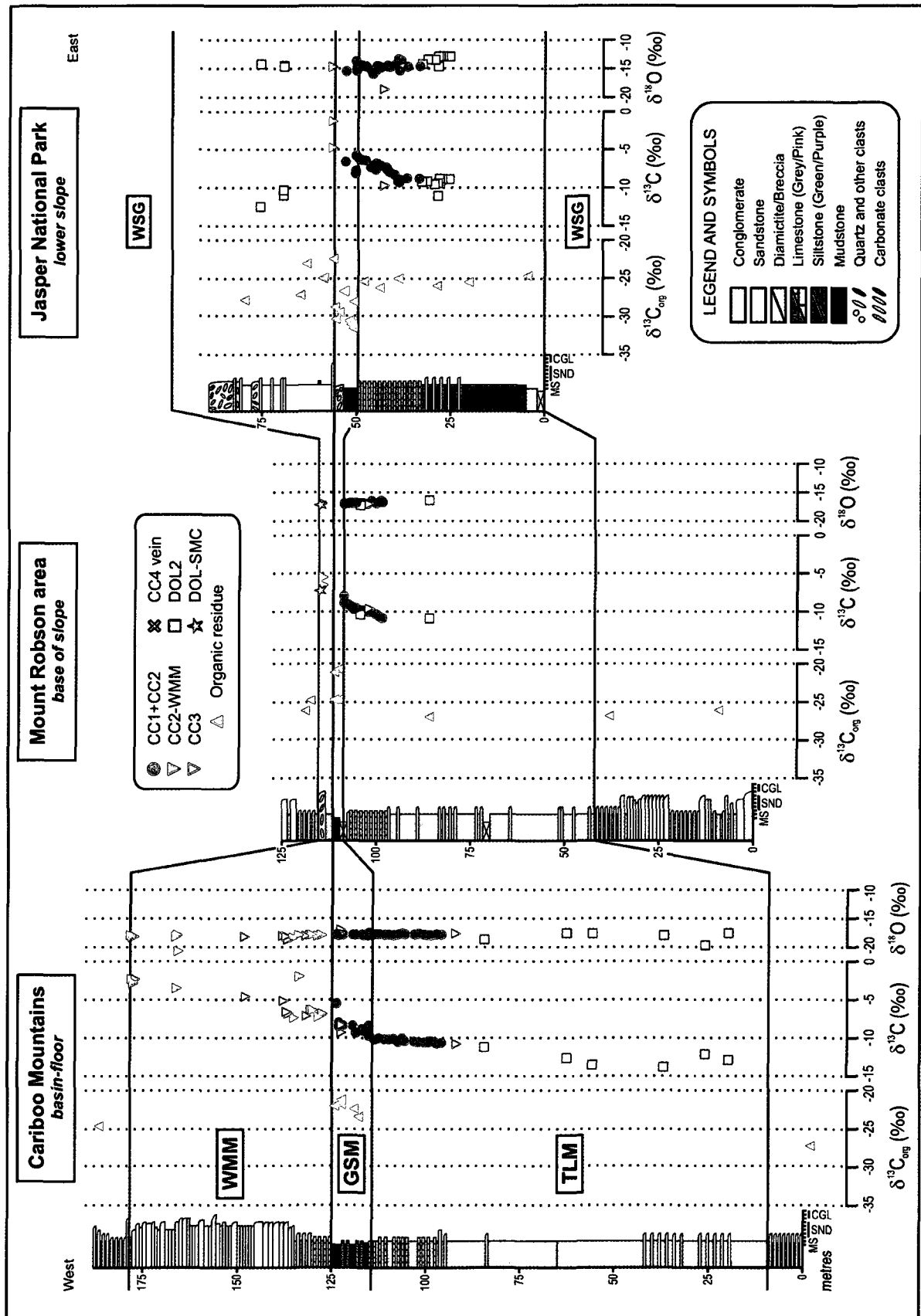


Figure 5.14: Simplified stratigraphic columns of the OFP, correlated cross-section and stable isotopic profiles ($\delta^{13}\text{C}_{\text{org}}$; carbonate $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) of the three members of the OFP in the Lake Louise area. Cross-section illustrates the correlation of the lower two members (TLM + GSM), prominent incision event and deposition of the WMM in a submarine canyon. The carbonate $\delta^{13}\text{C}$ profiles show a similar positive shift of approximately 4 to 5‰ through the TLM with a negative 2 to 3‰ shift in the GSM which corresponds to a prominent negative shift in the $\delta^{13}\text{C}_{\text{org}}$ values. $\delta^{18}\text{O}_{\text{carb}}$ values appear homogenized throughout the area with the exception of shallow-marine clasts from WMM breccia units at LL4 (not displayed, see Table 5.3).

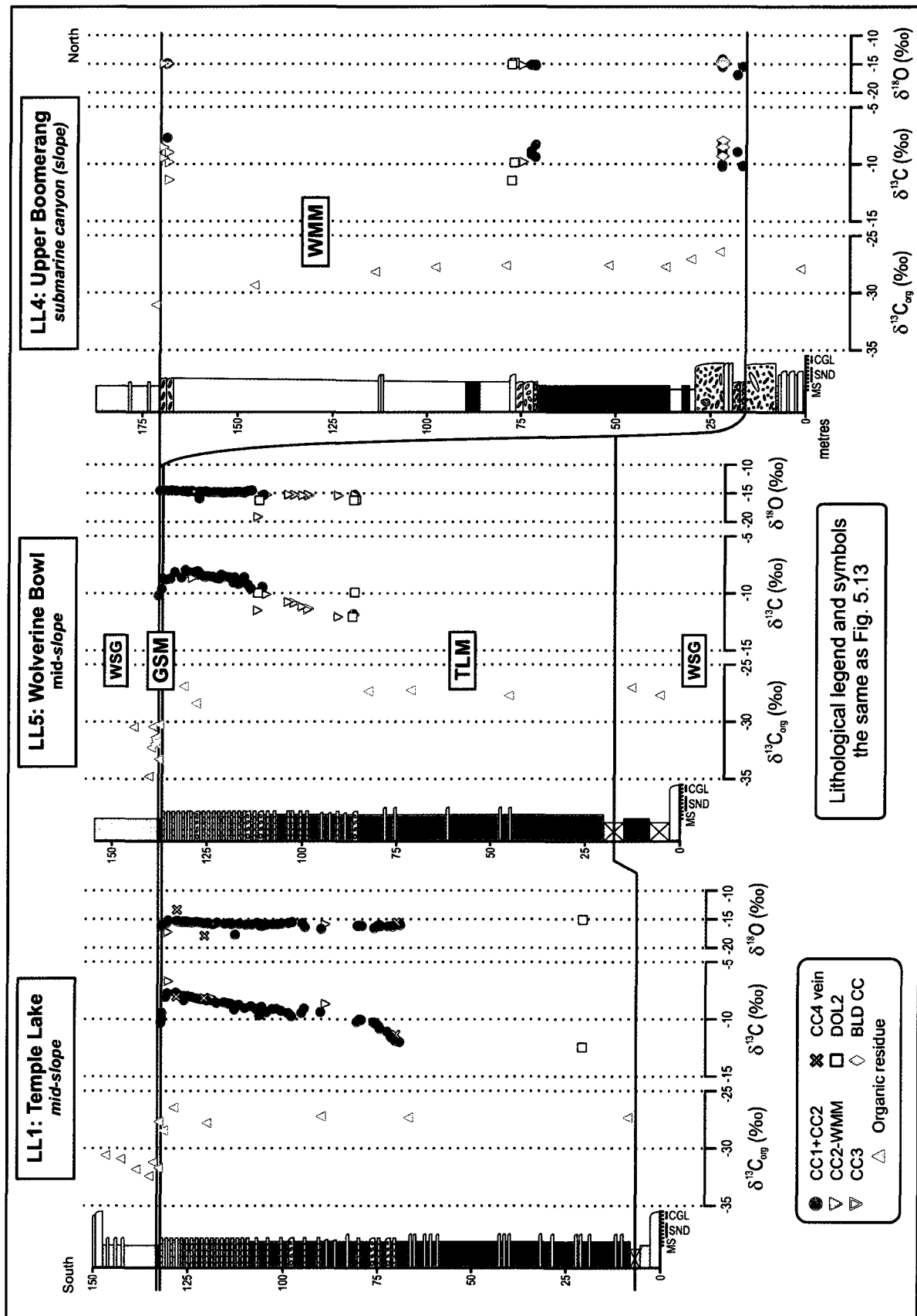
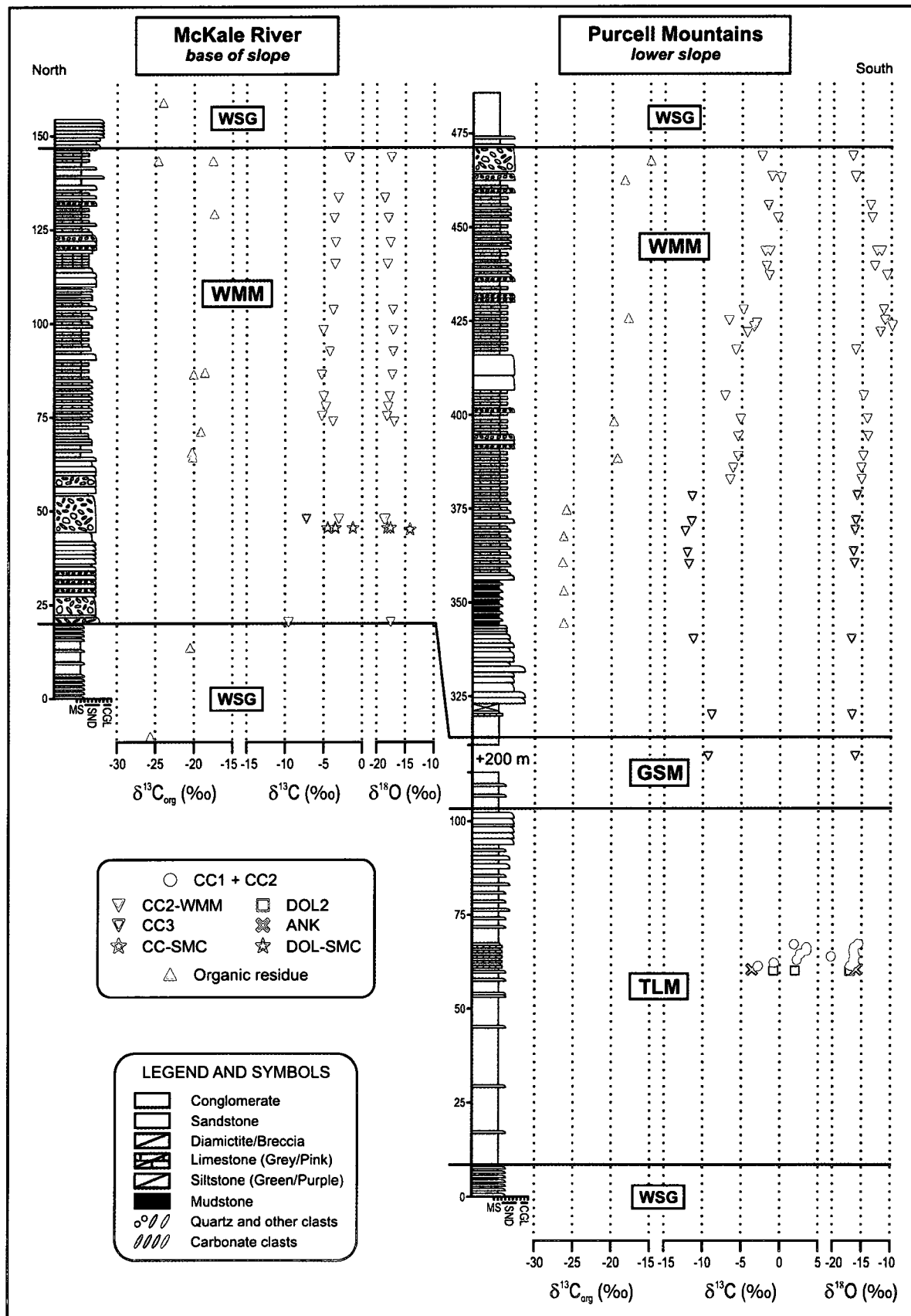


Figure 5.15: Simplified stratigraphic columns of the OFP from McKale River and Purcell Mountains and stable isotopic profiles ($\delta^{13}\text{C}_{\text{org}}$; carbonate $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$). The section from Frances Creek in the Purcell Mountains consists of an anomalously thick succession of the TLM and GSM strata related to syn-sedimentary growth faulting. Also, note the abnormally positive carbonate $\delta^{13}\text{C}$ values from TLM limestone rhythmites. Although separated by >500 km (palinspastically unrestored), the carbonate $\delta^{13}\text{C}$ profile through the WMM shows stratigraphically-upward, positive shift toward near-zero values (McKale River 2 to 3‰; Purcell Mountains ~6‰) like the WMM in the Cariboo Mountains (Fig. 5.13). The $\delta^{13}\text{C}_{\text{org}}$ profile appears to show a similar trend. Carbonate $\delta^{18}\text{O}$ values show similar homogenization from regional metamorphism with the exception of some WMM analyses from the Purcell Mountains section.



in shallower water than Jasper, the $\delta^{13}\text{C}$ isotopic values are 2 to 2.5‰ lower which is more comparable to results from the basinal Cariboo Mountains. Despite this regional variation in absolute isotopic values, limestone units of the TLM show remarkable stratigraphic consistency in their $\delta^{13}\text{C}$ isotopic pattern in spite of geographic separation of hundreds of kilometers. The lone exception is at the outcrop locality of Frances Creek in the Purcell Mountains where $\delta^{13}\text{C}$ values range from -2.80 to 6.66‰ (Fig. 5.15).

Within strata of the GSM, limestone units from the more proximal locations (Lake Louise and Jasper) show a reversal of the stratigraphically-upward positive trend, whereby $\delta^{13}\text{C}$ values decrease by approximately 2‰ (Figs. 5.13 and 5.14). Dark grey, organic-rich limestone strata from the WMM (CC2-WMM) are characterized by $\delta^{13}\text{C}$ values ranging from -7.36 to 1.34‰ ($n = 42$) and show a consistent upsection increase of approximately 3 to 6‰ towards near-zero values (Figs. 5.13, 5.14 and 5.15). Limestone strata in the WMM show a possible slight isotopic shift (~1 to 2‰) from slope to basin-floor settings, but it is not as well developed as in the TLM. Clasts of WMM limestone in breccia units show greater variability with $\delta^{13}\text{C}$ values ranging from -11.35 to 0.02‰ ($n = 15$). Values of secondary cement phase CC3 ($n = 37$) range from -12.34 to -2.32‰, whereas CC4 ($n = 3$) is more consistent from -11.37 to -8.04‰. The $\delta^{13}\text{C}$ values of DOL2 ($n = 28$) are consistently negative and range from -13.82 to -9.57‰, except at Frances Creek where they are near-zero (1.95 and -0.83‰). Calcite and dolomite phases ($n = 10$) from upslope clasts of shallow-marine carbonate (SMC) show a wide variation in $\delta^{13}\text{C}$ values ranging from -7.22 to 9.23‰.

Unlike $\delta^{13}\text{C}$, the $\delta^{18}\text{O}$ isotopic compositions exhibit little difference between OFP carbonate phases or stratigraphic position (Figs. 5.13, 5.14 and 5.15). Overall, the $\delta^{18}\text{O}$ values from most calcite and dolomite phases ranges from -19.92 to -13.29‰. Exceptions are CC2 from the WMM where values show a wider range from -18.70 to -9.89‰ and the non-OFP upslope shallow-marine carbonate (SMC) clasts (e.g. oolitic limestone, swaley-cross-stratified dolostone, dolomitic sandstone)

that range from -18.12 to -3.06‰. Cross-plots of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ for individual phases exhibit no obvious relationship, except for DOL2, which perhaps shows a co-linear relationship towards increasingly negative values (Fig. 5.16A and B). However, the $\delta^{18}\text{O}$ values from the OFP display a distinctive correlation between isotopic composition and geographic location. Eastern sections in the Jasper and Lake Louise areas are characterized by average values of -15.37‰ ($2\sigma = 1.03\%$) and -15.35‰ ($2\sigma = 0.78\%$), respectively. Proceeding westward, $\delta^{18}\text{O}$ values become more negative in the Mount Robson area (average: -16.75‰, $2\sigma = 0.24\%$), McKale River area (average: -17.74‰, $2\sigma = 0.62\%$) and lastly, the Cariboo Mountains (average: -18.01‰, $2\sigma = 0.36\%$). In the south at Frances Creek, most values average -16.04‰ ($2\sigma = 1.07\%$), but some samples are less negative and range from -13.63 to -9.89‰.

5.6.2 Organic residue: $\delta^{13}\text{C}$

Although OFP mudstone and carbonate units have undergone low-grade metamorphism, the measured $\delta^{13}\text{C}$ values from the organic matter residue are comparable to those reported from other Proterozoic successions (e.g. Hayes et al., 1983). The basal TLM has low TOC content (<0.2%) and siltstone units are characterized by $\delta^{13}\text{C}$ from -28.44 to -25.28‰ (Appendix K). The GSM is characterized by organic-rich (>0.5%) mudstone and limestone (Chapter 4). $\delta^{13}\text{C}$ values from organic residue in strata of the GSM deposited at slope sections (Jasper, Lake Louise) are more depleted compared to those in deeper-water environments (Mount Robson, Cariboo Mountains) (-33.25 to -27.40‰ versus -24.72 to -20.71‰, respectively) (Figs. 5.13, 5.14). Fine-grained siliciclastic strata of the WMM are generally organic-poor (<0.25%) and characterized by $\delta^{13}\text{C}$ values similar to the TLM (-29.35 to -23.80‰). The $\delta^{13}\text{C}$ values from organic residue in limestone strata tend to be more variable, ranging from -26.40 to -14.94‰ and display an upward stratigraphic trend towards progressively less negative values (Figs. 5.13, 5.15).

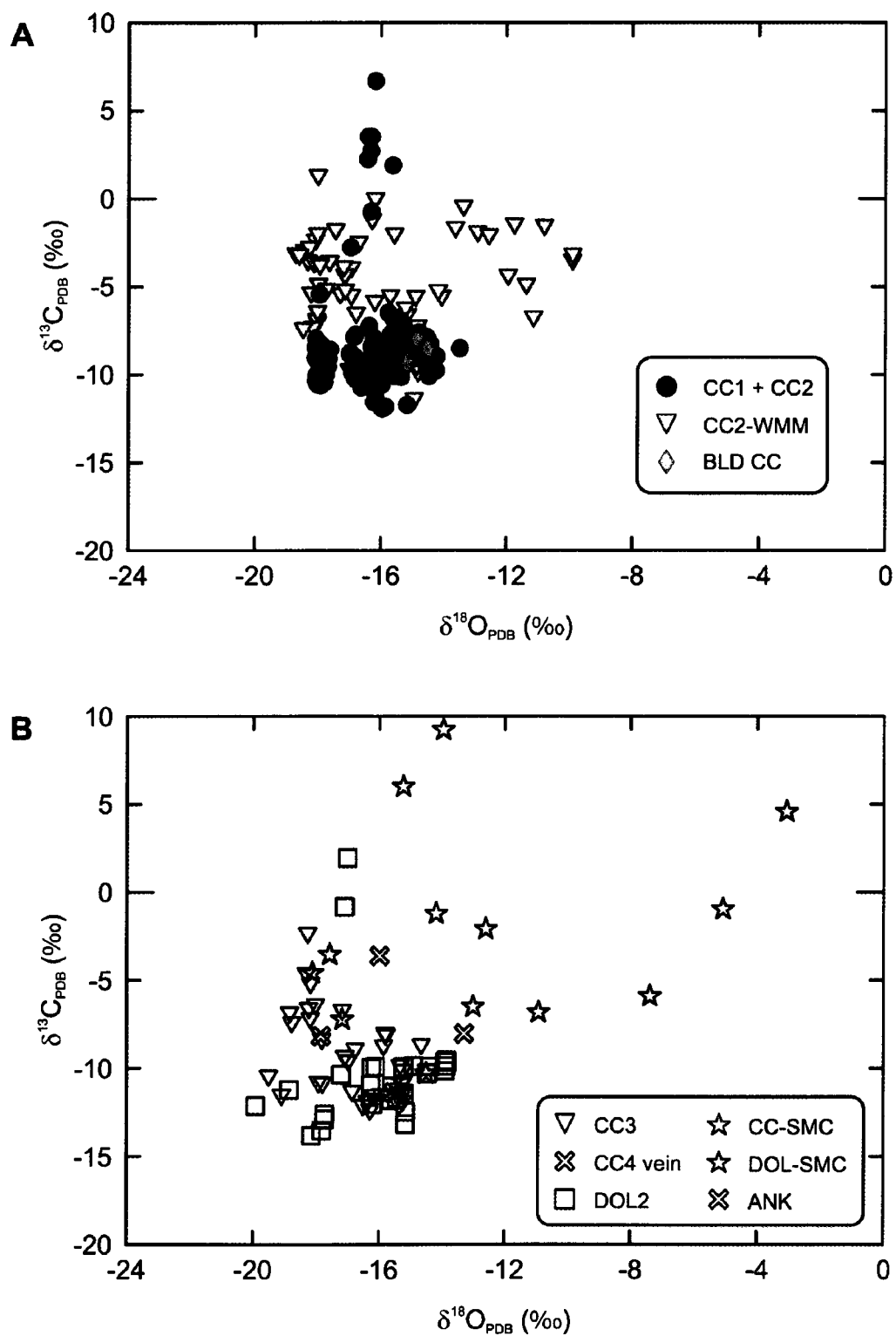


Figure 5.16: Isotopic cross-plots of $\delta^{18}\text{O}$ vs. $\delta^{13}\text{C}$. A) Carbonate phases CC1 + CC2, CC2-WMM and BLD CC. B) Carbonate phases CC3, CC4 vein, DOL2, ANK, CC-SMC and DOL-SMC.

5.6.3 Pyrite: $\delta^{34}\text{S}$

In the OFP, pyrite forms laminae of disseminated or isolated fine cubes within mudstone, siltstone and limestone, or as large metamorphically recrystallized cubes in sandstone. Fourteen replicate analyses from a single cube, multiple cubes or different parts of large cubes exhibited $<0.5\text{‰}$ difference, indicating the pyrite crystals are isotopically homogeneous, similar to the observations of Ross et al. (1995) and other studies (e.g. Maynard, 1980). The $\delta^{34}\text{S}$ values ($n = 58$) from the OFP show a broad range from -31.28 to 28.38‰ ($\Delta\delta^{34}\text{S}$ approximately 60‰) (Fig. 5.17), which is consistent with the wide spread reported earlier by Ross et al. (1995) for the Middle Kaza Group (MKG $\sim 24\text{‰}$), Upper Kaza Group (UKG $\sim 48\text{‰}$) and Isaac Formation (IF $\sim 54\text{‰}$).

In more proximal slope locations (e.g. Lake Louise, Jasper), pyrite is absent in the lower part of the TLM, but found locally in the upper part and also the overlying GSM (Fig. 5.18). These two regions exhibit prominent ($>20\text{‰}$), but opposing isotopic shifts in $\delta^{34}\text{S}$ values over a relatively thin stratigraphic interval, which contrasts their otherwise remarkable similarity in physical and other chemical traits. At Jasper (JP1) there is a negative shift from 28.38 to 0.31‰ over a stratigraphic interval about 6 m thick, whereas at Lake Louise (LL5) a positive shift from -13.90 to 7.49‰ over 17.5 m was measured (Fig. 5.18). In the Mount Robson area (Fig. 5.18) the TLM displays a systematic negative shift upsection through the basal part of the TLM from 23.70 to 11.26‰ , with a reversal towards more positive values near the gradational contact with the GSM. Here, the GSM is devoid of obvious pyrite, but in the overlying WMM large pyrite cubes are slightly negative (around -1.6‰). In the Purcell Mountains (Fig. 5.18), pyrite in WSG strata below the OFP are positive (9.15 to 18.34‰) with an abrupt shift to negative values in the TLM (-16.49 to -7.91‰). Pyrite is absent in the GSM, which likely is related, in part, to the unusually high sedimentation rate, and hence organic dilution observed at this location (Chapter 3). $\delta^{34}\text{S}$ values in the lower part of the WMM are negative (-14.59 to -15.78‰) with an abrupt shift to more negative values in overlying organic-rich

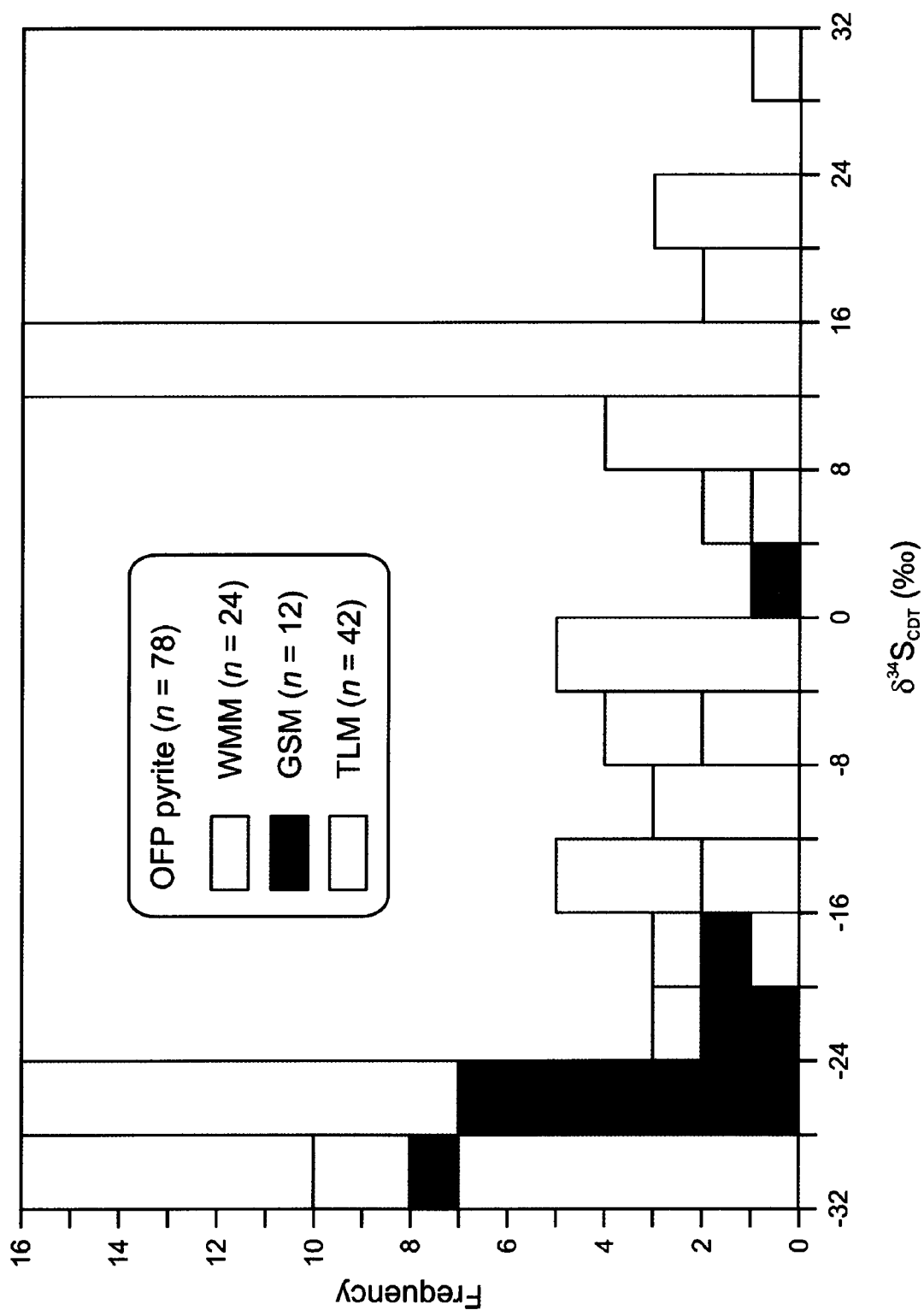
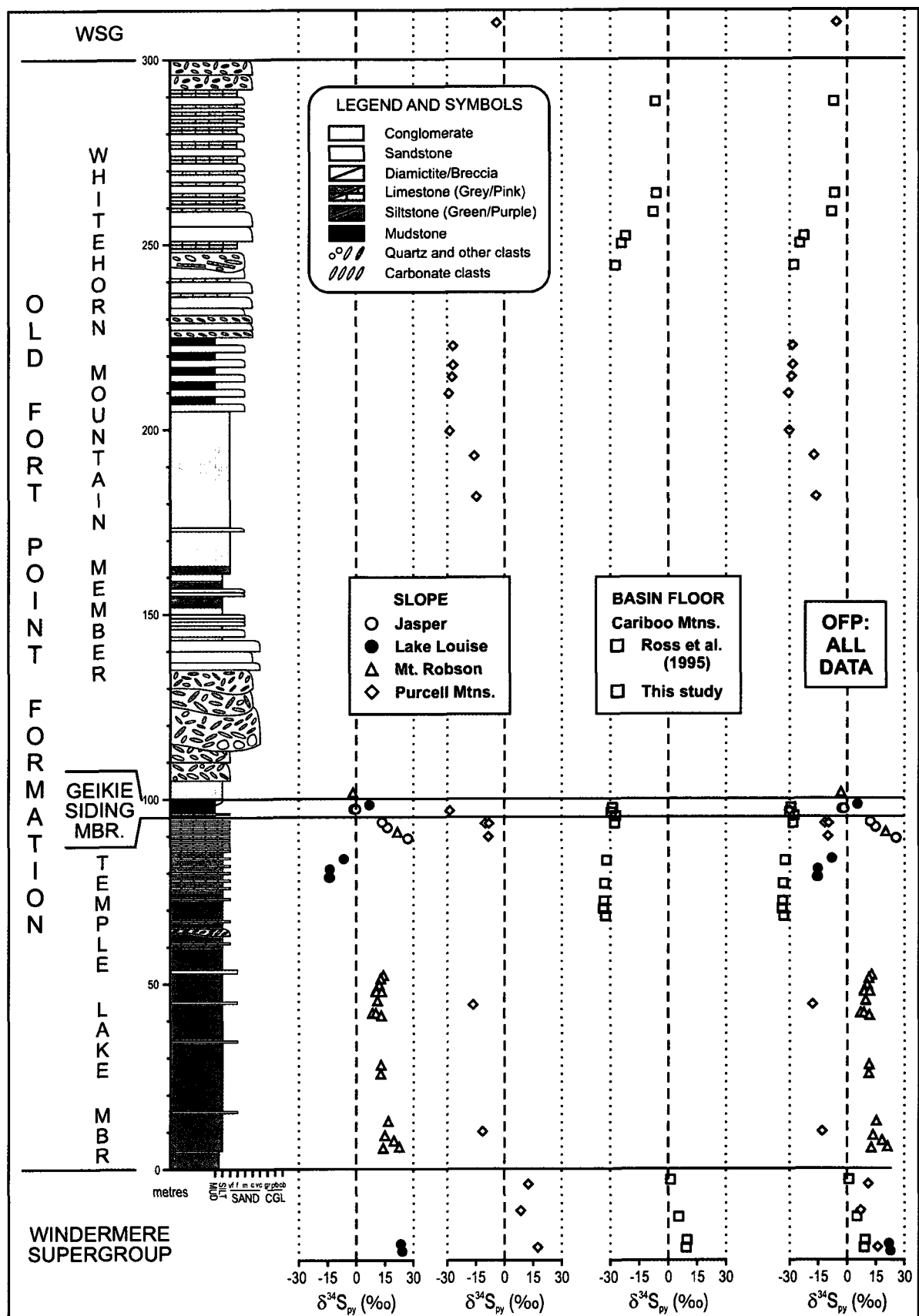


Figure 5.17: Histogram plot of sulfur isotopic analyses of pyrite from the OFP, divided up into its three constituent members. Plot includes analyses from this study and those previously published by Ross et al. (1995).

Figure 5.18: Schematic stratigraphic section of the OFP (Chapter 2), its three constituent members, sulfur stable isotopic profiles from sampled locations and a composite profile of all analyzed $\delta^{34}\text{S}_{\text{py}}$ values. Note the variability in isotopic values from slope strata the lower two members (TLM – GSM). Isotopic profile from Cariboo Mountains also includes results previously published by Ross et al. (1995).



mudstone units (-29.56 to -27.12‰). Overlying WSG strata display a slightly negative value (-3.95‰). Additional samples were analyzed from Eagle Valley (CM1), Cariboo Mountains and gave results similar to those reported by Ross et al. (1995) (Fig. 5.18). Here, the $\delta^{34}\text{S}$ values are generally positive in strata below the OFP and show an abrupt negative shift upward in the TLM (-18.1 to -31.9‰). Values are slightly less negative in the GSM (-27.7 to -25.3‰) and in the lower part of the WMM (-25.4 to -20.0‰), but return to near zero values in the upper part of the WMM (-5.2 to -3.70‰). Samples collected elsewhere in Cariboo Mountains were more variable with the TLM ranging from -29.8 to -9.4‰, the GSM from -25.2 to -19.1‰ and the WMM at 5.1‰ (Ross et al., 1995).

5.7 CARBONATE PARAGENESIS

Determining the process and timing of each OFP carbonate phase is crucial to understanding the physical and chemical conditions under which the mineral precipitated, and thus, how to meaningfully interpret the stable isotopic analyses. Because of the inferred *a priori* global significance of the isotopic results, many recent studies of Neoproterozoic carbonates do not first conduct a detailed petrogenetic analysis to understand the nature and effect of diagenesis on these ancient rocks (or at least, the petrographic data are not included). Instead, chemical screening tests are applied to identify the “least altered” phase as a proxy of coeval seawater, or all the various calcite and dolomite phases are analyzed and simply compared to ensure stratigraphic consistency as an indicator of a “primary” origin. The following is a detailed description of the paragenetic timing of the carbonate phases in the Ediacaran-aged OFP, as recommended by Fairchild and Kennedy (2007).

CC1 is the earliest calcite phase, and inherited its physical and chemical characteristics upslope before being transported downslope predominantly by sediment-gravity flows. Texturally, the lack of clear grain boundaries and its

inclusion-rich nature suggest its origin as shallow marine (shelf) cement. Its typically low Fe and Mn content indicates precipitation under relatively oxic conditions; suggesting either a seafloor precipitate and/or early diagenetic cement under pre-anoxic substrate conditions. Within the TLM and GSM, the low Sr content (<500 ppm) also suggests that CC1 may not have had an initial aragonitic mineralogy. Although the low Sr content could simply reflect replacement of Sr by Mn or Fe during diagenetic alteration to low-magnesium calcite (Veizer, 1983), there is no obvious negative correlation of Sr with either trace-element to support this scenario (e.g. Fig. 5.5B). However, the limited chemical data from the WMM, (Sr content of CC2 from 2621 to 4313 ppm) do suggest that aragonite was the precursor mineralogy upslope during later stages of OFP deposition.

The early deep-marine cement phase CC2 forms poikilotopic crystals that envelope CC1 in limestone strata. In the OFP, early diagenesis (CC1 + CC2) lithified the substrate and significantly reduced porosity and permeability, thereby limiting the effects of subsequent metamorphic fluids. At most locations in the southern Canadian Cordillera the low-grade metamorphism resulted in neomorphic recrystallization, simply obscuring textural relationships. However, at more proximal slope locations (Lake Louise, Jasper) where metamorphic grade is lower, stratigraphically ascending differences in textural features of CC1 + CC2 potentially indicate important chemical changes at, or just below the sediment-water interface. At these localities, and within the lower purple-coloured TLM limestone rhythmites, CC1 + CC2 are readily distinguishable on BSE images, with CC1 characterized by comparatively lower Fe and Mn concentrations than CC2. Trace-element concentrations in CC2 usually are not significantly elevated suggesting precipitation under at least sub-oxic conditions, perhaps in the nitrate reduction zone (e.g. Berner, 1981; Morad, 1998). Stratigraphically-upward, and in the same outcrop (Lake Louise, Jasper), CC1 + CC2 in green-coloured TLM and GSM strata are more recrystallized and difficult to differentiate either petrographically or geochemically. Because samples were collected from the same locality, it is unlikely

that this textural change is due to metamorphism. Rather, the greater dissolution of the pre-existing CC1 in the upper part of the TLM and overlying GSM was likely the result of increased carbonate alkalinity, possibly caused by an increase in organic matter oxidation during progressive microbial diagenesis (e.g. bacterial sulfate reduction) (e.g. Froelich et al., 1979; Arthur et al., 1983; Berner, 1981, 1984; Morad, 1998). This is consistent with the appearance of pyrite in the green-coloured TLM limestone units and the depositional character of the organic-rich GSM related to reducing/anoxic conditions. The availability of organic matter for microbial diagenetic reactions during deposition of later WMM limestones is also suggested by the consistently recrystallized mosaic of CC2 sparite with no relict CC1 features.

DOL1 was only observed in siliciclastic units of the TLM, both within the basal siltstone and limestone rhythmites. The near-euhedral morphology, detrital inclusions and low trace-element concentrations of DOL1 suggest that it is an early, shallow-subsurface cement that precipitated prior to significant iron reduction, unlike the subsequent ferroan DOL2. Both dolomite phases likely precipitated relatively soon after deposition from a carbonate precursor and an increase in carbonate alkalinity during anoxic, organic matter degradation (e.g. bacterial sulfate reduction); perhaps a mechanism similar to “organogenic” dolomites (e.g. Compton et al., 1988; Mazzuolli, 2000). In similar fashion to CC2 in calcite-rich strata, DOL1 and DOL2 perhaps played an important role in lithifying siliciclastic sediment shortly after deposition.

DOL1 is rimmed by well-zoned overgrowths of the more ferroan DOL2 (and ANK, see Fig. 5.19), which is commonly observed in immature siliciclastic rocks of all three OFP members. The good negative linear correlation between MgCO_3 and FeCO_3 concentrations in the dolomite phases (and ANK) (Fig. 5.5G) reflects progressively more reducing conditions during precipitation of DOL2 from dissolution of the pre-existing DOL1 and increasing incorporation of Fe into the dolomite crystal structure during burial. This chemical relationship suggests a continuous fluid history, although pore fluid underwent a change from approx-

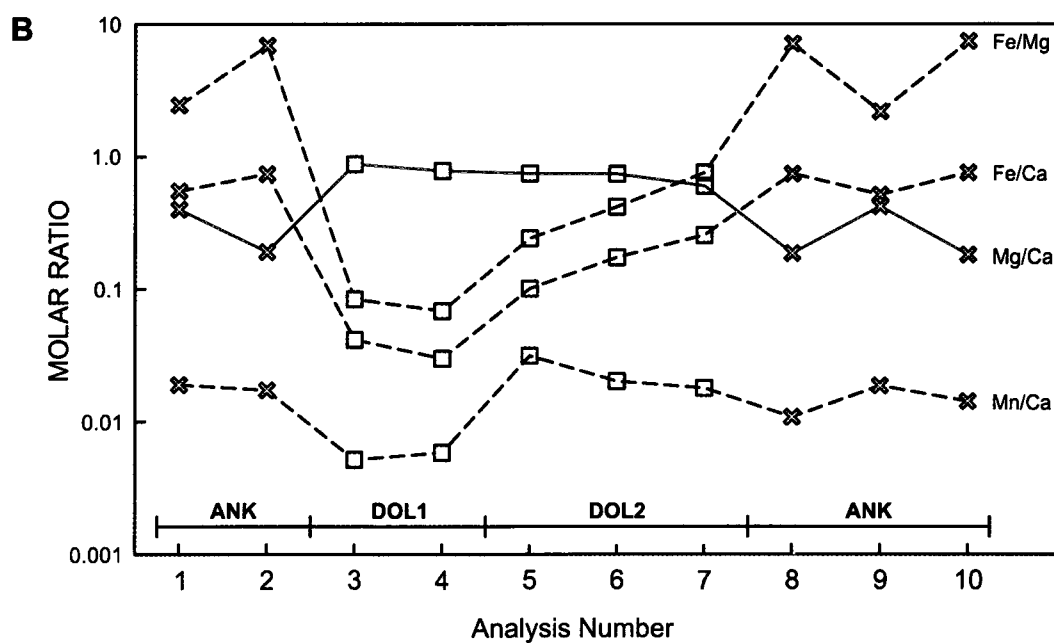
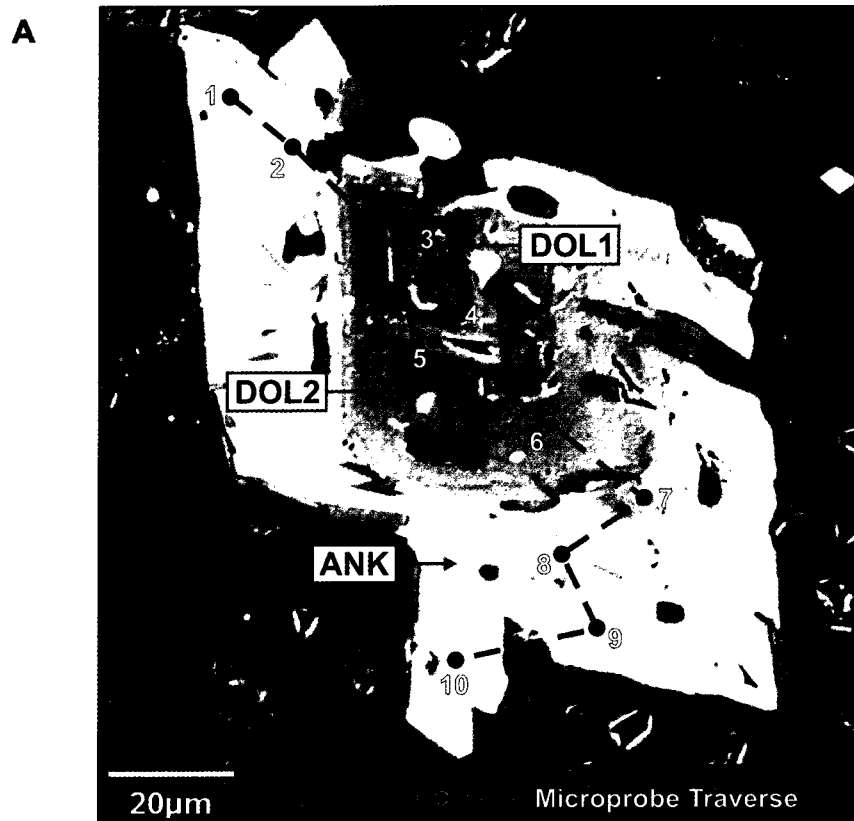


Figure 5.19: A) BSE image of electron microprobe chemical traverse of zoned dolomite crystal containing DOL1, DOL2 and ANK from MR1. B) Chemical analyses of Ca-normalized trace element ratios illustrating distinct chemical differences in diagenetic (DOL1 and DOL2) and metamorphic (ANK) phases.

-imately sub-oxic with low trace-element concentrations to anoxic with high concentrations of reduced iron. Such an evolution is most consistent with a microbially-mediated early diagenetic fluid and argues against the introduction of meteoric fluids or hydrothermal metamorphic brines. These types of fluids generally do not undergo a progressive redox transition and in many cases result in the precipitation of identifiable new dolomite phases with different physical and chemical characteristics (e.g. Warren, 2000).

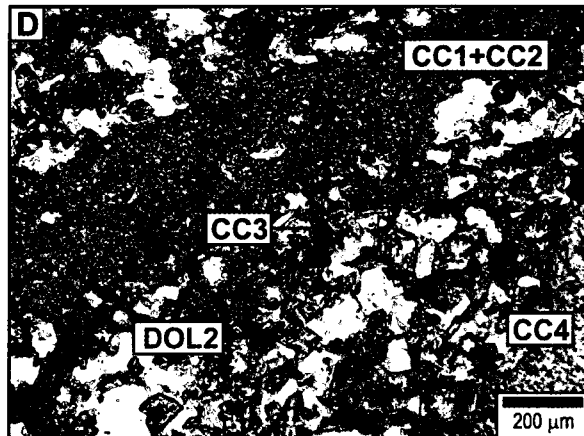
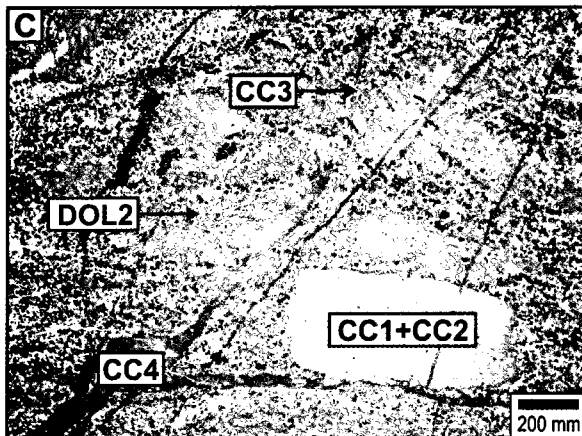
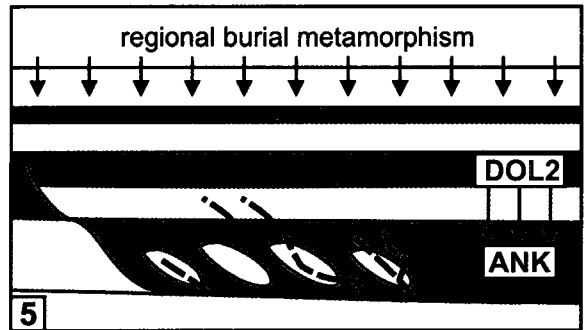
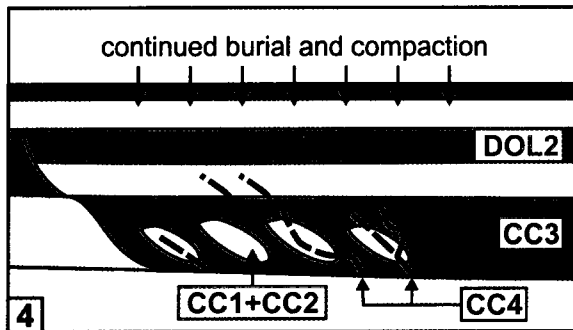
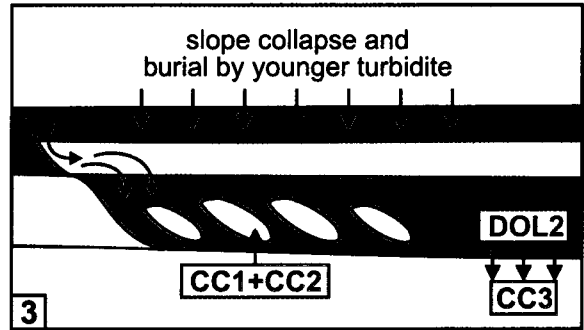
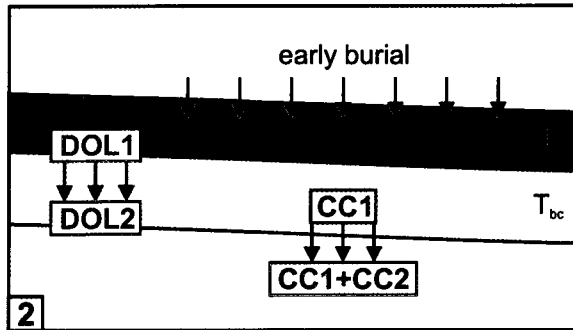
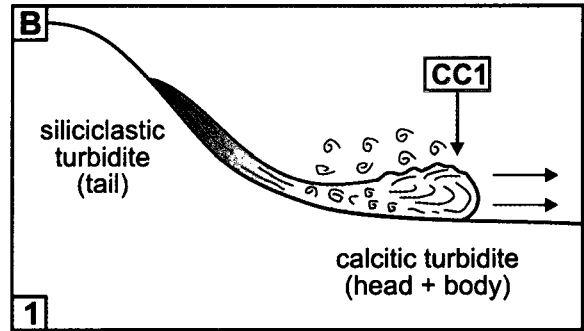
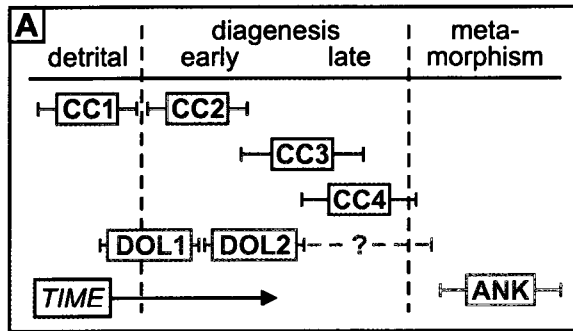
In terms of OFP diagenesis, late-stage carbonate burial cements include the coarse crystalline CC3 and vein CC4, which are generally more iron-rich than earlier calcite phases. Similar to dolomite, the later calcite phases show good linear chemical relationships suggesting that they were principally derived from the dissolution of pre-existing local calcite. CC3 is commonly observed replacing DOL2 and is responsible for cementing fine- and coarse-grained siliciclastic units prior to compaction. Therefore, it also is early diagenetic, and is the latest early diagenetic phase recognized. CC4 is a relatively late-stage vein phase that cross-cuts limestone beds containing CC1 + CC2 and DOL2 or CC3 cements. It is interpreted to be related to burial compaction that remobilized prior calcite phases, and infilled local fractures.

Carbonate cement phases DOL2 and CC3 are characterized by elevated trace-element content and are interpreted to have been formed in the shallow subsurface after deposition in the deep ocean. The observed continuum in their chemical compositions is consistent with precipitation from a fluid that underwent redox changes with progressive burial. Their preserved chemical composition is interpreted to reflect the dominant geochemical reduction zone where precipitation began: Mn-enrichment in the Mn-reduction zone; Fe-enrichment in the Fe-reduction zone; and Mn + Fe enrichment a combination of both (e.g. Froelich et al., 1979; Berner, 1981; Morad, 1998). Both stratigraphic position and geographic location show a basic correlation with chemical composition of the cements. Strata in the lower part of the TLM, and OFP strata at more proximal slope locations (Lake

Louise, Jasper), show elevated Mn or Mn + Fe trends. The GSM, and OFP strata in more basinward paleogeographic locations (Mount Robson, McKale River, Cariboo Mountains) show only enrichment in iron. These variations may be related to a greater availability of Fe in deeper waters in addition a combination of organic-matter fall-out and/or sedimentation rate and/or detrital composition (e.g. higher iron versus manganese fluxes to deep-ocean). The preservation of distinctive Mn and Fe chemical signatures in the carbonate cements implies precipitation initiated in the sub-oxic zone. With progressive burial, microbially-mediated processes such as bacterial sulfate reduction (BSR) and/or bacterial methane generation may have influenced the cement chemistry (see below).

Unlike the complex diagenetic history in many Paleozoic shallow-marine successions, interpretation of the Ediacaran deep-marine OFP is comparatively straightforward. The paragenetic sequence (Fig 5.20A and B) is interpreted to be CC1 → CC2 & DOL1 (?) → DOL2 → CC3 → CC4 → ANK. Although most petrographic sections were usually characterized by only one or two carbonate phases, a TLM breccia unit with local limestone clasts from Lake Louise provides perhaps the most complete picture of relative timing in the OFP (Fig. 5.20C and D) and is schematically presented in Fig 5.20B (1 to 5). Initial deposition in deep-ocean environments occurred from line-sourced, turbidity currents that transported detritus of CC1 from upslope staging areas. Physical, textural and chemical characteristics of CC1 suggest formation under relatively oxic conditions whereby it precipitated either on the seafloor and/or as early diagenetic cement, prior to the downslope transport event. Diagenesis and lithification took place in the shallow substrate soon after deposition with CC2 cement encompassing CC1. DOL1 (not observed in breccia unit) may be an early diagenetic cement, but would have been entirely replaced by DOL2 in the upper, finer-grained siliciclastic part of the bed. CC2 and DOL2 precipitated prior to emplacement of the next turbidite, and the slope collapse that deposited the breccia further downslope. Continued cementation occurred during burial with CC3 replacing DOL2. CC4 is a fracturing-

Figure 5.20: A) Relative paragenetic timing of OFP carbonate phases. B) Schematic diagrams (1 to 5) illustrating paragenetic timing observed in a TLM limestone breccia unit: 1) Turbidity current transport of CC1 from upslope staging area and deposition in the deep ocean; 2) Early burial and lithification whereby CC2 cement encompasses grains of CC1, DOL1 cementation in the siliciclastic bed (not observed in TLM breccia) with extensive replacement by DOL2 soon after; 3) Slope collapse and burial by younger turbidites, CC3 cement replaces DOL2 in siliciclastic units and breccia matrix; 4) Continued diagenetic cementation during burial (CC3) and compaction (CC4); 5) Regional metamorphism and recrystallization of DOL2 to ANK (not observed in TLM breccia). C) to D) Representative stained thin section photomicrographs from TLM breccia unit. Pink to red coloured staining indicated iron-poor calcite phases, purple to royal blue staining indicates iron-rich calcite phases, no staining indicates iron-poor dolomite and light blue to turquoise staining indicates iron-rich dolomite.



filling phase formed during compaction, with the final process being regional metamorphism and recrystallization of DOL2 to ANK (not observed in TLM breccia). In summary, the paragenetic sequence records the progressive effects of redox-mediated burial diagenesis controlled mainly by the precursor carbonate phase (CC1) and bacterial anaerobic oxidation of organic matter (e.g. Froelich et al., 1979; Berner, 1981; Morad, 1998), with the rate of sedimentation also playing a role. The presence of pyrite formed from bacterial sulfate reduction in addition to the filamentous texture of hematite (e.g. Juniper and Fouquet, 1988; Kennedy et al., 2004) also support the activity of microbial organisms during early diagenesis associated with episodic turbidite deposition.

5.8 $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ AND $\delta^{34}\text{S}$ ISOTOPIC SIGNATURES

5.8.1 Carbonate: $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$

5.8.1.1 *Effect of metamorphism*

An east to west transect in the southern Canadian Cordillera records the transition from slope to basin-floor environments, but also an increase in regional metamorphic grade. The fairly uniform $\delta^{18}\text{O}$ value at each location (Tables 5.2 and 5.3; Figs. 5.13, 5.14 and 5.15), which also varies little with stratigraphic position, is interpreted to result from metamorphic homogenization of the oxygen isotopic composition that overprinted any depositional or diagenetic signature. The progressively more negative values toward the west reflect increasing burial temperature during metamorphism (e.g. Morad, 1998) and thus, the $\delta^{18}\text{O}$ system is not be considered further.

Unlike the $\delta^{18}\text{O}$ system, the $\delta^{13}\text{C}$ isotopic record shows systematic stratigraphic variation throughout the OFP (Tables 5.2 and 5.3; Figs. 5.13, 5.14 and 5.15) and is characterized by negative $\delta^{13}\text{C}$ values, which is similar to many other basal Ediacaran post-glacial carbonate successions, (e.g. Kennedy, 1996; James et al., 2001; Halverson et al, 2005; Shen et al., 2005; Hoffman et al., 2007). $\delta^{13}\text{C}$ values are

commonly better preserved than $\delta^{18}\text{O}$ because most secondary metamorphic fluids that might alter the isotopic values are generally characterized by low carbon concentration relative to the carbon in the carbonate rock (e.g. Banner and Hanson, 1990). Additionally, reduced permeability in the OFP carbonate units from early lithification most probably contributed to isotopic preservation (e.g. Morad, 1998 and references therein). The basal part of the OFP at Frances Creek is unusual because $\delta^{13}\text{C}$ values are slightly negative to strongly positive (CC1 + CC2, and DOL2) unlike all other TLM outcrops. Compared to all other study locations, strata here are observed to be locally more tectonically deformed. Furthermore, limestone beds are more recrystallized and affected by ductile folding, brittle faulting and brecciation in addition to cross-cutting quartz-calcite-ankerite veins ($\delta^{13}\text{C} = -3.62\text{‰}$). Metamorphic recrystallization typically leads to progressively more negative isotopic signatures (e.g. Baumgartner and Valley, 2001 and references therein), so it would seem unlikely that this is the principal cause of the unusually positive and variable $\delta^{13}\text{C}$ values compared to the TLM elsewhere in the basin. This suggests that these data do not reflect the intensity of tectonic deformation, nor grade of metamorphism, but rather represent a local diagenetic process (see below).

Throughout the southern Canadian Cordillera, clasts of shallow-marine carbonate are characterized by variable $\delta^{13}\text{C}$ composition, including some values that are unique to clasts at a given locality, implying their pre-transport isotopic signatures (depositional or early diagenetic) remained intact during deeper burial and regional metamorphism. Additional support for the lack of metamorphic homogenization of the $\delta^{13}\text{C}$ isotopic signal is provided by the regional consistency in the OFP data and overall variability in results from other WSG deep-marine limestone units across the southern Canadian Cordillera. For example: Middle Miette Group (below OFP) -2.54 to -1.31 ‰; Upper Kaza Group, -6.82 to -0.62 ‰; Isaac Formation, -3.24 to 3.81‰; and Upper Miette Group, -1.50 to -3.33 ‰ (Table 5.3; G. M. Ross, unpublished data).

5.8.1.2 *Effect of diagenesis*

A detailed understanding of the carbonate phases and diagenetic history of the OFP allows assessment of the impact of burial diagenesis on the $\delta^{13}\text{C}$ isotopic record. The textural features, chemical characteristics and isotopic compositions of the OFP carbonate units are interpreted to record depositional and/or diagenetic processes with no evidence of significant alteration by secondary fluid movement. CC1 is interpreted to have precipitated under relatively oxic marine conditions and likely is the best possible candidate in the OFP for a $\delta^{13}\text{C}$ isotopic proxy for coeval Ediacaran seawater or interstitial shallow-marine pore-water isotopically indistinct from seawater. Unfortunately, the detrital grains of CC1 and the early, deep-marine syn-sedimentary cement CC2 form a recrystallized mixture inseparable for stable isotopic analyses.

In order to evaluate the preservation of the stable isotopic signature in carbonate rocks, a number of chemical techniques have been proposed (e.g. Brand and Veizer, 1980, 1981; Veizer, 1983; Fairchild and Spiro, 1987; Kaufman et al., 1991, 1992; Derry et al., 1992; Narbonne et al., 1994; Kaufman and Knoll, 1995). The Mn/Sr ratio is the most commonly used, since Mn (and Fe) commonly replaces Sr during diagenetic recrystallization of calcite in Phanerozoic carbonate rocks (e.g. Brand and Veizer, 1980, 1981; Veizer, 1983). In Proterozoic shallow-marine carbonate successions, samples with Mn/Sr < 2 to 3 are considered to be the “least-altered” and therefore reflect primary isotopic compositions (e.g. Derry et al., 1992; Kaufman et al., 1992, Kaufman and Knoll, 1995), although modeling suggests that even when Mn/Sr ~1, large isotopic shifts may have occurred (Jacobsen and Kaufman, 1999). However, many of these studies are not preceded by a detailed petrographic analysis to identify and isolate the various carbonate phases present prior to chemical screening. As consequence, isotope data potentially represent a *mélange*, and hence, an average of some number of different phases, each with a potentially unique geochemical composition. Furthermore, many $\delta^{13}\text{C}$ isotopic signatures are cited as reasonably unaltered despite Mn/Sr >10 (e.g. Narbonne et

al., 1994; Kaufman and Knoll, 1995). Microprobe analyses of the carbonate phases show a wide spread of Mn/Sr ranging from 0.1 to 200 (Fig. 5.5D), irrespective of mineralogy, paragenetic timing, or $\delta^{13}\text{C}$ isotopic values. Cross-plots of the limited $\delta^{13}\text{C}$ database with corresponding microprobe analyses (average of 3 or 4 points) show no obvious FeCO_3 trend for the calcite phases, with DOL2 exhibiting a positive $\delta^{13}\text{C}$ shift ($\sim 2\text{‰}$) as FeCO_3 increases by approximately 12 mol% (Fig. 5.21A). With respect to increasing MnCO_3 , both DOL2 and CC3 show progressively more negative values (Fig. 5.21B) suggesting that slight changes in Mn content in these later diagenetic cements may have impacted the carbon isotopic signature. DOL2 was also the only OFP phase with a co-linear negative trend of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ (Fig. 5.16B), usually indicative of diagenetic alteration (e.g. Ripperdan, 2001). The basis for the Mn/Sr cutoff of Jacobsen and Kaufman (1999) was from modeling the effect of meteoric or metamorphic fluids, but it did not include early diagenetic phases influenced by reduction of organic matter. Together these data suggest that the Mn/Sr screening tool is not a reliable discriminator for the $\delta^{13}\text{C}$ isotopic signal of carbonate phases in the OFP, and likely the remainder of the deep-marine WSG.

A number of internal trials were performed in an attempt to quantify the effects of progressive microbial-mediated diagenesis on $\delta^{13}\text{C}$ signatures in the OFP including: CC1 + CC2 changes at the bed-scale; early CC1 + CC2 in limestone compared to later CC3 in the overlying siltstone of the same turbidite; CC1 + CC2 compared to a late-stage CC4 veins in the same bed; and overall early calcite phase (CC1 + CC2) versus later burial cements (DOL2, CC3, CC4). In the first trial, a TLM limestone bed (CC1 + CC2) collected from basin deposits in the Cariboo Mountains showed an apparent progressive decrease in iron-content from base to top in the stained thin section (Fig. 5.22A). Microprobe analyses from three zones (base, middle, top) confirmed the initial observation as FeCO_3 decreased from 1.18 to 0.85 to 0.38 mol% (each an average of 3 or 4 points). Corresponding $\delta^{13}\text{C}$ values from base to top displayed a correlative shift from -9.70 to -9.55 to -8.62‰, a change of about 1‰. Higher in this section, a GSM limestone bed showed a similar iron

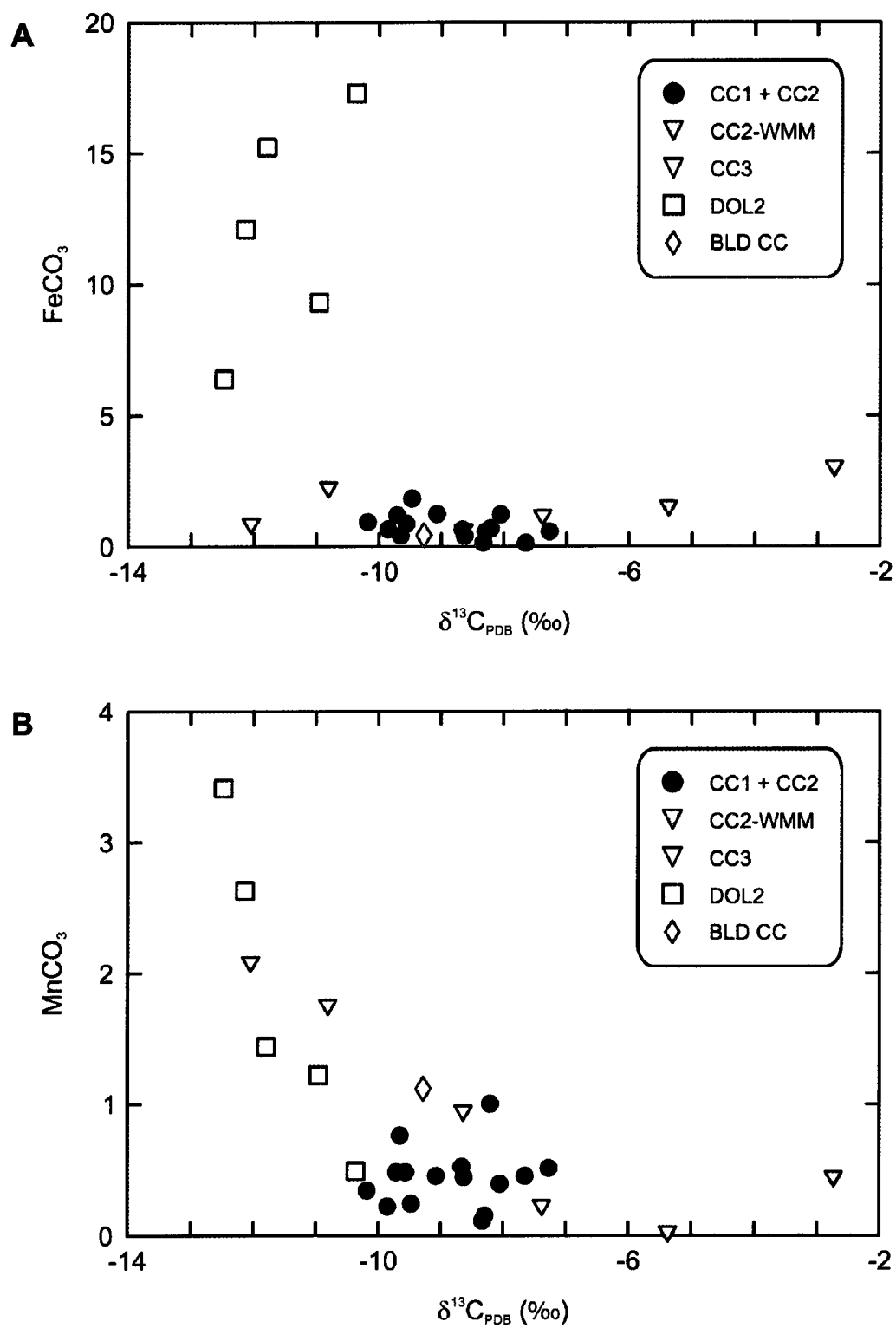


Figure 5.21: A) – B) Cross plots of $\delta^{13}\text{C}$ isotopic analyses and corresponding averaged trace-element analyses from the electron microprobe. A) $\delta^{13}\text{C}$ vs. FeCO_3 . B) $\delta^{13}\text{C}$ vs. MnCO_3 .

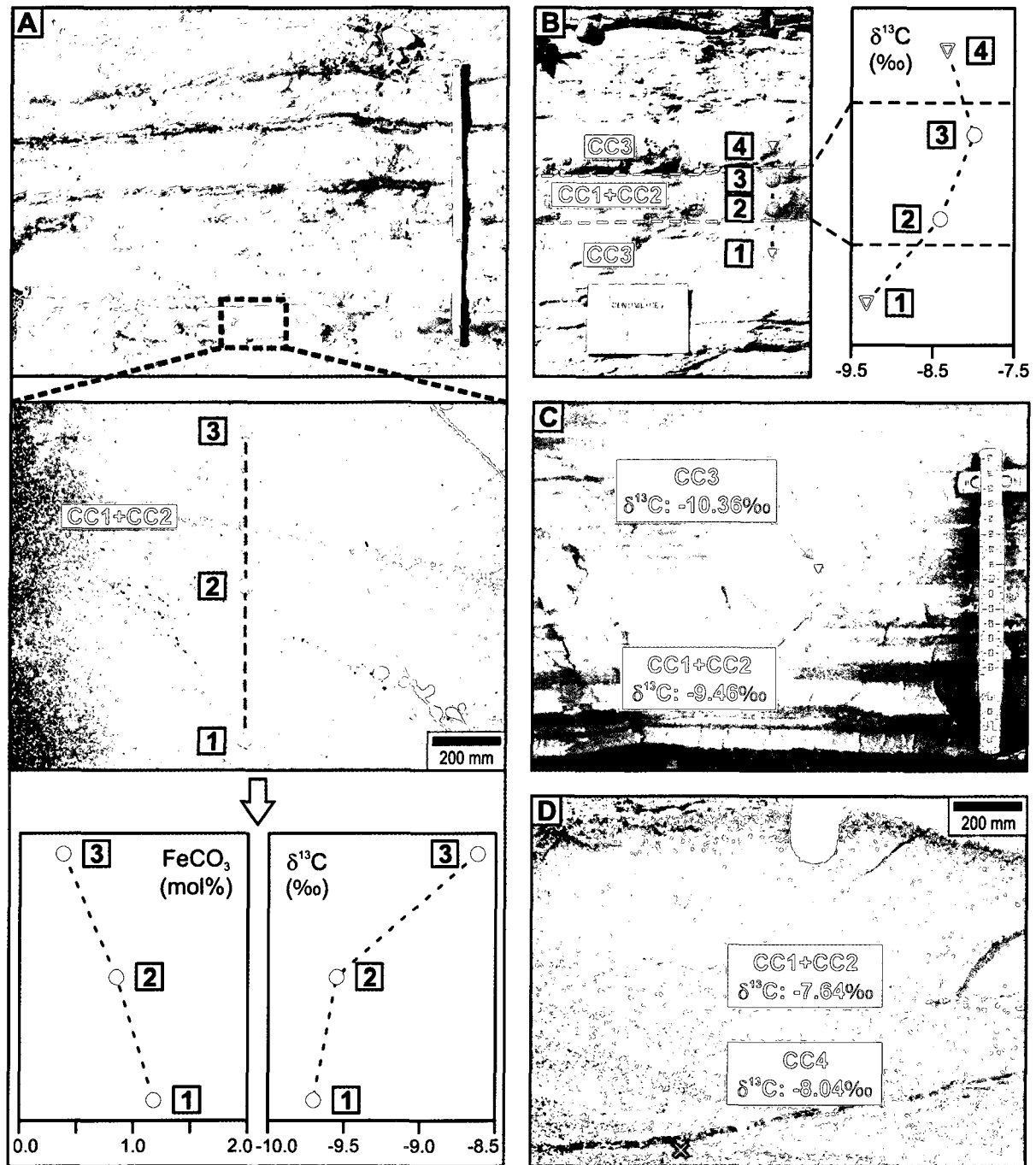


Figure 5.22: A) Example of a TLM limestone bed from CM1 illustrating physical, chemical and isotopic changes that take place during burial diagenesis. Outcrop photo of the bed (dashed box) showing upward colour change from dark grey to white. Ruler is 50 cm. Photomicrograph showing upward change in staining characteristics from purple to red and locations of electron microprobe analyses. Plots that show the upward decrease in FeCO_3 content, and positive shift in $\delta^{13}\text{C}$ values. B) GSM limestone bed from CM1 showing a positive shift in $\delta^{13}\text{C}$ from a CC3 cemented to a CC1 + CC2 bed, then a negative shift in the overlying CC3 cemented bed. C) $\delta^{13}\text{C}$ isotopic values from a TLM limestone (CC1 + CC2) - siltstone (CC3) couplet from MR1. D) $\delta^{13}\text{C}$ isotopic values from a TLM limestone (CC1 + CC2) bed and cross-cutting CC4 vein LL1.

pattern from base to top as the $\delta^{13}\text{C}$ values shifted approximately 0.5‰ from -8.41 to -7.99‰ (Fig. 5.22B). Both the underlying (-9.31‰) and overlying (-8.33‰) ferroan carbonate-cemented (CC3) fine-grained sandstone bed is slightly more negative (<0.5 to 1‰) compared to the proximal CC1 + CC2 in the limestone bed. The results suggest that in deep basinal environments, there is redox stratification within individual turbidite beds whereby the upper portions of the substrate likely had a longer connection with overlying surface water, and therefore was less influenced by progressive early diagenesis (e.g. CC1>CC2 at top of the bed; CC1<CC2 at bottom of bed).

Near-identical results of a <0.5 to 1‰ difference between the TLM limestone (CC1 + CC2) and overlying carbonate-cemented siltstone (CC3) was observed also in rhythmic couplets at Lake Louise (-8.20‰ and -8.64‰) and Mount Robson (-9.46‰ and -10.36‰) (Fig. 5.22C). In these examples, CC3 in the overlying siltstone bed is more iron-rich than CC1 + CC2 in the underlying limestone bed. Thus, a redox stratification effect is observed similar to the Cariboo Mountains example described above, but at the couplet-scale, rather than the bed-scale. These consistent shifts in iron content and $\delta^{13}\text{C}$ values within a single turbidite bed in the basinal section and within a turbidite bed-set in more proximal slope sections implies that the redox stratification is directly linked to sedimentation rate: lower in basin-floor versus higher in slope depositional settings. Additionally, the $\delta^{13}\text{C}$ of a cross-cutting late-stage CC4 vein (-8.04‰) was <0.5‰ different to the CC1 + CC2 in the same limestone bed (-7.64‰) (Fig. 5.22D). In fact, the three later burial cement phases (DOL2, CC3, and CC4) are generally characterized by values only slightly more negative (<0.5 to 3‰) compared to CC1 + CC2 in a similar stratigraphic interval.

There are two notable exceptions where these later carbonate cements within the OFP likely precipitated in deeper zones and the $\delta^{13}\text{C}$ values were altered by the processes of bacterial sulfate reduction (BSR) and/or bacterial fermentation. The first is during transgressive and highstand deposition of the upper part of the TLM

and organic-rich GSM, where bottom-water conditions are interpreted to have been highly reducing to anoxic (Chapter 4). In more proximal slope locations (Lake Louise, Jasper), $\delta^{13}\text{C}$ shows a slight negative perturbation ($\sim 2\%$) in strata of the GSM, superimposed on the overall positive trend. This negative excursion in the GSM also corresponds with highly negative $\delta^{13}\text{C}$ values from its organic-rich mudstone units (-32.30 to -28.44%). BSR operates where there is no dissolved oxygen (seawater or porewater) and takes place at the water-sediment interface or in the water column in anoxic environments (Curtis, 1987; Morad, 1998). During post-glacial GSM deposition, an increase in productivity led to an increase in available organic material for anaerobic oxidation at the seafloor along with bottom-water anoxia (Chapter 4). Coupled with depleted bicarbonate from BSR of this organic matter (Raiswell, 1987, 1988), the resulting precipitation of CC_2 likely incorporated more of the negative $\delta^{13}\text{C}$ signature from the organic matter. However, if correct, it is unclear why a similar negative $\delta^{13}\text{C}$ shift is not recorded in limestone beds from the basinal section in the Cariboo Mountains where bottom-water conditions are interpreted to have been similarly anoxic at this time (Ross and Murphy, 1988; Ross et al., 1995; Chapter 4), although local variations in the overall diffusion rate possibly related to differences in sedimentation rate may have played a role.

The second example is the unusual slightly negative to elevated $\delta^{13}\text{C}$ values in the tectonically deformed lower OFP at Frances Creek in the Purcell Mountains. These values are 10 to 15‰ more positive than typical TLM, implying the in-situ generation of ^{13}C -rich bicarbonate porewaters, and may record the large fractionation effect associated with deeper bacterial methane generation (carbonate reduction and fermentation) (e.g. Irwin et al., 1977). Sedimentation rates, however, were unusually high at Frances Creek, and attributed to syn-sedimentary growth fault activity (Chapter 3). This site was the only location sampled in the Purcell Mountains, and thus it remains unclear if the TLM rhythmites elsewhere in this

region (e.g. Kubli, 1990; Warren, 1997) record similar positive $\delta^{13}\text{C}$ values or are negative as observed in the rest of the Windermere basin.

Overall, the identifiable and measurable minor changes between the early CC1 + CC2 and progressively later diagenetic phases (DOL2, CC3 and CC4) suggests that the contribution from organic-matter with a significantly negative $\delta^{13}\text{C}$ signature did not result in distinctively more negative $\delta^{13}\text{C}$ values during the re-precipitation of later diagenetic phases, which may occur (e.g. Irwin et al., 1977; Hudson, 1978; Coniglio, 1989). However, it is important to note that all of the above diagenetic phases in the OFP formed by bacterial mediated processes do result in minor and measurable modification of the $\delta^{13}\text{C}$ isotopic signature. Studies that rule out these processes based solely on isotopic comparison may be overlooking their effects. It is also evident that factors such as lithology (limestone versus siltstone), grain-size, organic-matter availability, and sedimentation rate may all combine to play a role in the resultant $\delta^{13}\text{C}$ values of deep-marine deposits.

5.8.1.3 Preservation of the $\delta^{13}\text{C}$ carbonate signature

The $\delta^{13}\text{C}$ isotopic analyses from CC1 + CC2 in the OFP are interpreted as reasonable approximations of the original CC1 isotopic composition, and which have not undergone significant isotopic alteration (i.e. >1 to 2‰) during early deep-marine diagenesis. This assertion is based on a combination of textural, isotopic and stratal considerations:

- 1) CC2 is an early, diagenetic cement that precipitated under sub-oxic conditions in shallow subsurface pore-fluids from the precursor CC1. It is not a distinctly zoned overgrowth and is characterized by only slightly elevated trace-element chemistry. Thus, its isotopic character should mostly reflect CC1 with slight modification from the more depleted organic matter involved in the diagenetic reactions, as opposed to new calcite that precipitated with a completely different isotopic composition.

- 2) Individual limestone beds or limestone-siltstone couplets with a measurable increase in trace-element concentration (Mn, Fe) during early diagenesis show evidence for alteration of the $\delta^{13}\text{C}$ isotopic record, however this impact is consistently $<2\text{‰}$. Conversely, $\delta^{13}\text{C}$ values from later cement phases (DOL2 and CC3) do show evidence for precipitation from fluids whose chemical (Mn, Fe) character changed from progressive redox reactions.
- 3) Stratigraphically upwards, the $\delta^{13}\text{C}$ profile at most locations (except Purcell Mountains) in the TLM trends toward less negative values, which coincides also with increasing recrystallization (i.e. more diagenetic alteration of CC1 and precipitation of CC2; therefore $\text{CC2} > \text{CC1}$ upsection). If the $\delta^{13}\text{C}$ value of diagenetic CC2 was significantly more negative than CC1, it would be expected that the opposite trend towards more negative values should result, recording the increasing volumetric dominance of CC2.
- 4) The WMM exhibits a similar stratigraphic upward trend of decreasing $\delta^{13}\text{C}$ isotopic composition, which consistently approaches near-zero values at three widely separated locations despite the limestone beds being consistently recrystallized to CC2 (CC2-WMM).
- 5) Similar negative $\delta^{13}\text{C}$ values were derived from clasts with bladed-calcite crystals (neomorphosed aragonite), which are interpreted to have precipitated and grew on the sea-floor, although they may also be syn-sedimentary replacement of stromatolites (James et al., 2001).

Overall, petrographic observations and isotopic tests suggest that most OFP carbonate cements (e.g. CC2) precipitated under sub-oxic conditions following the dissolution of the pre-existing CC1 carbonate material, and therefore, likely inherited its “original” negative isotopic signature. The origins of the highly negative $\delta^{13}\text{C}$ values that characterize CC1 are less clear. Texturally and chemically it suggests crystallization as cement within an oxic zone, possibly from seawater, although more likely from near-surface marine pore waters (perhaps 1‰ different).

The regionally correlatable, stratigraphic pattern of negative $\delta^{13}\text{C}$ values that steadily increase towards near-zero values (Figs. 5.13, 5.14 and 5.15) is also consistent with other basal Ediacaran carbonate successions around the globe (e.g. Halverson et al., 2005).

5.8.2 Organic residue: $\delta^{13}\text{C}$

Overall, there appears to be reasonable stratal co-variance between the $\delta^{13}\text{C}$ values of carbonate and organic matter in the OFP (Figs. 5.13, 5.14 and 5.15). However, the $\Delta\delta^{13}\text{C}$ ($\delta^{13}\text{C}_{\text{carb}} - \delta^{13}\text{C}_{\text{org}}$) of near 20‰ in the TLM and GSM, and approximately 14‰ in the WMM are both less than the range of $\Delta\delta^{13}\text{C}$ from -32 to -25‰ commonly recorded in other Neoproterozoic successions (e.g. Knoll et al., 1986; Narbonne et al., 1994; Hayes et al., 1999; Dehler et al., 2005). Thermal alteration during burial diagenesis and regional metamorphism of the OFP has most probably preferentially shifted the original $\delta^{13}\text{C}$ isotopic signal in the organic residue to less negative values compared to the carbonates (e.g. Valley, 2001; Des Marais, 2001 and references therein). However, if the magnitude of the $\delta^{13}\text{C}$ isotopic shift during burial metamorphism was regionally consistent, then this constant relative change, when used in conjunction with strata where $\Delta\delta^{13}\text{C}$ was measured (paired analyses carbonate and organics), may prove useful in constructing a reliable $\delta^{13}\text{C}$ curve for the siliciclastic-dominated WSG sedimentary pile.

An interesting observation is that the paleogeographic location of the shift from a negative to positive isotopic excursion in GSM strata (Fig. 5.13) corresponds to other identifiable physical (e.g. colour of TLM strata) and chemical changes (e.g. TOC content, $\delta^{13}\text{C}_{\text{carb}}$) in the OFP (Chapters 3 and 4). These consistent changes are interpreted to mark the position of a change in paleo-slope gradient at or near the toe of slope (Chapter 3), and potentially could represent a relatively long-lived (TLM + GSM deposition) ancient oceanic chemical gradient. However, the prominent change in the $\delta^{13}\text{C}$ composition ($\sim 8\%$) of the GSM may simply reflect an increase in metamorphic grade, a common characteristic in other low-grade meta-

sedimentary rocks of Precambrian age (e.g. Hayes et al., 1983 and references therein).

5.8.3 Pyrite: $\delta^{34}\text{S}$

At Eagle Valley in the Cariboo Mountains, the good correlation between changes in lithofacies and $\delta^{34}\text{S}$ values led Ross et al. (1995) to interpret that the sulfur isotopic composition of pyrite was relatively unaffected by the effects of regional metamorphism. Similar to previous studies (e.g. Mohr and Newton, 1983) these authors suggested that there had been no significant transport of sulfur in the metamorphic fluids, and that the system remained rock-buffered (Ross et al., 1995). Most of the pyrite samples collected for this study were at lower metamorphic grade than those of Ross et al. (1995) and show similar systematic stratigraphic trends. This, therefore, suggests that the sulfur isotopic system has not been significantly altered by later regional metamorphic fluids.

Pyrite cubes from the OFP display internal isotopic homogeneity, which contrasts other studies that have noted $\delta^{34}\text{S}$ differences in crystals showing multiple stages of precipitation as a result of the significant fractionation of sulfur during biological or diagenetic processes (Strauss and Schieber, 1980; Raiswell, 1982; McKibben and Ricipuiti, 1998; Katz et al., 1998). Unfortunately, the recrystallized aspect of the pyrite has obscured or completely destroyed primary internal features (e.g. framboid morphology, crystal zoning), which might indicate specific crystallization mechanisms or water-column chemistry (e.g. Strauss and Schieber, 1980; Raiswell, 1982; Lyons and Berner, 1992; Katz et al., 1998; Strauss, 1999). Thus, pyrite in the OFP (and WSG) may reflect an unquantifiable mixture of biogenic and diagenetic phases, each with distinctive isotopic compositions.

Ross et al. (1995) interpreted the pyrite in the WSG (and OFP) to have formed under syn-sedimentary to early diagenetic conditions with the wide range and prominent depletion of the $\delta^{34}\text{S}$ indicative of bacterial mediated sulfate reduction (BSR) (e.g. Chambers and Trudinger, 1979; Berner, 1981; Schidlowski et al., 1983;

Berner, 1984; Canfield, 2001 and references therein). This process occurs in the water column or shallow subsurface pore-waters devoid of oxygen as seawater sulfate is reduced to H_2S , which then reacts with detrital iron minerals to form iron sulfides (e.g. Berner, 1984). Although diagenetic pyrite commonly has a sulfur isotopic composition of -40 to -20‰, laboratory studies have demonstrated that the maximum fractionation between sulfate and sulfide is approximately 45‰ (e.g. Chambers and Trudinger, 1979; Canfield and Teske, 1996; Canfield, 2001 and references therein). These data indicate that other processes are needed in order to generate the significantly negative sulfur values, including, perhaps, repeated oxidation and cycling during disproportionation of sulfur intermediate compounds (e.g. Canfield and Thamdrup, 1994; Canfield and Teske, 1996; Habicht and Canfield, 2001; Canfield, 2001).

Similar to other studies (e.g. Maynard, 1980; Bloch and Krouse, 1992), the observed correlation between $\delta^{34}\text{S}$ pyrite composition and sedimentary facies of the OFP at Eagle Valley (CM1) led Ross et al. (1995) to suggest that diffusion-controlled sulfate availability (seawater sulfate) was the primary control on the resultant sulfur isotopic composition. In their model, the wide range of values reflected the relative rate of diffusion, which generally was assumed to be dependent on sedimentation rate. During times of high sedimentation (sandstone units), and consequently slow diffusion of sulfate from the water column, the rate of sulfate reduction exceeded replenishment, leading to near complete elimination of sulfate in the sediment. This resulted in more positive $\delta^{34}\text{S}$ values in the sulfide that approached the initial isotopic composition (i.e. seawater) of the sulfate. During conditions of low sedimentation (mudstone units), on the other hand, the more negative values are observed because sulfate diffusion was sufficiently rapid to give the substrate an unlimited supply of sulfate (from seawater) for bacterial reduction, with the produced biogenic H_2S binding to reduced iron in the sediment. At other locations in the Cariboo Mountains, however, values from the OFP were more variable and this correlation was not evident in samples from the overlying Isaac Formation

(Ross et al., 1995). Moreover, there is debate about the validity of Rayleigh distillation models to determine isotopic fractionations from sediment pore-water data (e.g. Canfield, 2001).

The OFP displays moderately consistent stratigraphic trends that locally correlate with sedimentary facies, although the new data show considerably more variability (~60‰) than those originally reported by Ross et al. (1995), especially within the lower two members. It is also important to note that although pyrite is ubiquitous in basin to slope strata in the Cariboo Mountains (Ross et al., 1995), it is only present locally in OFP units elsewhere in the southern Canadian Cordillera. The TLM exhibits an extremely wide range of $\delta^{34}\text{S}$ values: highly positive in slope settings at Jasper and Mount Robson (11.26 to 28.38‰); slightly negative in slope settings at Lake Louise and Frances Creek (-16.49 to -6.42‰); and highly negative in the basinal sections of the Cariboo Mountains (-31.9 to -18.1‰; except one positive sample of 9.4‰). $\delta^{34}\text{S}$ values of the GSM at Lake Louise and Jasper are positive (7.49 and 0.31‰, respectively) compared to highly negative values in the basinal Cariboo Mountains (-27.7 to -19.1‰). The TLM and GSM both show a broadly correlative shift from highly negative values in basinal deposits towards less negative and highly positive values in slope settings. Although the same lithological units were deposited by the same process (e.g. turbidity current deposition of limestone, siltstone, mudstone) within the lower two members across the basin, the shift in $\delta^{34}\text{S}$ values is likely related to the difference in sedimentation rate (and diffusion-controlled sulfate availability) at the various paleogeographic locations. Basinal turbidite deposition is interpreted to be characterized by slower rates of sedimentation compared to the more proximal slope settings, and as a result higher diffusion of sulfate from the water column, and thus, more negative values. The local variability in pyrite presence and $\delta^{34}\text{S}$ values in the slope settings, suggest that other factors, in addition to diffusion-controlled sulfate availability linked to sedimentation rate (Ross et al., 1995), were important. Both iron and organic matter have been demonstrated to be important factors in the formation of pyrite by BSR

(e.g. Berner, 1984; Gautier, 1987). As a whole, the WSG shows no evidence of being an iron-limited system (e.g. abundant iron-bearing minerals, iron-carbonate cements), and regional metamorphism eliminates the possibility of distinguishing the type and reactivity of the organic matter (e.g. Gautier, 1987). However, the depth at which BSR processes operate may be limited by the amount of organic-matter available to the system (e.g. Berner, 1982, 1984). The lower two members of the OFP are characterized by the transition from organic-poor (TLM) to organic-rich (GSM) deposition during the Ediacaran post-glacial transgression and early highstand. Although difficult to quantify in rocks of this age, the local sedimentation rate may have had an important control on the resultant amount of organic-matter present when the substrate reached the zone of BSR. Thus, in addition to sulfate availability, the amount of organic matter present in slope settings during deposition of the TLM and GSM likely played an important role in the wide range of values observed in the sulfur isotopic compositions: variations recorded over a regional, basin-wide scale (e.g. TLM $\Delta\delta^{34}\text{S}$ $\sim 60\text{‰}$); and variations recorded over a local, short stratal thickness (e.g. TLM to GSM transition at Jasper, 28.38 to 0.31‰ over 6 m). The WMM presents the most consistent correlation between sedimentary facies, sedimentation rate and $\delta^{34}\text{S}$ values: fine-grained mudstone and limestone units are moderately negative (-29.56 to -14.59‰); whereas coarse-grained sandstone slightly negative to positive (-5.2 to 5.1‰).

At certain locations, the highly negative $\delta^{34}\text{S}$ values of OFP pyrite suggest that sulfate availability was not a limiting factor, usually consistent with sulfidic oceanic water columns. However, S-isotopic data from pyrite in other Neoproterozoic successions (e.g. Gorjan et al., 2000; Shen et al., 2008) and all three members OFP show a wide range of $\delta^{34}\text{S}$ values irrespective of interpreted water column redox conditions (e.g. oxic TLM to anoxic GSM). Thus, similar to the interpretation of Shen et al. (2008) in the northern Canadian Cordillera, $\delta^{34}\text{S}$ values of the OFP pyrite do not reflect basal Ediacaran water column redox chemistry. The values may argue for evidence of a sulfate-rich ocean (e.g. Halverson and Hurtgen,

2007; Shen et al., 2008) during the post-glacial transgression and highstand as a result of the global-scale burial of depleted $\delta^{34}\text{S}$ sulfides in passive continental margin settings (Ross et al., 1995). The issue with this interpretation is that other OFP localities are characterized by consistently high positive $\delta^{34}\text{S}$ pyrite values that approach the coeval seawater sulfate isotopic composition ($\sim 30\text{‰}$) (Claypool et al., 1980); and as a consequence are suggestive of the opposite, namely low-sulfate availability (either within the water column or below the substrate) (e.g. Shen et al., 2003). Collectively, the heterogeneity displayed in the S-isotopic data from the OFP suggests that local or regional factors (e.g. organic matter, sedimentation rate, substrate redox conditions, microbial influences) played an important role in the pyrite $\delta^{34}\text{S}$ value and therefore, making global ocean chemistry inferences from this dataset is questionable.

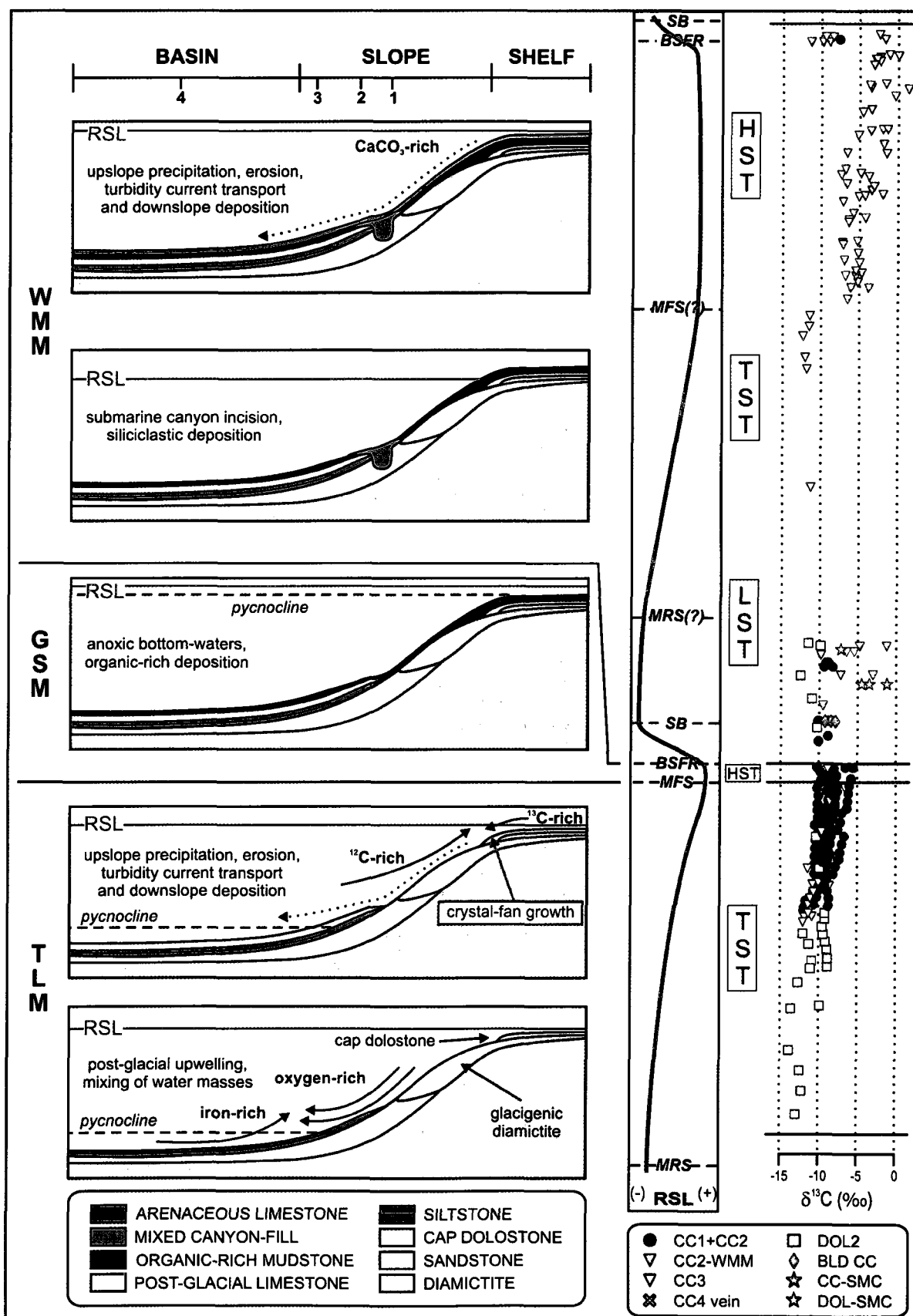
5.9 DISCUSSION

5.9.1 Old Fort Point Formation (OFP): post-glacial depositional model

5.9.1.1 *Temple Lake (TLM) and Geikie Siding (GSM) members*

The lower two members of the OFP are interpreted to represent regional, basin-wide line-sourced deposition in response to a major eustatic rise associated with continental glacial melting (Ross and Murphy, 1988; Ross et al., 1995; Chapter 3) (Fig. 5.23). The onset of OFP deposition is marked by deposits of the post-glacial transgressive systems tract that consist of variably coloured TLM siltstone that contrast strikingly the more typical fine- and coarse-grained, feldspar-rich WSG strata below. More proximal sections display abundant early diagenetic hematite, whose filamentous morphology suggests the influence of bacteria during its precipitation (e.g. Juniper and Fouquet, 1988; Kennedy et al., 2004). Furthermore, it suggests the influx of fresh, oxygen-rich surface water and its mixing with reduced iron (Chapter 3). The basal siltstone grades upwards into the distinctive limestone-siltstone rhythmic couplets. Detrital calcite grains (CC1) in the TLM precipitated

Figure 5.23: Schematic cartoon illustrating deposition of the three members of the OFP, position of relative sea-level and carbon isotopic profile. Numbered locations on shelf - slope - basin profile refer to paleogeographic locations of the OFP: 1) Mid-slope, Lake Louise (LL) and Purcell Mountains (PM); 2) Lower slope, Jasper (JP); 3) Base of slope, Mount Robson (MR), McKale River (MK); and 4) Basin-floor, Cariboo Mountains. Abbreviations: HST - highstand systems tract; LST - lowstand systems tract; TST - transgressive systems tract; BSFR - basal surface of forced regression; MFS - maximum flooding surface; MRS - maximum regressive surface; SB - sequence boundary. Note: diagenetically altered values in the TLM from the Frances Creek locality are not plotted.



upslope in an oxic shallow-marine environment and potentially may preserve coeval local seawater (or pore water) chemistry, although grains might also include a component of early syn-sedimentary diagenesis during shallow-marine lithification. Nevertheless, following their genesis in shallow-water, grains were episodically eroded and transported into deeper slope and basinal environments by turbidity currents. Erosion most probably occurred soon after deposition as grains exhibit no obvious physical or chemical characteristics suggesting meteoric diagenesis or dolomitization. Evidence for a mechanism leading to the episodic nature of TLM turbidite deposition is suggested by the bladed-calcite crystal observed in limestone clasts of the overlying WMM. The TLM limestone-siltstone rhythmites are interpreted to correlate directly with the timing of repeated growth and erosion of the bladed-calcite crystals. During periods of shallower-marine crystal growth, a depositional hiatus occurred in the deep-ocean environments. Subsequent remobilization of calcitic sediment by turbidity currents effectively “drowned” crystal growths. The body and tail of the turbidity current deposited the TLM basal limestone and upper siltstone parts, respectively. In addition to the sedimentologic similarity, $\delta^{13}\text{C}$ isotopic analyses of both the bladed-calcite crystals (-9.28 to -7.93‰) and overlying limestone turbidite bed (-10.17 to -8.30‰); are comparable to TLM limestone units (-11.96 to -7.64‰) in the same paleogeographic region (Lake Louise).

Although there is some local variability in $\delta^{13}\text{C}$ values in strata of the OFP, and is most probably related to subsurface diagenetic processes (e.g. Purcell Mountains), isotopic and chemical tests conducted on carbonates of the OFP imply that in general, the isotopic system has not been significantly altered by burial diagenesis or metamorphism. Because calcite grains were transported into deeper water by turbidity currents, instead of being precipitated directly at depth, this suggests that most, if not all of the carbon isotopic signature was imported from upslope. The TLM and GSM limestone units are generally characterized by: negative $\delta^{13}\text{C}$ values (-11.96 to -5.48‰); show a consistent, stratigraphically-upward

positive shift of 3 to 5‰ during transgressive to highstand systems tract; with strata deposited in deeper-water being typically about 1 to 2‰ more negative (Fig. 5.23). Spatial variation in ocean chemistry during transgression may have existed as suggested by the approximately 2 to 2.5‰ isotopic difference between the two similar, proximal paleogeographic slope locations (Lake Louise and Jasper). This regional variation could also simply reflect differences in organic-matter oxidation during early diagenesis.

Overall, these observations are consistent with trends observed in other deep-water (below storm wave base) Neoproterozoic carbonate strata (e.g. Kennedy, 1996, 1998; James et al., 2001; Shen et al., 2005; Giddings and Wallace, 2009), although the TLM does not exhibit the initial depletion excursion from 0 to -6‰ commonly reported from lower cap dolostone directly overlying the glacial deposits (e.g. Fairchild and Kennedy, 2007; Halverson et al., 2005 and references therein). In mid- to lower slope strata, organic-rich condensed section and highstand systems tract deposits of the GSM exhibit a ~2‰ trend towards more negative $\delta^{13}\text{C}$ values, which is likely related to the incorporation of light carbon from the abundantly available organic matter during this period.

5.9.1.2 *Whitehorn Mountain Member (WMM)*

The upper member of the OFP (WMM) is interpreted to have coincided with an abrupt fall of a relative sea-level, related, in part, to regional uplift (Chapter 3) (Fig. 5.23). Locally, the base of the WMM is deeply eroded, and in places has completely removed the lower two members. This contact is interpreted to be a sequence boundary, most likely overprinting the pre-existing basal surface of forced regression associated with the initiation of relative sea-level fall (Chapter 3). Lithofacies and thickness of the WMM are highly variable and are controlled primarily by the location of incised submarine canyons created by erosive bypass flows, mass wasting and/or syn-sedimentary growth faults. Canyon fills reflect the evolution of the system from immature, fluvial-derived sediment deposited during

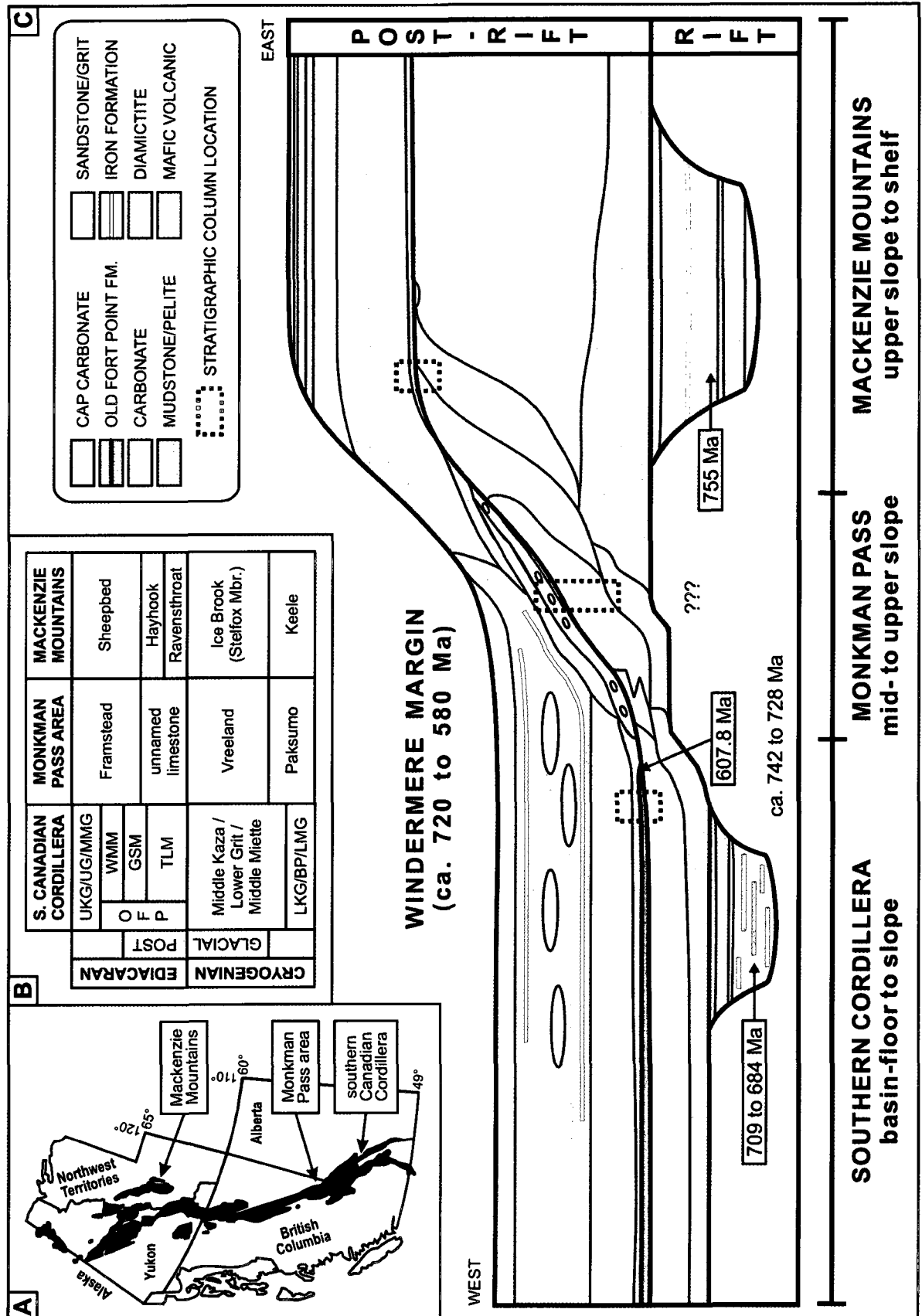
the falling-stage, lowstand and early transgressive systems tracts, to intercalated mature quartz-rich sandstone and limestone during late transgression to highstand conditions associated with the ensuing sea-level rise (Chapter 3).

In general, the WMM is characterized by: Sr-rich limestone suggesting original precipitation as aragonite; negative $\delta^{13}\text{C}$ values (-7.36 to 1.34‰); a consistent, upsection positive shift of 3 to 6‰, returning toward near-zero values during the later transgressive and highstand systems tracts; and potentially, a ~1 to 2‰ isotopic gradient from slope to basin-floor settings (Fig. 5.23). The original aragonite mineralogy suggests precipitation from oceanic water supersaturated in CaCO_3 during this time frame. Like the TLM, most of the detrital calcite grains (CC2-WMM) were transported into deep-water by turbidity currents implying that much of its carbon isotopic signature reflects upslope conditions. The upper contact of the WMM (and OFP) is interpreted to be a major, regionally widespread sequence boundary that marks the termination of highstand deposition and the return of typical lowstand arkosic fine- and coarse-grained deposits of the WSG.

5.9.2 Windermere Supergroup (WSG): regional stratigraphic correlation of the glacial Cryogenian to post-glacial Ediacaran transition

The OFP is one of three WSG lithostratigraphic successions in the Canadian Cordillera that has been linked to the globally synchronous, terminal Cryogenian (ca. 635 Ma) glacial episode (e.g. Fairchild and Kennedy, 2007; Hoffman et al., 2007; Halverson et al., 2005). Each of the three stratal successions are interpreted to document the same Cryogenian glacial to Ediacaran post-glacial transition, albeit on different parts of a conceptual shelf to basin transect (Fig. 5.24). Glacigenic diamictite (Stelfox Member) of the Ice Brook Formation and its overlying cap carbonate (Ravensthorpe and Hayhook formations) in the Mackenzie Mountains, Northwest Territories were deposited in a shallow marine carbonate shelf to shelf-margin setting (Aitken, 1991a, b; Narbonne et al., 1994; James et al., 2001; Hoffman and Halverson, submitted) (Fig. 5.24). The Vreeland Formation diamictite, an

Figure 5.24: A) Outcrop distribution of the WSG in the Canadian Cordillera showing locations of the Mackenzie Mountains, Monkman Pass area and southern Canadian Cordillera (modified from Ross, 1991). B) Stratigraphic columns with corresponding nomenclature for WSG Cryogenian to Ediacaran strata (glacial to post-glacial transition) from the three regions of the Canadian Cordillera. C) Schematic representation showing a conceptual shelf to basin profile of rift to post-rift WSG strata in the Canadian Cordillera. Figure is re-drafted using information originally presented in McMechan (1987, 2000), Ross et al. (1995), Ross (2000), James et al. (2001) and Hoffman and Halverson (submitted). No absolute thicknesses for strata or distances are implied in the schematic representation. Maximum age constraint of 755 ± 18 Ma for deposition in the Mackenzie Mountains area is from a leucogranite clast in the Sayunei Formation (Ross and Villeneuve, 1997). Age constraints in the southern Canadian Cordillera include: local basement, which ranges from 742 to 728 Ma (Evenchick et al., 1984; Scammell and Parrish, 1988; McDonough and Parrish, 1991); interpreted Irene Formation volcanic correlatives from Idaho, USA ranging from 709 to 684 Ma (Lund et al., 2003; Fanning and Link, 2003); and 607.8 ± 4.7 Ma from the GSM of the OFP (Kendall et al., 2004).



overlying unnamed thin limestone, and Framstead Formation in the Monkman Pass area of north-central British Columbia, accumulated in a mid-slope setting (McMechan, 2000) (Fig. 5.24). The OFP in the southern Canadian Cordillera is interpreted to be a post-glacial slope to basin-floor succession that overlies deep-marine turbidites interpreted to be lateral equivalents of the Vreeland Formation diamictite (Ross et al, 1995; McMechan, 2000) (Fig. 5.24). The original basis for the broad lithostratigraphic correlation (Ross et al., 1995) is based on the consistent presence of the distinctive bladed-calcite crystals in all three WSG successions, a hallmark of Neoproterozoic cap carbonates (e.g. Fairchild and Kennedy, 2007 and references therein). Bladed crystals have been reported from the Hayhook Formation (James et al., 2001; Hoffman and Halverson, submitted), as carbonate olistoliths in Framstead Formation mudstone units (McMechan, 2000) and as clasts in coarse-grained strata of the WMM (Ross et al., 1995; Chapter 3; this chapter).

Diamictites of the Icebrook (Stelfox Member) and Vreeland formations are interpreted to be correlative, glaciogenic deposits (e.g. Aitken, 1991a, b; McMechan, 2000; Hoffman and Halverson, submitted), with the Vreeland also displaying a lateral facies change to coarse-grained turbidites towards the west and south (McMechan, 1987; McMechan and Thompson, 1995a) (Fig. 5.24). Nowhere is the OFP observed to overlie directly diamictite of the Vreeland Formation. Rather, the OFP gradationally overlies fine- and coarse-grained, feldspar-rich turbidites typical of the WSG which, in turn, are interpreted to be correlated with the Vreeland Formation (Ross et al., 1995; McMechan, 2000).

In the Mackenzie Mountains, dolostone of the Ravensthorpe Formation and limestone of the Hayhook Formation comprise the cap carbonate succession (James et al., 2001; Hoffman and Halverson, submitted). Both are interpreted as microbial-influenced CaCO_3 precipitates. The Ravensthorpe exhibits no characteristics of precursor aragonite whereas the Hayhook indicates predominantly aragonite precipitation (James et al., 2001). The surface between the two units has been interpreted by some authors to represent a karst unconformity related to isostatic

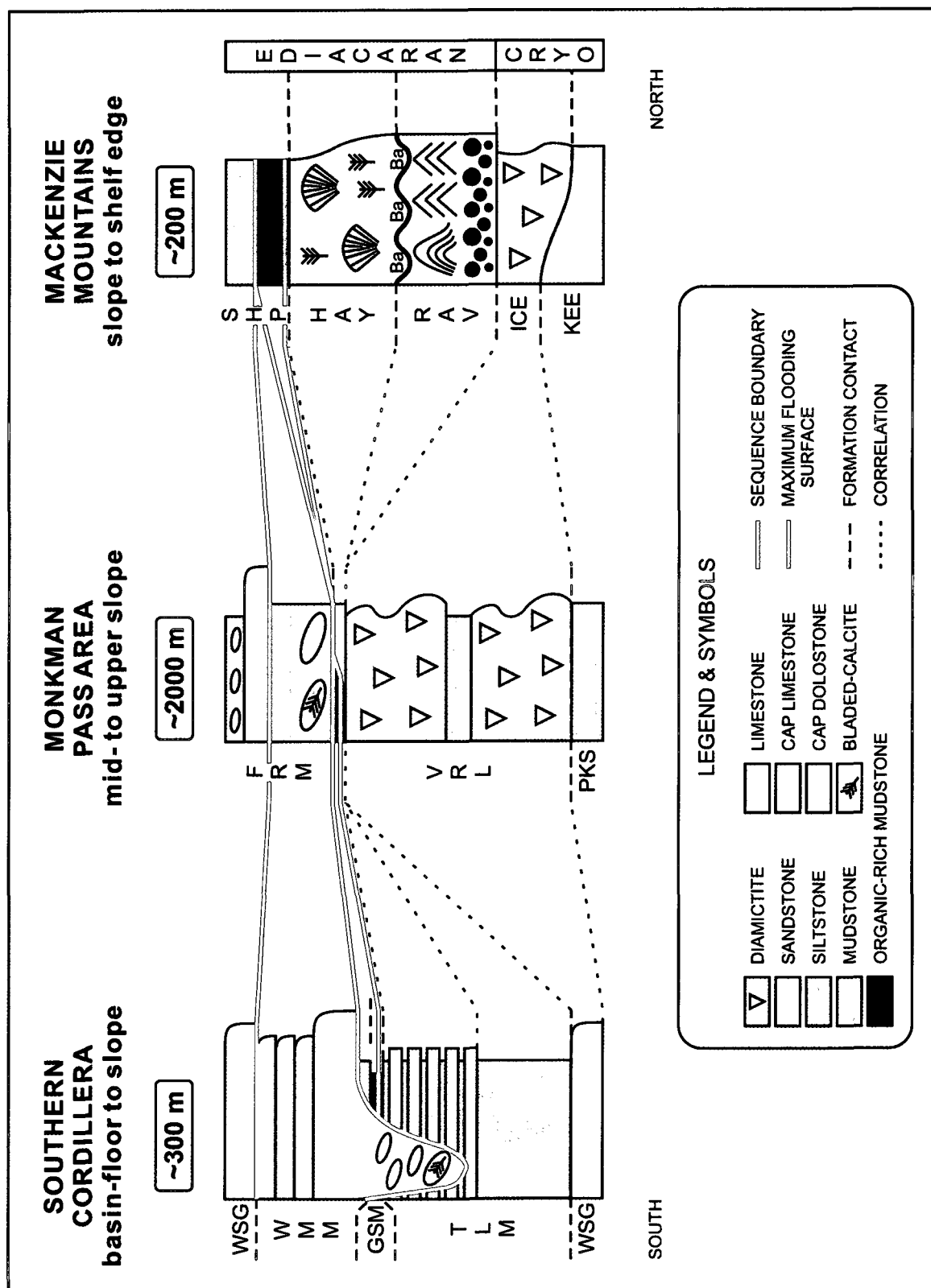
rebound (James et al., 2001). Subaerial exposure during this period was responsible for diagenetic dolomitization of the Ravensthorpe Formation (James et al., 2007). Conversely, other authors interpret the contact to be marked by barite cementation pseudo-morphosed to calcite (Hoffman and Schrag, 2002; Hoffman et al., 2007; Hoffman and Halverson, submitted); and challenge the premise of subaerial exposure caused by isostatic adjustment (Hoffman and Halverson, submitted), instead re-interpreting some of the structures to be tectonic in origin. $\delta^{13}\text{C}$ values of an early dolomite phase of the Ravensthorpe Formation generally range from -3 to 0‰ and display a slight (-2.5‰) decrease upsection (James et al., 2001; Hoffman and Halverson, submitted). Later dolomite phases of the Ravensthorpe and carbonate phases of the overlying Hayhook limestone show more variability in isotopic composition from -6 to -3‰ (mostly -5 to -4‰), with an upsection shift (~1‰) toward less negative values (James et al., 2001; Hoffman and Halverson, submitted). The Ravensthorpe was interpreted to reflect rapid sea-level rise associated with global glacial melting, whereas the Hayhook recorded more local events during continued sea-level rise (James et al., 2001). Overlying the Hayhook Formation is a succession of interbedded limestone and mudstone that stratigraphically-upwards changes colour from red to green to grey before transitioning into the >400 m thick, organic-rich mudstone of the Sheepbed Formation (e.g. James et al., 2001; Shen et al., 2008; Hoffman and Halverson, submitted). The Sheepbed Formation is interpreted to be a long-term Ediacaran transgression associated with melting of the terminal Cryogenian glacial event, and at an approximate stratigraphic height of 140 to 160 m, shows a shift from anoxic to oxic deep-water based on the FeHR/FeT (highly reactive iron/total iron) paleoredox proxy (Shen et al., 2008).

The Vreeland Formation and overlying stratigraphy has received little detailed study other than the description and paleogeographic interpretation of McMechan (2000). Locally, the top of the diamictite is marked by a pyrite-rich zone (~30 cm) or overlain by a discontinuous thin (few metres) laminated limestone

(McMechan, 2000). The mudstone-dominated Framstead Formation conformably overlies the Vreeland, although its basal contact is potentially a surface of local erosion based on the large (up to 650 m) carbonate olistoliths in the Framstead Formation at, or near this contact (McMechan, 2000). The presence of these large carbonate olistoliths indicate slope instability and extensive mass wasting, possibly related to uplift or rapid relative sea-level fall, with downslope movement of parts of the carbonate shelf edge (McMechan, 2000). The olistoliths display a wide range of shallow marine carbonate lithologies, including those commonly observed in cap carbonate successions. Limited $\delta^{13}\text{C}$ isotopic analyses (Table 5.3; G. M. Ross, unpublished data) show consistently negative values for the limestone unit (-1.94 to -3.60‰), with a wider range in the Framstead clast dolomite phases (-19.5 to -15.98‰ or -5.89 to -2.20‰).

Integrating the new sedimentologic, stratigraphic and geochemical data from the deep-marine OFP provides new detail into the WSG regional stratigraphic framework and their correlations (e.g. Ross et al., 1995) during the glacial to post-glacial transition and helps to constrain the relative timing of physical and chemical processes during accumulation of basal Ediacaran post-glacial strata (Fig. 5.25). Clasts of bladed calcite-crystals in strata of the WMM are almost identical to features observed in the Hayhook Formation of the Mackenzie Mountains. These limestone clasts have a depleted $\delta^{13}\text{C}$ signature like those in carbonate strata in the underlying TLM. Thus, TLM limestone rhythmites are interpreted to be coeval with the Hayhook Formation, and to have accumulated also during the rapid rise in sea-level caused by continental deglaciation (James et al., 2001; Chapter 3) (Fig. 5.25). The implication of this correlation is that there is no stratal equivalent, or at least, preserved carbonate equivalent, of the Ravensthorpe Formation dolostone (or its precursor mineralogy) in deep-marine settings in the southern Canadian Cordillera. Rather, basal siliciclastic siltstone deposits of the TLM are interpreted to be correlative to the Ravensthorpe Formation (Fig 5.25). The $\delta^{13}\text{C}$ values of the bathyal to upper abyssal TLM are approximately 4 to 8‰ more negative compared to the

Figure 5.25: Schematic stratigraphic columns and correlation of Cryogenian to Ediacaran, glacial to post-glacial WSG strata in the Canadian Cordillera from the Mackenzie Mountains, Monkman Pass area and southern Canadian Cordillera. Each location represents a different paleogeographic position on a conceptual shelf to basin profile. Approximate total thickness of each schematic column is provided, with relative thickness of each geological unit roughly represented in the figure; however, no absolute thickness is implied in any of the columns. Schematic column of the Monkman Pass area is re-drafted using information from McMechan (2000) and the Mackenzie Mountains from James et al. (2001), Hoffman et al. (2007), Shen et al., (2008) and Hoffman and Halverson (submitted). Timing of the Icebrook Formation (Stelfox Member) is interpreted to be ca. 635 Ma based on global correlation with other well-constrained glaciogenic deposits (e.g. Condon et al., 2005; Hoffman et al., 2007). Age of the GSM in the OFP is constrained by the Re-Os isochron of 607.8 ± 4.7 Ma (Kendall et al., 2004). Diamictite of the Icebrook Formation is correlated with Vreeland Formation and coarse-grained arkosic turbidites of the Windermere Supergroup. The Ravensthorpe Formation dolostone is correlated with the basal TLM siliciclastic siltstone and the overlying Hayhook Formation is correlated with the TLM limestone rhythmites to the Hayhook Formation. Robust regional correlation of the discontinuous limestone overlying diamictite of the Vreeland Formation remains equivocal. The ~608 Ma organic-rich GSM is interpreted to correlate to the pyrite-rich zone at the top of the Vreeland Formation and the lower part of the Sheepbed Formation with $\text{FeHR}/\text{FeT} > 0.38$ (Shen et al., 2008). The maximum flooding surface is located within these units (green line). The WMM correlates to the Framstead Formation. The deep-marine erosion surface (sequence boundary – red line) of the WMM is interpreted to correlate with the basal contact of the Framstead Formation. Clasts of bladed calcite-crystals similar to the Hayhook Formation are in overlying strata of the WMM and Framstead Formation. The sequence boundary (red line) separating the OFP and overlying WSG strata is marked by a shift in the FeHR/FeT ratio from anoxic to oxic conditions (Canfield et al., 2008, supplementary data) and may correlate to a similar FeHR/FeT shift recorded in the Sheepbed Formation (Shen et al., 2008). Old Fort Point Formation: TLM – Temple Lake Member; GSM – Geikie Siding Member; WMM – Whitehorn Mountain Member. WSG – Windermere Supergroup; PKS – Paksumo Formation; VRL – Vreeland Formation; FRM – Framstead Formation; KEE – Keele Formation; ICE – Icebrook Formation; RAV – Ravensthorpe Formation; HAY – Hayhook Formation; SHP – Sheepbed Formation. Ba – barite crusts)



shallower Hayhook Formation with both formations showing a trend towards more negative values in deeper-water environments. If correct, this correlation would imply a $\delta^{13}\text{C}$ isotopic gradient of 7 to 8‰ in a conceptual transect from coeval WSG shallow- to deep-water environments; a significantly larger isotopic difference between surface and deep-water compared to the ~2‰ observed in modern oceans (Kroopnick, 1985); but not unlike the inferred gradient (5‰) stratigraphically higher in the WSG succession (Ross et al., 2001) or the 8 to 11‰ gradient recorded in Cryogenian and Ediacaran platform to basinal carbonate successions from China (Shen et al., 2005; Jiang et al., 2007) and Australia (Giddings and Wallace, 2009). An important caveat to this inferred $\delta^{13}\text{C}$ isotopic gradient for the WSG transect is that the carbonate in the OFP is interpreted to have precipitated upslope, possibly at similar, neritic water depths as the Hayhook Formation, and not in the bathyal to upper abyssal depths where it accumulated. Unfortunately, the limited work in the Monkman Pass thus far, makes stratigraphic correlation of the discontinuous limestone unit equivocal. Its physical features and slightly negative $\delta^{13}\text{C}$ values more resemble limestone strata of the WMM than the TLM; however, the possibility remains for its stratal correlation to either the Ravensthorpe or TLM and Hayhook Formation (Fig. 5.25).

Strata of the TLM grade upward into the organic-rich GSM, which represents reduced rates of sedimentation, increased organic productivity, and an overall shutdown of coarse clastic sediment flux related to maximum flooding during late transgression to highstand (Ross and Murphy, 1988; Chapter 3). The GSM is the only unit in the OFP that accumulated under at least, episodic anoxic deep-ocean bottom-waters (Chapter 3, 4) and potentially correlates with the pyrite-rich zone at the top of the Vreeland Formation (Fig. 5.25). A reasonably robust correlation of the GSM condensed section to the lower portion of the Sheepbed Formation seems plausible based on relative stratigraphic position and independent redox-proxies indicating anoxia bottom-water conditions (GSM: Mo and TOC contents, Chapter 3; Sheepbed Formation: FeHR/FeT, Shen et al., 2008) (Fig. 5.25).

In many locations, the base of the WMM is a deep scour surface (e.g. submarine canyon), which coincided with short-lived relative sea-level fall, related in part, to regional uplift that temporarily interrupted the long-term rise of relative sea-level (Chapter 3). This deep-marine erosion surface (sequence boundary) and overlying breccia units potentially correlate upslope to the basal contact of the Framstead Formation and with large carbonate olistoliths in its lower part (McMechan, 2000) (Fig. 5.25). Thick mudstone of the Framstead and Sheepbed formations likely correlate to upper limestone units of the WMM which deposited during late transgression and highstand of the continued rise of sea level (Fig. 5.25). How the prominent erosional surface recorded at the base of the WMM correlates to the Mackenzie Mountains is less clear. The karst unconformity separating the Ravensthorpe and Hayhook formations (James et al., 2001) provides a possible candidate, and the barite crusts that are found along the contact (e.g. Hoffman et al., 2007) could have formed from upwelling GSM anoxic bottom-waters and mixing with sulfate-rich shallow seawater. However, as noted earlier, the validity of the subaerial unconformity has been questioned (Hoffman and Halverson, submitted), and the fairly robust correlation between the TLM and Hayhook Formation eliminates the possibility of the link between the base of the WMM and Ravensthorpe-Hayhook contact (Fig. 5.25).

In slope-settings outside the submarine canyons where the WMM is fine-grained and thinly developed (<0.5 m), the anoxic GSM appears to be overlain directly by fine-grained mudstone turbidites of the WSG that deposited under background oxic conditions (Chapter 4). This three-fold (GSM-WMM-WSG) mudstone contact is difficult to recognize in outcrop, and usually requires the aid of geochemical techniques (e.g. gamma-ray counts, TOC content, molybdenum concentration) to identify its location (Chapter 4), and thereby is somewhat similar to the anoxic – oxic transition in the Sheepbed Formation described by Shen et al. (2008) (however, see Canfield et al., 2008, supplementary data where the Sheepbed Formation remains anoxic for >400 m based on the same FeHR/FeT ratio

technique). In the Cariboo Mountains, the contact between the OFP and overlying WSG also exhibits a shift in FeHR/FeT ratio (Canfield et al., 2008, supplementary data). The shift in redox conditions recorded in mudstones of the Sheepbed Formation may correlate to the regionally extensive sequence boundary at the top of the OFP that marks the end of its distinctive, mostly transgressive and highstand deposits (episodically anoxic) from a major eustatic sea-level rise, and return to lowstand arkosic deposition (oxic) of the WSG (Chapter 4) (Fig.5.25).

5.9.3 Neoproterozoic post-glacial cap carbonate models

Currently, there are a number of competing hypotheses to explain the global deposition of Neoproterozoic post-glacial cap carbonate strata with their characteristic suite of remarkable physical features and the source of the alkalinity that resulted in their negative $\delta^{13}\text{C}$ signatures (see recent reviews in Shields, 2005; Fairchild and Kennedy, 2007):

- 1) snowball Earth (e.g. Hoffman et al., 1998; Hoffman and Schrag, 2002; Higgins and Schrag, 2003). This model proposes global glaciation and ice cover for millions of years with complete shutdown of the hydrological cycle and continental weathering. The continuous build up of volcanically-derived atmospheric CO_2 during the glacial episode leads to gradual warming and eventual rapid deglaciation. This, followed by an increase in chemical (carbonate) weathering related to elevated CO_2 , resulted in the delivery of large volumes of alkaline-rich water into the oceans causing precipitation of a global blanket of cap carbonate.
- 2) oceanic stratification and post-glacial upwelling (Grotzinger and Knoll, 1995; Knoll et al., 1996; Kaufman et al., 1997; Ridgeway et al., 2003). This model proposes widespread glaciation, which leads to a chemically stratified ocean with the action of a biological pump imparting an isotopic gradient of ^{13}C -rich surface water and ^{12}C -rich deep-water. Post-glacial oceanic overturn

occurs, allowing alkalinity-rich deep-water to be delivered to shallow-marine environments resulting in cap carbonate precipitation. The recent hypothesis by Giddings and Wallace (2009) is a slight modification of this model and suggests that Neoproterozoic oceans were characterized by long-lived oceanic stratification, and not only during glacial to post-glacial transitions. The model of Shields (2005) is again a slight modification of the Grotzinger and Knoll (1995) model and in this case proposes density stratification during deglaciation with a buoyant plume of low salinity meltwater and microbially mediated cap carbonate precipitation. Upwelling occurs later and leads to inorganic precipitation of aragonite and barite in the upper parts of cap carbonate strata.

- 3) gas hydrate destabilization (Kennedy et al., 2001; Jiang et al., 2003, 2006; Kennedy et al, 2008). This model proposes that the increase in alkalinity was from methane oxidation by sulfate reduction in the ocean during the post-glacial sea-level rise. Methane was trapped in marine gas hydrates and possibly terrestrial permafrost during the glacial episode along wide continental shelf margins.
- 4) microbial-mediated dolomite precipitation (Nedelec et al., 2006; Font et al., 2006, Elie et al., 2007). This model suggests the dolomite is a primary precipitate aided by sulfate-reducing bacteria under suboxic to anoxic conditions at or near the sediment-water interface.

With the exception of bladed-calcite clasts in the WMM, the OFP displays none of the sedimentary attributes commonly reported from shallower-marine cap carbonate strata. However, because of its preserved calcite mineralogy and deep-marine depositional environment, it may capture the full stratigraphic and chemical evolution of Ediacaran oceanic conditions compared to the more extensively studied, but possibly incomplete shallow-marine cap carbonate record.

5.9.4 Deep-marine perspective of post-glacial cap carbonate deposition

Throughout the Windermere basin, the OFP overlies directly fine- and coarse-grained turbidites mapped as lateral equivalents of glaciogenic diamictite of the Vreeland Formation (McMechan, 1987; McMechan and Thompson, 1995a). As observed in other Neoproterozoic successions, the WSG glacial deposits grade laterally into deep-marine sedimentary rocks (Eyles and Eyles, 1983; Leather et al., 2002), which combined with evidence for open water (e.g. Kennedy et al., 2001; Allen et al., 2004) and intercalated glacial and non-glacial units (e.g. Leather et al., 2002; Arnaud and Eyles, 2002; Allen et al., 2004; Arnaud and Eyles, 2006) contrasts models invoking complete shutdown of the hydrological cycle under global ice cover (e.g. Hoffman et al., 1998; Hoffman and Schrag, 2002). In addition, the deep-marine WSG exhibits no physical (Chapter 3) or chemical attributes (Chapter 4) indicating thick hemipelagic deposition beneath floating ice-cover (Halverson et al., 2004) with stagnant, syn-glacial euxinic deep-oceanic conditions (e.g. Hoffman et al., 1998; Hurtgen et al., 2006). Furthermore, compared to the rest of the WSG, the relatively low CIA (chemical index of alteration) values in the OFP (Chapter 4) suggest the influx of post-glacial sediment that had not undergone intense chemical weathering associated with extreme concentrations of atmospheric CO₂ (e.g. Higgins and Schrag, 2003).

Based on stratigraphic and isotopic considerations, the upper TLM limestone rhythmites are interpreted to be deep-marine deposits that correlated with the limestone unit (e.g. Hayhook Formation in the Mackenzie Mountains) that overlies cap dolostones in many basal Ediacaran post-glacial successions. Thus, the deep-marine stratigraphic (and chemical) record of cap dolostone deposition correlates in time with the variably-coloured siltstone turbidites in the lower part of the TLM. The absence of a deep-water carbonate equivalent for the cap dolostone would suggest that the precipitation event may have instead been restricted to shallow marine environments rather than being a pan-oceanic phenomena (e.g. Hoffman et al., 1998; Hoffman and Schrag, 2002). As a result, there is no evidence for direct

dolomite precipitation either from mixed layer seawater under low-sulfate concentrations (e.g. Hoffman et al., 2002) or BSR-mediated precipitation under anoxic conditions (Nedelec et al., 2006; Font et al., 2006, Elie et al., 2007). However, this does not rule out mechanisms that involve direct precipitation of dolomite, but in deep-marine environments any precipitated or transported dolomite phase (DOL1?) and its isotopic signal have been completely overprinted by later burial diagenetic phases (DOL2 and ANK).

One of the current hypotheses which might explain the carbonate isotope signatures in the OFP is that increased seawater alkalinity resulted from the oxidation of methane in seawater released during widespread destabilization of methane clathrates during post-glacial sea-level rise (Kennedy et al., 2001, 2008; Jiang et al. 2006). If the prevailing mechanism of carbonate precipitation is indeed linked to the destabilization of near-equatorial permafrost clathrates, then the regionally line-sourced deposition of the TLM whose turbidity currents initiated in shallower water would fundamentally require the extraordinary development of widespread permafrost clathrates across broad continental shelves (e.g. hundreds of kilometers in area) as proposed by Kennedy et al. (2008). However, neither the limestones of the OFP nor the bladed-calcite crystal fans from which they are interpreted to have been eroded, exhibit the physical characteristics, nor the locally extreme range (-50 to +6‰) and highly depleted values used as direct evidence of methane-influenced precipitation (e.g. Kennedy et al., 2008; Wang et al., 2008; Jiang et al., 2006 and references therein). Rarely is the full range of values preserved as they may have been homogenized during diagenesis (e.g. Jiang et al., 2003). However, in the OFP, the $\delta^{13}\text{C}$ values show a protracted and consistent recovery towards near-zero values, which, therefore makes it unlikely that the observed stratigraphic trend would result from rapid and consistent diagenetic homogenization in the shallow-marine environment prior to erosion and transport into deeper water. The lack of significant isotopic difference between $\delta^{13}\text{C}$ values of the CC1 and subsequent cement phases in the OFP also argues against diagenetic

methane production from buried organic matter to precipitate these cements, similar to the observations of Jiang et al. (2006); however, methanogenesis may have played a role in cementation of coarse-grained sandstone units of the OFP similar to observations higher up in WSG strata (Meyer and Ross, 2003; Meyer, 2004).

The OFP records a number of traits that are consistent with oceanic stratification and post-glacial upwelling with mixing of deep-waters and Ca-rich surface waters (e.g. Grotzinger and Knoll, 1995; Kaufman et al., 1997). The isotopic characteristics of the OFP are also similar to other Cryogenian to Ediacaran carbonate successions that show a $\delta^{13}\text{C}$ difference (few per mil to 11‰) from shallow to deeper water environments (Kennedy, 1996; Kennedy et al., 1998; James et al., 2001; Ross et al., 2001; Zhou et al., 2004; Shen et al., 2005; Jiang et al., 2007; Giddings and Wallace, 2009) and may provide further evidence for oceanic stratification and a prominent $\delta^{13}\text{C}$ depth gradient from the operation of a shallow-water biological pump. The biological pump operates by the preferential uptake of ^{12}C by primary producers in the photic zone which serves to enrich shallow, surface ocean waters in ^{13}C . Particulate organic matter depleted in ^{13}C suspension settles down through the oceanic water column where it undergoes degradation. The result of the biological pump is that carbonates precipitated in shallow-waters are enriched in ^{13}C (i.e. more positive values) whereas carbonates precipitated at or near the sea bottom incorporate greater amounts of ^{12}C and are depleted in $\delta^{13}\text{C}$ (i.e. more negative values) (e.g. Kroopnick, 1985; Berger and Vincent, 1986). In the well-mixed modern oceans, this process leads to a C-depth gradient of $\sim 2\text{‰}$ with deep-waters depleted in ^{13}C compared to surface waters (Kroopnick, 1985). In areas with greater primary productivity and/or prolonged oceanic stratification with continued biological pumping, the downward flux of organic matter increases and the surface waters become increasingly enriched in ^{13}C . The modern Black Sea is an example where there is sluggish circulation and stagnant deep-waters are ~ 7 to 8‰ more depleted than their shallower counterparts (Deuser, 1970). The model of Shen et al. (2005) for the Neoproterozoic invokes a more intense biological pump related

to high $p\text{CO}_2$ in the atmosphere during deglaciation (e.g. Grotzinger and Knoll, 1995; Hoffman et al., 1998). A relatively rapid rise in sea-level may have reduced vertical circulation resulting in a favourable situation for maintaining stratified C-isotopic stratified conditions in the post-glacial Ediacaran ocean (Shen et al., 2005). An oceanic redox gradient and upwelling is also a common theme in many of the models of Neoproterozoic oceanic chemistry based on the sulfur isotopic record, either from sulfides (e.g. Canfield, 1998) or carbonate associated sulfate (CAS) (e.g. Hurtgen et al., 2002). These models invoke a low-sulfate ocean because of sulfate consumption by BSR in a syn-glacial anoxic ocean, followed by post-glacial upwelling of ^{34}S -enriched deep-water onto the shelf and precipitation with a distinctive positive signature (Hurtgen et al., 2002, 2005, 2006; Halverson and Hurtgen, 2007; Shen et al., 2008).

Recent work by Giddings and Wallace (2009) on a Cryogenian carbonate platform to basin succession in Australia observed a ^{13}C -depth gradient of up to 11‰ from strata unrelated to any glacial episodes. Combined with data from similar studies that identified highly negative ^{13}C values not associated with glacial events (e.g. Le Guerroué et al., 2006a, b), they suggested that the Neoproterozoic oceans were different and physically stratified for long periods of time ($>10^5$ years). This density stratification would have reduced oceanic circulation, stabilized deep-water anoxia and limited mixing with oxygenated surface waters. Such a condition would have led to an enhancement of the C-depth gradient and the accompanying isotopic difference between of shallow and deep-water carbonates (Grotzinger and Knoll, 1995). In the case of a long-lived stratified ocean, a large reservoir of organically-derived carbon would accumulate in deep-water via the ongoing biological pump and not be returned to the surface. The end result would be a drawdown of atmospheric CO_2 to levels that might initiate a major glacial event. In turn, this would renew oceanic circulation and increase CO_2 levels in surface waters, thereby leading to a re-equilibration of the ocean-atmosphere system and massive deglaciation (Grotzinger and Knoll, 1995; Giddings and Wallace, 2009).

Post-glacial upwelling of alkaline-rich deep-waters to shallow-marine environments would cause the precipitation of carbonates with negative $\delta^{13}\text{C}$ values (e.g. Grotzinger and Knoll, 1995; Kaufmann et al., 1997; James et al., 2001). The implication of this interpretation is that Neoproterozoic carbon isotopic excursions may not be wholly secular in origin, but instead coincide with eustatic sea-level changes (i.e. not restricted to post-glacial scenarios) (Giddings and Wallace, 2009); a correlation that has been noted by other authors (e.g. Kennedy, 1996; Shields et al., 1997; Calver, 2000). In this manner, the negative excursions indicate eustatic rise (transgression) whereas positive excursions coincide with eustatic fall (regression) (Giddings and Wallace, 2009). An argument against this model is the overall issue with maintaining physical ocean stratification and stagnation over a time-scale of millions of years (Zhang et al., 2001; Shields, 2005).

The bathyal to upper abyssal OFP offers some unique insights into oceanic upwelling and stratification models during the glacial to post-glacial Cryogenian to Ediacaran transition. The first is the lack of physical and chemical evidence for syn-glacial anoxic bottom-waters (Chapters 3 and 4) as proposed by many models based on shallow-marine carbonate rocks. The green colour (inherited from detrital chlorite) in basin-floor WSG deposits immediately below, and within the basal TLM, however does suggest the presence of reduced iron in deep-water during this specific period. These deposits are consistently characterized by low TOC values (Chapter 3) suggesting that if there was a large pool of dissolved organic carbon in the deep-ocean waters (e.g. Giddings and Wallace, 2009), a negligible amount was deposited and preserved on the ocean floor. The lower siltstone unit of the TLM in proximal slope section is marked by its distinctive and unique purple colour from the presence of hematite. The deep-water equivalent of these purple colored strata are lithologically identical, but green coloured siltstones, which suggests a shift (in deep-water) to reducing (but not necessarily anoxic) conditions. Upwelling of these iron-rich, reduced fluids and their interaction with low salinity, oxygen-rich during early post-glaciation transgression resulted in the formation of the diagenetic

hematite in TLM slope strata. The bathyal depth (>500 m) at which the hematite formed suggests that a meltwater plume, such as that proposed by Shields (2005), may not have been limited to surface-water and that the pycnocline may have been much deeper. Cessation of the input of oxygen-rich shallow waters and their mixing with deep-water masses is marked by the purple to green transition in the TLM limestone units. Subsequently, anoxic bottom-waters developed below the newly raised pycnocline during deposition of the organic-rich GSM.

The transgressive TLM limestone units are 1 to 2‰ lighter in basin-floor environments than their slope counterparts. Compared to the $\delta^{13}\text{C}$ values from its potential shallow-marine correlative, the Hayhook Formation, the TLM limestones are 4 to 8‰ more depleted and the lithologically similar bladed-calcite crystals in clasts of the WMM, are >2 to 4‰ lighter. However, in the case OFP, carbonate material is interpreted to have precipitated upslope, and likely in a paleogeographic staging area not too dissimilar to the Hayhook Formation. Nevertheless, unlike the Hayhook, carbonate sediment was then remobilized downslope by turbidity currents. Thus, C-isotopic values in strata of the OFP do not represent seawater chemistry from the bathyal to upper abyssal depths where it deposited, but instead, mostly the neritic water depths from which they originated. The negative isotopic characteristics exhibited by the deep-marine OFP are consistent with shallow-marine carbonate precipitation that reflects a mixing of isotopically distinctive surface and deep-water consistent with the scenario of post-glacial upwelling from a stratified ocean (e.g. Grotzinger and Knoll, 1995). The regional C-isotopic difference observed between the Hayhook, clasts of the WMM and within the TLM itself (e.g. JP vs. LL) might reflect the relative proportions of the two mixing water masses or an isotopic gradient during the post-glacial transgression. An alternate scenario is that the original $\delta^{13}\text{C}$ isotopic values of CC1 were similar in fact similar to the Hayhook Formation but subsequent CC2 early cement precipitation in the shallow substrate pore-waters incorporates C-isotopic composition of the deep-waters (i.e. more negative $\delta^{13}\text{C}$). Thus, the isotopic analyses of CC1 + CC2 from

limestones are simply an unquantifiable mixture of CC1 (shallow and deep) and CC2 (deep). The observed 1 to 2‰ basinward shift in the TLM (and in the WMM as well) may be similar to the isotopic difference (~2‰) between surface and deep-water in modern oceans (Kroopnick, 1985), although this same shift might simply be the result of more prolonged diagenetic reactions with deeper fluids as a result of slower sedimentation rates. The OFP exhibits a stratigraphically-ascending trend from highly negative $\delta^{13}\text{C}$ values (-12‰) towards near zero values at its top. The most negative values in the OFP are associated with the early stages of transgression (TLM). As the overall transgression proceeded, the trend toward less negative values (TLM to WMM) suggests that in the shallow-marine realm (where the carbonate material of the OFP originated), mixing between an isotopically depleted deep source and a heavy shallow-marine carbonate source became progressively reduced. The near-zero value at the top of the WMM likely approaches the actual shallow marine value with the overall OFP trend suggesting gradual isotopic recovery during the post-glacial transgression. This return to normal isotopic conditions in shallow-marine environments may suggest that oceanic stratification may indeed be linked to glacial events (e.g. Grotzinger and Knoll, 1995; Shen et al., 2005) but does not necessarily rule it out as a general condition of Neoproterozoic oceans (e.g. Giddings and Wallace, 2009).

Stable isotopic data from other Cryogenian and Ediacaran successions (Shen et al., 2005; Jiang et al., 2007; Giddings and Wallace, 2009), is interpreted to suggest that $\delta^{13}\text{C}$ stratification during this timeframe was more common and stable for long periods of time, although difficulties with maintaining it over timescales $>10^5$ years have been noted (Zhang et al., 2001; Shields, 2005). For the example of the Ediacaran OFP, the duration of the stratification is less clear. The sedimentologic and stratigraphic record of the TLM and GSM is more consistent with relatively slow, repetitive turbidite deposition, and therefore, comparable to younger modern condensed sections (Loutit et al., 1988) that accumulated in response to relative sea-level rise. Determining whether this slow deposition represents thousands versus

millions of years is difficult to ascertain without the aid of biostratigraphy, magnetostratigraphy or radiometric age dates (e.g. Loutit et al., 1988). The ~608 Ma Re-Os age from the GSM (Kendall et al., 2004) is interpreted as too young, and only a minimum timing of deposition; however, if it were accurate and the base of the purple-coloured TLM roughly corresponds to terminal Cryogenian (~635 Ma) deglaciation event, then these data suggest a relatively uninterrupted, protracted period (>25 Myr) of oceanic stratification and C-isotopic recovery. An alternative explanation if the ~608 Ma age is accurate is that the OFP is not related to the basal Ediacaran glaciation at all, but a younger transgressive event that may or may not be linked to a local glacial event. This, however, this is not supported by the sedimentological and stratigraphic observations, in particular the stratal presence of bladed calcite-crystal clasts in the overlying WMM, which are physical and chemically similar to those in the Hayhook Formation, approximately 1500 km away in the northern Canadian Cordillera. Overall, the regional physical and isotopic characteristics exhibited by the deep-marine OFP are most consistent with the scenario of post-glacial upwelling from a stratified ocean of limited duration (e.g. Grotzinger and Knoll, 1995; Shen et al., 2005).

Future work on the OFP to better constrain Ediacaran ocean chemistry during this period should include studies of CAS (carbonate-associated sulfate) from limestone units to provide better constraints on the $\delta^{34}\text{S}$ sulfate of post-glacial seawater. The presence of barite in the late-stage CC3 cements also indicates that it may be possible to identify the diagenetic signature and distinguish it from primary values, a challenging problem in most CAS studies from the Neoproterozoic (e.g. Shields et al., 2004). The application of stable Fe-isotopes to the bacterial-mediated diagenetic hematite which may have formed from the interaction of oxygen-laden surface waters and upwelling deep-water rich in reduced iron may also hold promise for unraveling further details for post-glacial Ediacaran oceanic biogeochemistry.

5.10 CONCLUSIONS

The Old Fort Point Formation (OFP) in the southern Canadian Cordillera is a mixed siliciclastic and carbonate succession that provides a rare bathyal to upper abyssal perspective into the stratigraphic and chemical evolution of post-glacial deposition during basal Ediacaran time. The OFP is characterized by regionally identifiable calcite and dolomite phases that reflect detrital, diagenetic and metamorphic origins and collectively define a consistent paragenetic sequence. Detrital calcite in limestone units of the OFP precipitated in shallow-marine environments and was subsequently transported into the deep ocean by turbidity currents. This calcite phase (CC1) shows physical, textural and chemical characteristics suggesting formation under relatively oxic conditions with subsequent diagenetic phases forming in the subsurface primarily through the progressive effects of redox-mediated diagenesis. Precipitation of the diagenetic phases may have been controlled by the availability of organic matter and local sedimentation rate. The OFP is characterized by mostly negative $\delta^{13}\text{C}$ values that stratigraphically-upward exhibit a $\sim 12\text{‰}$ positive shift, in addition to a 1 to 2 ‰ shift towards more negative values from shallow to deep-water environments. The $\delta^{13}\text{C}$ -isotopic system in OFP limestones underwent minor alteration (1 to 2 ‰) at most, from diagenesis. In addition, unlike the $\delta^{18}\text{O}$ system in carbonates and the $\delta^{13}\text{C}$ values from organic residue, the $\delta^{13}\text{C}$ values from carbonates show no evidence of metamorphic modification. The $\delta^{34}\text{S}$ values from local pyrite in the OFP show a broad range ($\sim 60\text{‰}$) of values and display heterogeneity on local and regional scales. This implies that a numbers of factors (e.g. organic matter, sedimentation rate, substrate redox conditions, microbial influences) may have been responsible for the final recorded S-isotopic composition and that interpretations based on this dataset are equivocal.

Petrographic observations combined with regionally correlatable stratigraphic trends suggest that the $\delta^{13}\text{C}$ values were preserved during transport

and deposition from its original source. The pattern of negative $\delta^{13}\text{C}$ values that increase steadily towards near-zero and values 1 to 2‰ lighter in deeper-water environments corresponds with other global basal Ediacaran carbonate successions. The basal transgressive Temple Lake Member (TLM) represents the onset of post-glacial deposition with its striking purple colour in slope sections reflecting the upwelling of deep-ocean water enriched in reduced iron and its interaction with oxygen-laden surface water sourced from continental glacial melting. These siliciclastic deposits represent the deep-marine time equivalent of the cap dolostones, such as the Ravensthorpe Formation in the northern Canadian Cordillera. TLM siltstone grades upward into rhythmic limestone-siltstone turbidites which are interpreted to correlate directly with the timing of repeated growth and erosion of shallow-marine bladed-calcite crystals, commonly observed in the overlying limestone deposits of cap carbonate successions (e.g. Hayhook Formation). The Geikie Siding Member (GSM) gradationally overlies the TLM and represents maximum flooding and development of regionally widespread bottom-water anoxia within the Windermere Basin. The contact between the GSM and overlying Whitehorn Mountain Member is a sequence boundary linked to an abrupt fall of a relative sea-level. During the ensuing transgression and highstand, carbonate strata were composed of Sr-rich limestone, having originally precipitated as aragonite in shallow CaCO_3 -supersaturated oceanic waters, and subsequently were remobilized downslope.

Overall, the physical and isotopic characteristics of the bathyal to upper abyssal OFP are most consistent with the cap carbonate model of post-glacial upwelling and oceanic stratification, perhaps linked to the relatively rapid eustatic rise (e.g. Grotzinger and Knoll, 1995). TLM limestone units are interpreted to have precipitated in similar neritic water depths as the Hayhook Formation; however the $\delta^{13}\text{C}$ isotopic differences between the two time-equivalent units may reflect a C-isotopic gradient, or regional variation in the relative amounts of mixing between deep-water rich in light carbon and shallow-water rich in heavy carbon. The

upward stratigraphic return to near-zero $\delta^{13}\text{C}$ values in the OFP during the eustatic rise is interpreted to reflect a slow, gradual return to normal seawater conditions in the shallow-marine realm following the major global glaciation event.

CHAPTER 6: Thesis Summary

The terminal Neoproterozoic (~750 to 542 Ma) was a time of fundamental change in Earth history that ushered in the emergence of metazoan life in concert with extreme climatic fluctuations, dispersal of the supercontinent Rodinia, and dramatic changes in geochemical cycles. Most of the competing hypotheses (e.g. snowball Earth, oceanic stratification and upwelling, methane gas hydrate destabilization, plumeworld) which globally link the interaction of these processes are based primarily on the potentially fragmented, continental to shallow-marine strata; and thus, may not capture the full paleo-oceanographic changes during this period. The Old Fort Point Formation (OFP) is a widespread, unique regional marker in the Windermere Supergroup (WSG) of the southern Canadian Cordillera that provides a key element in linking the deep-marine WSG basin with global Neoproterozoic events. The OFP is dated at 607.8 ± 4.7 Ma (Kendall et al. 2004), which provides a minimum age for its deposition and correlates it broadly with other basal Ediacaran post-glacial cap carbonate deposits. The significance of this comprehensive study on the OFP is that it is the first to study a deep-marine equivalent of post-glacial, shallow-water cap carbonate strata and thus, provides new observations into the stratigraphic and geochemical evolution of the terminal Neoproterozoic.

The OFP is interpreted to have deposited in deep-marine basin-slope to basin-floor environments (upper bathyal to upper abyssal plain) along the ancestral continental margin of Laurentia. It separates two thick successions composed of fine- and coarse-grained arkose turbidites, typical of the WSG. The OFP comprises three distinctive lithostratigraphic members, which are mappable and correlatable on regional scale, and define a consistent stratigraphic relationship across the Windermere basin. The new detailed sedimentologic and stratigraphic work presented in this dissertation builds on earlier works and demonstrates that the OFP

and its three constituent members deserve formal recognition according to the revised North American Stratigraphic Code. The basal Temple Lake Member (TLM) is composed of variably-coloured siltstone to mudstone that grades upward into rhythmically interstratified limestone-siltstone. Gradationally overlying the TLM is the Geikie Siding Member (GSM), a thin, organic-rich mudstone that locally is sulfidic. In contrast to the lower two members, the Whitehorn Mountain Member (WMM) is usually characterized by a sharp basal contact, commonly exhibiting significant erosion and composed of variable, sometimes location-specific lithofacies. Overall depositional mechanisms for the OFP include a variety of mass movement and sediment gravity flows and suspension fallout.

Geochemical analyses of mudstone units from the OFP (GSM and organic-rich WMM) indicate important similarities but also differences compared to other fine grained WSG strata. Spatially and temporally consistent Th/Sc, Cr/Th, Eu anomalies and REE profiles for all WSG fine-grained sedimentary rocks suggest a well-homogenized provenance consisting of Archean and Proterozoic igneous components similar to Alberta basement domains indicated by earlier U-Pb detrital zircon work. WSG strata show relative enrichments in Al_2O_3 , K_2O , Rb, and Ba that most probably reflect post-depositional potassic-metasomatism. Calculated pre-metasomatic CIA (Chemical Index of Alteration) values (67 to 85) suggest changes in weathering conditions in hinterland continental settings. Overall, CIA values from the WSG are elevated (>80) with these high values interpreted as periods of tropical to temperate climate and associated intense chemical weathering related to Laurentia's low-latitude setting. There are two prominent intervals (pre-OFP to OFP and upper IF) where CIA values are lowered and are interpreted as periods of cooler climatic conditions and a predominance of physical weathering prior to transport and deposition in deep-water environments. These periods of lowered CIA also correspond with periods of transgression with the first interval (pre-OFP to OFP) coincident with the timing of the terminal Cryogenian glaciation event and interpreted post-glacial Ediacaran deposition. Within the Windermere basin, TOC,

Mo, V and V/Cr are interpreted as the most sensitive redox-proxies for identifying bottom-water anoxia. The GSM of the OFP shows significant enrichments in these redox-proxies when compared to other WSG strata, suggesting an episode of regionally widespread bottom-water anoxia during its deposition. These geochemical signals suggest that regionally widespread bottom-water anoxia was a relatively short-term event linked to post-glacial highstand deposition. These findings contrast many of the current models which propose oceanic anoxia during the major Cryogenian glaciation, or as a consistent, long-term feature indicative of Neoproterozoic deep-water conditions. Within the WMM and Isaac Formation, some organic-rich mudstone units show similar enrichments in redox-sensitive enrichments, suggesting local development of anoxic conditions during other periods of WSG deposition.

The OFP is characterized by regionally identifiable carbonate phases that reflect detrital, diagenetic and metamorphic origins and collectively define a consistent paragenetic sequence. Detrital calcite grains in limestone units of all three members of the OFP precipitated under relatively oxic conditions in shallow-marine environments and were subsequently transported into the deep ocean by turbidity currents. The OFP is characterized by mostly negative $\delta^{13}\text{C}$ values that stratigraphically-upward exhibit a $\sim 12\text{‰}$ positive shift, in addition to a 1 to 2 ‰ shift towards more negative values from shallow to deep-water environments; both characteristics consistent with other global basal Ediacaran carbonate successions. Petrographic observations combined with regionally correlatable stratigraphic trends suggest that primary $\delta^{13}\text{C}$ values were mostly preserved during transport and deposition, with minor diagenetic alteration (1 to 2 ‰) and no evidence of metamorphic modification. Conversely, $\delta^{18}\text{O}$ values of the OFP limestones are fairly uniform at each location, show little variation with stratigraphic position, and progressively exhibit more negative values from east to west reflecting the increase in regional metamorphic grade of the WSG. Overall, the $\delta^{34}\text{S}$ values from local pyrite in all three members of the OFP show a broad range ($\sim 60\text{‰}$) of values. At

some locations, the S-isotopic data displays moderately consistent upward-stratigraphic trends that locally correlate with sedimentary facies and are interpreted to reflect diffusion-controlled sulfate availability linked to the sedimentation rate. However, the $\delta^{34}\text{S}$ values of the OFP also show significant spatially heterogeneity (e.g. TLM to GSM transition) suggesting additional local or regional factors, for example availability of organic matter, substrate redox conditions or microbial influences, played an important role in the resultant isotopic signature.

Fine-grained strata of the TLM and GSM are regionally uniform in thickness and lithofacies suggesting synchronous, basin-wide deep-marine deposition. These two members are interpreted to have accumulated during transgression and highstand related to a post-glacial eustatic rise and a shutdown of the supply of coarse, feldspar-rich sediment into the Windermere basin. The basal transgressive TLM represents the onset of post-glacial deposition with its striking purple colour in slope sections reflecting the upwelling of deep-ocean water enriched in reduced iron and its interaction with oxygen-laden surface water sourced from continental glacial melting. These siliciclastic deposits represent the deep-marine time equivalent of the cap dolostones, such as the Ravensthorpe Formation in the northern Canadian Cordillera. TLM siltstone grades upward into rhythmic limestone-siltstone turbidites interpreted to correlate directly with the timing of repeated growth and erosion of shallow-marine bladed-calcite crystals, commonly observed in the upper limestone part of cap carbonate successions (e.g. Hayhook Formation). In the TLM (and GSM) these limestone deposits are characterized by negative $\delta^{13}\text{C}$ values that become increasingly negative along a shallow to deep-water transect, but stratigraphically upward show a positive shift; observations that are consistent with other global basal Ediacaran post-glacial carbonate successions. The GSM gradationally overlies the TLM, is enriched in redox-proxies (TOC, Mo, V and V/Cr) compared to other WSG mudstone units, and is interpreted to have been deposited under predominantly anoxic conditions. The GSM represents maximum

flooding and is the only recorded stratal occurrence of a regionally widespread, bottom-water anoxia event within the Windermere Basin. The GSM deposited during the post-glacial late transgression to highstand, and therefore is counter to many current models for the Cryogenian - Ediacaran transition that correlate anoxia with glacial conditions or other models that propose deep-water anoxia as a persistent condition of Neoproterozoic oceans.

Compared to the lower two members, WMM deposition was controlled mostly by local factors including: paleogeographic location, mass wasting, position of submarine canyons, topography along the slope, structural activity, and/or positions of relative sea-level. Regional tectonic uplift, possibly initiated by post-glacial isostatic rebound led to an abrupt fall of relative sea-level, erosional mass wasting, submarine canyon incision, and syn-sedimentary growth faulting. Newly created sediment transport fairways controlled the timing and location of the subsequent WMM deposition during renewed relative sea-level rise. The contact between the GSM and overlying WMM is a sequence boundary linked to an abrupt fall of relative sea-level. Canyons active during the initial falling-stage, lowstand and transgressive conditions were filled with mostly immature siliciclastic, hinterland-sourced sediment. These canyons shut down after flooding of the shelf and new canyon conduits became active during late transgression and highstand. These canyons were filled with mixed quartz-rich siliciclastic and carbonate sediment that was winnowed and matured during residence on the shelf coupled with longshore transport processes. These strata are composed of Sr-rich limestone, interpreted to have originally precipitated as aragonite in CaCO_3 -supersaturated oceanic waters. $\delta^{13}\text{C}$ values from WMM limestone show a steady upward-stratigraphic increase and approach near-zero values towards the termination of OFP deposition.

Overall, the physical and isotopic characteristics of the upper bathyal to upper abyssal OFP are most consistent with the cap carbonate model of post-glacial upwelling and oceanic stratification, perhaps linked to the relatively rapid eustatic

rise. TLM limestone units are interpreted to have precipitated in similar neritic water depths as the Hayhook Formation; however the $\delta^{13}\text{C}$ isotopic differences between the two time-equivalent units may reflect an isotopic gradient, or regional variations in the relative amounts of mixing between deep-water rich in light carbon and shallow-water rich in heavy carbon. The upward stratigraphic return to near-zero $\delta^{13}\text{C}$ values in the OFP during the eustatic rise is interpreted to reflect a gradual cessation of the mixing between the two isotopically distinctive water sources and return to normal seawater conditions in the shallow- and deep-marine realms following the major global glaciation event. The predominance of fine-grained strata within the OFP are consistent with relatively slow deposition suggesting the return to normal seawater conditions and breakdown of oceanic stratification was not a geologically rapid event. However, without additional age constraints, determining the precise timing of this evolution remains uncertain, potentially ranging from tens of thousands of years to tens of millions of years.

REFERENCES

- Aalto, K. R. 1971. Glacial marine sedimentation and stratigraphy of the Toby conglomerate (upper Proterozoic), southeastern British Columbia, northwestern Idaho and northeastern Washington. *Canadian Journal of Earth Sciences*, 8, 753-787.
- Adelson, J. M., G. R. Helz, and C. V. Miller, 2001, Reconstructing the rise of Recent coastal anoxia; molybdenum in Chesapeake Bay sediments: *Geochimica et Cosmochimica Acta*, v. 65, p. 237-252.
- Aitken, J. D. 1969. Documentation of the sub-Cambrian unconformity, Rocky Mountains main ranges, Alberta. *Canadian Journal of Earth Sciences*, 6, 193-200.
- Aitken, J. D., 1991a, The Ice Brook Formation and post-Rapitan, late Proterozoic glaciation, Mackenzie Mountains, Northwest Territories, *Geological Survey of Canada Bulletin* 404, p. 43.
- Aitken, J. D., 1991b, Two late Proterozoic glaciations, Mackenzie Mountains, northwestern Canada: *Geology*, v. 19, p. 445-448.
- Algeo, T. J., and J. B. Maynard, 2004, Trace-element behavior and redox facies in core shales of Upper Pennsylvanian Kansas-type cyclothems: *Chemical Geology*, v. 206, p. 289-318.
- Algeo, T. J., and T. W. Lyons, 2006, Mo-total organic carbon covariation in modern anoxic marine environments; implications for analysis of paleoredox and paleohydrographic conditions: *Paleoceanography*, v. 21, p. no.1, 23.
- Allan, J. A., 1913, Rocky Mountains, Bankhead to Golden.
- Allan, J. A., P. S. Warren, and R. L. Rutherford, 1932, A preliminary study of the eastern ranges of the Rocky Mountains in Jasper Park, Alberta: *Transactions of the Royal Society of Canada = Memoires de la Societe Royale du Canada*, v. 26, p. 225-249.
- Allen, P. A., and P. F. Hoffman, 2005, Extreme winds and waves in the aftermath of a Neoproterozoic glaciation: *Nature*, v. 433, p. 123-127.
- Allen, P. A., J. Leather, and M. D. Brasier, 2004, The Neoproterozoic Fiq glaciation and its aftermath, Huqf Supergroup of Oman: *Basin Research*, v. 16, p. 507-534.
- Anderson, K. S., S. A. Graham, and S. M. Hubbard, 2006, Facies, architecture, and origin of a reservoir-scale sand-rich succession within submarine canyon fill; insights from Wagon Caves Rock (Paleocene), Santa Lucia Range, California, U.S.A: *Journal of Sedimentary Research*, v. 76, p. 819-838.
- Arnaud, E., and C. H. Eyles, 2002a, Catastrophic mass failure of a Neoproterozoic glacially influenced continental margin, the Great Breccia, Port Askaig Formation, Scotland: *Sedimentary Geology*, v. 151, p. 313-333.

- Arnaud, E., and C. H. Eyles, 2002b, Glacial influence on Neoproterozoic sedimentation; the Smalfjord Formation, Northern Norway: *Sedimentology*, v. 49, p. 765-788.
- Arnaud, E., and C. H. Eyles, 2006, Neoproterozoic environmental change recorded in the Port Askaig Formation, Scotland; climatic vs tectonic controls: *Sedimentary Geology*, v. 183, p. 99-124.
- Arnott, R. W., and F. J. Hein, 1986, Submarine canyon fills of the Hector Formation, Lake Louise, Alberta; late Precambrian syn-rift deposits of the proto-Pacific Miogeocline: *Bulletin of Canadian Petroleum Geology*, v. 34, p. 395-407.
- Arthur, M. A., H. C. Jenkyns, H. J. Brumsack, and S. O. Schlanger, 1990, Stratigraphy, geochemistry, and paleo-oceanography of organic-rich Cretaceous sequences, in R. N. Ginsburg, and B. Beaudoin, eds., *Cretaceous Resources, Events and Rhythms*: Amsterdam, Kluwer Academic Publishing, p. 75-119.
- Arthur, M. A., T. F. Anderson, I. R. Kaplan, J. Veizer, and L. S. Land, 1983, Stable isotopes in sedimentary geology.
- Atkinson, S. J. 1975. Surface geology of the Paradise Basin (82K/8W). *Geology in British Columbia*, British Columbia Ministry of Mines and Petroleum Resources 1975: G7-G12.
- Banner, J. L., and G. N. Hanson, 1990, Calculation of simultaneous isotopic and trace element variations during water-rock interaction with applications to carbonate diagenesis: *Geochimica et Cosmochimica Acta*, v. 54, p. 3123-3137.
- Barnes, N. E., and W. R. Normark, 1985a, Diagnostic parameters for comparing modern submarine fans and ancient turbidite systems, in A. H. Bouma, W. R. Normark, and N. E. Barnes, eds.: New York, Springer-Verlag.
- Barnes, N. E., and W. R. Normark, 1985b, Diagnostic parameters for comparing modern submarine fans and ancient turbidite systems; map [modified].
- Baumgartner, L. P., and J. W. Valley, 2001, Stable isotope transport and contact metamorphic fluid flow: *Reviews in Mineralogy and Geochemistry*, v. 43, p. 415-467.
- Bennett, S. 1986. *Geology of the Mount Forster map area*. British Columbia Ministry of Energy, Mines and Petroleum Resources, Preliminary Map 62.
- Berger, W. H., and E. Vincent, 1986, Deep-sea carbonates; reading the carbon-isotope signal: *Geologische Rundschau*, v. 75, p. 249-269.
- Berner, R. A., 1970, Sedimentary pyrite formation: *American Journal of Science*, v. 268, p. 1-23.
- Berner, R. A., 1981, A new geochemical classification of sedimentary environments: *Journal of Sedimentary Petrology*, v. 51, p. 359-365.
- Berner, R. A., 1982, Burial of organic carbon and pyrite sulfur in the modern ocean; its geochemical and environmental significance: *American Journal of Science*, v. 282, p. 451-473.
- Berner, R. A., 1984, Sedimentary pyrite formation; an update: *Geochimica et Cosmochimica Acta*, v. 48, p. 605-615.

- Berner, R. A., and R. Raiswell, 1983, Burial of organic carbon and pyrite sulfur in sediments over Phanerozoic time; a new theory: *Geochimica et Cosmochimica Acta*, v. 47, p. 855-862.
- Boetius, A., K. Ravensschlag, C. J. Schubert, D. Rickert, F. Widdel, A. Gieseke, R. Amann, B. B. Jorgensen, U. Witte, and O. Pfannkuche, 2000, A marine microbial consortium apparently mediating anaerobic oxidation of methane: *Nature*, v. 407, p. 623-626.
- Boghossian, N. D., P. J. Patchett, G. M. Ross, and G. E. Gehrels, 1996, Nd isotopes and the source of sediments in the miogeocline of the Canadian Cordillera: *Journal of Geology*, v. 104, p. 259-277.
- Bond, G. C. and Kominz, M. A. 1984. Construction of tectonic subsidence curves for the early Paleozoic miogeocline, southern Canadian Rocky Mountains-implications for subsidence mechanisms, age of breakup, and crustal thinning. *Geological Society of America Bulletin*, 95, 155-173.
- Bouma, A. H., 1962, Sedimentology of some Flysch deposits; a graphic approach to facies interpretation.
- Boyd, R., K. Ruming, I. Goodwin, M. Sandstrom, and C. Schroeder-Adams, 2008, Highstand transport of coastal sand to the deep ocean; a case study from Fraser Island, southeast Australia: *Geology*, v. 36, p. 15-18.
- Brand, U., and J. Veizer, 1980, Chemical diagenesis of a multicomponent carbonate system; 1, Trace elements: *Journal of Sedimentary Petrology*, v. 50, p. 1219-1236.
- Brand, U., and J. Veizer, 1981, Chemical diagenesis of a multicomponent carbonate system; 2, Stable isotopes: *Journal of Sedimentary Petrology*, v. 51, p. 987-997.
- Brand, U., J. Veizer, and Anonymous, 1981, Stable isotope diagenesis of multicomponent carbonate system, *AAPG Bulletin*, v. 65, p. 905-906.
- Brown, D. A., T. P. Dougherty, and P. Stinson, 1995, Preliminary geology of the Creston map area, southeastern British Columbia (82F/2), *Geological Fieldwork 1994, Paper 1995-1*, British Columbia Geological Survey, p. 135-155.
- Buckley, D. E., and R. E. Cranston, 1988, Early diagenesis in deep sea turbidites; the imprint of paleo-oxidation zones: *Geochimica et Cosmochimica Acta*, v. 52, p. 2925-2939.
- Burwash, R. A., and R. R. Culbert, 1976, Multivariate geochemical and mineral patterns in the Precambrian basement of western Canada: *Canadian Journal of Earth Sciences = Journal Canadien des Sciences de la Terre*, v. 13, p. 1-18.
- Calver, C. R., 2000, Isotope stratigraphy of the Ediacarian (Neoproterozoic III) of the Adelaide rift complex, Australia, and the overprint of water column stratification: *Precambrian Research*, v. 100, p. 121-150.
- Calvert, S. E., and T. F. Pedersen, 1993, Geochemistry of Recent oxic and anoxic marine sediments; implications for the geological record: *Marine Geology*, v. 113, p. 67-88.

- Campbell, R. B., E. W. Mountjoy, and F. G. Young, 1973, Geology of McBride map-area, British Columbia, Geological Survey of Canada Paper 72-35, p. 104.
- Canfield, D. E., 1998, A new model for Proterozoic ocean chemistry: *Nature*, v. 396, p. 450-453.
- Canfield, D. E., 2001, Biogeochemistry of sulfur isotopes: *Reviews in Mineralogy and Geochemistry*, v. 43, p. 609-636.
- Canfield, D. E., and A. Teske, 1996, Late Proterozoic rise in atmospheric oxygen concentration inferred from phylogenetic and sulphur-isotope studies: *Nature*, v. 382, p. 127-132.
- Canfield, D. E., S. W. Poulton, A. H. Knoll, G. M. Narbonne, G. Ross, T. Goldberg, and H. Strauss, 2008, Ferruginous conditions dominated later Neoproterozoic deep-water chemistry: *Science*, v. 321, p. 949-952.
- Canfield, D. E., S. W. Poulton, and G. M. Narbonne, 2007, Late-Neoproterozoic deep-ocean oxygenation and the rise of animal life: *Science*, v. 315, p. 92-95.
- Canfield, D., B. Thamdrup, and Anonymous, 1994, The production of (super 34) S-depleted sulfide during bacterial S (super 0) disproportionation, *Eos, Transactions, American Geophysical Union*, v. 75, p. 326.
- Carey, J. A., 1984, Geology of late Proterozoic Miette Group, southern Main Ranges, Cushing Creek area, B.C: Master's thesis, University of Calgary, Calgary, 119 p.
- Carey, J. A., and P. S. Simony, 1985, Stratigraphy, sedimentology and structure of late Proterozoic Miette Group, Cushing Creek area, B.C: *Bulletin of Canadian Petroleum Geology*, v. 33, p. 184-203.
- Carvajal, C. R., and R. J. Steel, 2006, Thick turbidite successions from supply-dominated shelves during sea-level highstand: *Geology*, v. 34, p. 665-668.
- Chambers, L. A., and P. A. Trudinger, 1979, Microbiological fractionation of stable sulfur isotopes; a review and critique: *Geomicrobiology Journal*, v. 1, p. 249-293.
- Chamley, H., 1989, *Clay sedimentology*, Springer-Verlag, Berlin, Federal Republic of Germany (DEU), 623 p.
- Charlesworth, H. A. K., and D. B. Remington, 1960, Precambrian rocks in the vicinity of Jasper, Alberta: *Edmonton Geological Society*, v. Second Annual Field Trip Guide Book, p. 11-18.
- Charlesworth, H. A. K., C. R. Evans, and M. R. Stauffer, 1961, Precambrian geology in the Jasper-Geikie area: *Edmonton Geological Society*, v. Third Annual Field Trip Guide Book, p. 3-13.
- Charlesworth, H. A. K., J. L. Weiner, A. J. Akehurst, H. U. Bielenstein, C. R. Evans, R. E. Griffiths, D. B. Remington, M. R. Stauffer, and J. Steiner, 1967, *Precambrian Geology of the Jasper Region, Alberta*, v. 23, 74 p.
- Charlesworth, H. A. K., Weiner, J. L., Akehurst, A. J., Bielenstein, H. U., Evans, C. R., Griffiths, R. E., Remington, D. B., Stauffer, M. R. & Steiner, J. 1967. *Precambrian Geology of the Jasper Region*. Research Council of Alberta Bulletin 23.

- Christie-Blick, N., and Anonymous, 1990, Tectonic and eustatic controls on sedimentary successions at passive continental margins, *AAPG Bulletin*, v. 74, p. 628.
- Christie-Blick, N., and M. Levy, 1989a, Concepts of sequence stratigraphy, with examples from strata of late Proterozoic and Cambrian age in the Western United States, in N. Christie-Blick, M. Levy, and P. M. Hanshaw, eds.: Washington, Am. Geophys. Union.
- Christie-Blick, N., and M. Levy, 1989b, Stratigraphic and tectonic framework of upper Proterozoic and Cambrian rocks in the Western United States, in N. Christie-Blick, M. Levy, and P. M. Hanshaw, eds.: Washington, Am. Geophys. Union.
- Christie-Blick, N., I. A. Dyson, and C. C. von der Borch, 1995, Sequence stratigraphy and the interpretation of Neoproterozoic Earth history: *Precambrian Research*, v. 73, p. 3-26.
- Christie-Blick, N., M. A. Garcia del Cura, J. Soria, J. C. Canaveras, M. A. Garcia del Cura, J. Soria, A. Melendez Hevia, and A. R. Soria, 1998, Messinian-style drawdown model supported by new stratigraphic data from the Wonoka Canyons (terminal Proterozoic), South Australia: Alicante, Univ. Alicante.
- Clapham M. E. & Corsetti, F. A. 2005. Deep valley incision in the terminal Neoproterozoic (Ediacaran) Johnnie Formation, eastern California, USA: Tectonically or glacially driven? *Precambrian Research*, 141, 154-164.
- Claypool, G. E., W. T. Holser, I. R. Kaplan, H. Sakai, and I. Zak, 1980, The Age Curves of Sulfur and Oxygen Isotopes in Marine Sulfate and Their Mutual Interpretation: *Chemical Geology*, v. 28, p. 199-260.
- Cloetingh, S., and H. Kooi, 1992, Intraplate stresses and dynamical aspects of rifted basins, in P. A. Ziegler, ed., *Tectonophysics*, v. 215, p. 167-185.
- Cloetingh, S., F. M. Gradstein, H. Kooi, A. C. Grant, and M. Kaminski, 1990, Plate reorganization; a cause of rapid late Neogene subsidence and sedimentation around the North Atlantic: *Journal of the Geological Society of London*, v. 147, p. 495-506.
- Cloud, P., L. A. Wright, E. G. Williams, P. E. Diehl, and M. R. Walter, 1974, Giant Stromatolites and Associated Vertical Tubes from the Upper Proterozoic Noonday Dolomite, Death Valley Region, Eastern California: *Geological Society of America Bulletin*, v. 85, p. 1869-1882.
- Coleman, J. M., and D. B. Prior, 1988, Mass wasting on continental margins: *Annual Review of Earth and Planetary Sciences*, v. 16, p. 101-121.
- Colpron, M., J. M. Logan, and J. K. Mortensen, 2002, U-Pb zircon age constraint for late Neoproterozoic rifting and initiation of the lower Paleozoic passive margin of western Laurentia: *Canadian Journal of Earth Sciences = Revue Canadienne des Sciences de la Terre*, v. 39, p. 133-143.
- Compton, J. S., 1988, Degree of supersaturation and precipitation of organogenic dolomite: *Geology*, v. 16, p. 318-321.

- Condie, K. C., 1993, Chemical composition and evolution of the upper continental crust; contrasting results from surface samples and shales: *Chemical Geology*, v. 104, p. 1-37.
- Condie, K. C., and C. Martell, 1983, Early Proterozoic metasediments from north-central Colorado; metamorphism, provenance, and tectonic setting: *Geological Society of America Bulletin*, v. 94, p. 1215-1224.
- Condie, K. C., and D. J. Wronkiewicz, 1990, The Cr/Th ratio in Precambrian pelites from the Kaapvaal Craton as an index of craton evolution: *Earth and Planetary Science Letters*, v. 97, p. 256-267.
- Condon, D., M. Zhu, S. Bowring, W. Wang, A. Yang, and Y. Jin, 2005, U-Pb ages from the Neoproterozoic Doushantuo Formation, China: *Science*, v. 308, p. 95-98.
- Coniglio, M., 1989, Neomorphism and cementation in ancient deep-water limestones, Cow Head Group (Cambro-Ordovician), western Newfoundland, Canada: *Sedimentary Geology*, v. 65, p. 15-33.
- Coniglio, M., and G. R. Dix, 1992, Carbonate slopes, in R. G. Walker, and N. P. James, eds.: *St. Johns*, Geological Association of Canada.
- Coniglio, M., and N. P. James, 1990, Origin of fine-grained carbonate and siliciclastic sediments in an early Palaeozoic slope sequence, Cow Head Group, western Newfoundland: *Sedimentology*, v. 37, p. 215-230.
- Corsetti, F. A., and J. P. Grotzinger, 2005, Origin and significance of tube structures in Neoproterozoic post-glacial cap carbonates; example from Noonday Dolomite, Death Valley, United States: *Palaaios*, v. 20, p. 348-362.
- Covault, J. A., W. R. Normark, B. W. Romans, and S. A. Graham, 2007, Highstand fans in the California borderland; the overlooked deep-water depositional systems: *Geology*, v. 35, p. 783-786.
- Cruse, A. M., and T. W. Lyons, 2004, Trace metal records of regional paleoenvironmental variability in Pennsylvanian (Upper Carboniferous) black shales: *Chemical Geology*, v. 206, p. 319-345.
- Crusius, J., S. E. Calvert, T. Pedersen, and D. Sage, 1996, Rhenium and molybdenum enrichments in sediments as indicators of oxic, suboxic and sulfidic conditions of deposition: *Earth and Planetary Science Letters*, v. 145, p. 65-78.
- Crusius, J., T. F. Pedersen, S. E. Calvert, G. L. Cowie, T. Oba, and Anonymous, 1999, A 36 kyr geochemical record from the Sea of Japan of organic matter flux variations and changes in intermediate water oxygen concentrations: *Paleoceanography*, v. 14, p. 248-259.
- Cullers, R. L., 1994, The controls on the major and trace element variation of shales, siltstones, and sandstones of Pennsylvanian-Permian age from uplifted continental blocks in Colorado to platform sediment in Kansas, USA: *Geochimica et Cosmochimica Acta*, v. 58, p. 4955-4972.
- Cullers, R. L., 2000, The geochemistry of shales, siltstones and sandstones of Pennsylvanian-Permian age, Colorado, USA; implications for provenance and metamorphic studies: *Lithos*, v. 51, p. 181-203.

- Curtis, C., 1987, Mineralogical consequences of organic matter degradation in sediments; inorganic/organic diagenesis, in J. K. Leggett, and G. G. Zuffa, eds.: London, Graham and Trotman.
- Dalrymple, R. W. & Narbonne, G. M. 1996. Continental slope sedimentation in the Sheepbed Formation (Neoproterozoic, Windermere Supergroup), Mackenzie Mountains, N.W.T. *Canadian Journal of Earth Sciences*, 33, 848-862.
- Dalziel, I. W. D., 1991, Pacific margins of Laurentia and East Antarctica-Australia as a conjugate rift pair; evidence and implications for an Eocambrian supercontinent: *Geology*, v. 19, p. 598-601.
- de Alvarenga, C. J. S., R. V. Santos, and E. L. Dantas, 2004, C-O-Sr isotopic stratigraphy of cap carbonates overlying Marinoan-age glacial diamictites in the Paraguay Belt, Brazil: *Precambrian Research*, v. 131, p. 1-21.
- Dean, W. E., D. Z. Piper, and L. C. Peterson, 1999, Molybdenum accumulation in Cariaco Basin sediment over the past 24 k.y.; a record of water-column anoxia and climate: *Geology*, v. 27, p. 507-510.
- Dechesne, R. G., 1989, Stratigraphy and sedimentology of the late Proterozoic Old Fort Point Formation, Miette Group, Jasper, Alberta, Program with Abstracts - Geological Association of Canada; Mineralogical Association of Canada; Canadian Geophysical Union, Joint Annual Meeting, vol.14, v. 14, p. 42.
- Dechesne, R. G., 1990a, Geology of the Ptarmigan Creek map area (east half) and adjacent regions, Main Ranges, Rocky Mountains, British Columbia, Current Research, Part E, Geological Survey of Canada Paper, v. 90-1E, p. 81-89.
- Dechesne, R. G., 1990b, Old Fort Point Formation in the Meadow Creek Anticlinorium, in J. D. Aitken, and M. R. McDonough, eds., Late Proterozoic Glaciation, Rifting and Eustasy, as Illustrated by the Windermere Supergroup, Geological Association of Canada, Nuna Research Conference, p. 5.11-5.16.
- Dechesne, R. G., and E. W. Mountjoy, 1990, Geology of the Lucerne east-half map area, Rocky Mountain Main Ranges, Alberta and British Columbia: Current Research, Part D, Geological Survey of Canada Paper, v. 90-1D, p. 95-100.
- Dehler, C. M., M. Elrick, J. D. Bloch, L. J. Crossey, K. E. Karlstrom, and D. J. Des Marais, 2005, High-resolution $\delta^{13}\text{C}$ stratigraphy of the Chuar Group (ca. 770-742 Ma), Grand Canyon; implications for mid-Neoproterozoic climate change: *Geological Society of America Bulletin*, v. 117, p. 32-45.
- Derry, L. A., A. J. Kaufman, and S. B. Jacobsen, 1992, Sedimentary cycling and environmental change in the late Proterozoic; evidence from stable and radiogenic isotopes: *Geochimica et Cosmochimica Acta*, v. 56, p. 1317-1329.
- Des Marais, D. J., 2001, Isotopic evolution of the biogeochemical carbon cycle during the Precambrian: *Reviews in Mineralogy and Geochemistry*, v. 43, p. 555-578.
- Deuser, W. G., 1970, Carbon-13 in black sea waters and implications for the origin of hydrogen sulfide: *Science*, v. 168, p. 1575-1577.
- Devlin, W. J., and G. C. Bond, 1988, The initiation of the early Paleozoic Cordilleran miogeocline; evidence from the uppermost Proterozoic-Lower Cambrian

- Hamill Group of southeastern British Columbia: *Canadian Journal of Earth Sciences = Journal Canadien des Sciences de la Terre*, v. 25, p. 1-19.
- Devlin, W. J., Brueckner, H. K. & Bond, G. C. 1988. New isotopic data and a preliminary age for volcanics near the base of the Windermere Supergroup, northeastern Washington, U.S.A. *Canadian Journal of Earth Sciences*, 25, 1906-1911.
- Deynoux, M., R. Trompette, and L. J. G. Schermerhorn, 1976, Late Precambrian mixtites; glacial and/or nonglacial? Dealing especially with the mixtites of West Africa: *American Journal of Science*, v. 276, p. 1302-1315.
- Dickson, J. A. D., 1966, Carbonate identification and genesis as revealed by staining: *Journal of Sedimentary Petrology*, v. 36, p. 491-505.
- Egger, H., M. Homayoun, and W. Schnabel, 2002, Tectonic and climatic control of Paleogene sedimentation in the Rhenodanubian flysch basin (Eastern Alps, Austria): *Sedimentary Geology*, v. 152, p. 247-262.
- Eisbacher, G. H. 1981a. Sedimentary tectonics and glacial record in the Windermere Supergroup, Mackenzie Mountains, northwestern Canada. *Geological Survey of Canada Paper* 80-27.
- Eisbacher, G. H. 1981b. The Late Precambrian Mount Lloyd George diamictites, northern British Columbia. In: Hambrey, M. J. & Harland W. B. (eds) *Earth's pre-Pleistocene glacial record*, Cambridge University Press, 728-730.
- Elie, M., A. C. R. Nogueira, A. Nedelec, R. I. F. Trindade, and F. Kenig, 2007, A red algal bloom in the aftermath of the Marinoan snowball Earth: *Terra Nova*, v. 19, p. 303-308.
- Elrick, M., and L. A. Hinnov, 2007, Millennial-scale paleoclimate cycles recorded in widespread Palaeozoic deeper water rhythmites of North America: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 243, p. 348-372.
- Emerson, S. R., and S. S. Huested, 1991, Ocean anoxia and the concentrations of molybdenum and vanadium in seawater: *Marine Chemistry*, v. 34, p. 177-196.
- Erickson, B. E., and G. R. Helz, 2000, Molybdenum(VI) speciation in sulfidic waters; stability and lability of thiomolybdates: *Geochimica et Cosmochimica Acta*, v. 64, p. 1149-1158.
- Evans, C. R., 1961, The Precambrian rocks of the Old Fort Point Formation, Jasper, Alberta: Master's thesis, University of Alberta, Edmonton, 83 p.
- Evans, C. S., 1933, Brisco-Dogtooth Map-Area, British Columbia, *Geological Survey of Canada Summary Report* 1932, Part A II, p. 106-176.
- Evenchick, C. A., Parrish, R. R., & Gabrielse, H. 1984. Precambrian gneiss and Late Proterozoic sedimentation in north-central British Columbia. *Geology*, 12, 233-237.
- Eyles, C. H., and N. Eyles, 1983, Glaciomarine model for upper Precambrian diamictites of the Port Askaig Formation, Scotland: *Geology*, v. 11, p. 692-696.
- Eyles, C. H., N. Eyles, and A. D. Miall, 1985, Models of glaciomarine sedimentation and their application to the interpretation of ancient glacial sequences, in M.

- Deynoux, ed., *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 51, p. 15-84.
- Fairchild, I. J., and B. Spiro, 1987, Petrological and isotopic implications of some contrasting late Precambrian carbonates, NE Spitsbergen: *Sedimentology*, v. 34, p. 973-989.
- Fairchild, I. J., and M. J. Kennedy, 2007, Neoproterozoic glaciation in the Earth system: *Journal of the Geological Society of London*, v. 164, p. 895-921.
- Fan, J., and R. Kerrich, 1997, Geochemical characteristics of aluminum depleted and undepleted komatiites and HREE-enriched low-Ti tholeiites, western Abitibi greenstone belt; a heterogeneous mantle plume-convergent margin environment: *Geochimica et Cosmochimica Acta*, v. 61, p. 4723-4744.
- Fanning, C. M. & Link, P. K. 2004. U-Pb SHRIMP ages of Neoproterozoic (Sturtian) glaciogenic Pocatello Formation, southeastern Idaho. *Geology*, 32, 881-884.
- Fedo, C. M. & Cooper, J. D. 2001. Sedimentology and sequence stratigraphy of Neoproterozoic and Cambrian units across a craton-margin hinge zone, southeastern California, and implications for the early evolution of the Cordilleran margin. *Sedimentary Geology*, 141-142, 501-522.
- Fedo, C. M., and J. D. Cooper, 1990, Braided fluvial to marine transition; the basal Lower Cambrian Wood Canyon Formation, southern Marble Mountains, Mojave Desert, California: *Journal of Sedimentary Petrology*, v. 60, p. 220-234.
- Fedo, C. M., G. M. Young, and Anonymous, 1996b, Regional potassic and sodic metasomatism in the southern province of the Canadian Shield revealed by the paleo-Proterozoic Serpent Formation, Huronian Supergroup, Abstracts with Programs - Geological Society of America, v. 28, p. 229.
- Fedo, C. M., G. M. Young, and H. W. Nesbitt, 1997a, Paleoclimatic control on the composition of the Paleoproterozoic Serpent Formation, Huronian Supergroup, Canada; a greenhouse to icehouse transition: *Precambrian Research*, v. 86, p. 201-223.
- Fedo, C. M., G. M. Young, H. W. Nesbitt, and J. M. Hanchar, 1997b, Potassic and sodic metasomatism in the Southern Province of the Canadian Shield; evidence from the Paleoproterozoic Serpent Formation, Huronian Supergroup, Canada: *Precambrian Research*, v. 84, p. 17-36.
- Fedo, C. M., H. W. Nesbitt, and G. M. Young, 1995, Unraveling the effects of potassium metasomatism in sedimentary rocks and Paleosols, with implications for paleoweathering conditions and provenance: *Geology*, v. 23, p. 921-924.
- Fedo, C. M., J. D. Cooper, P. G. Eriksson, O. Catuneanu, L. B. Aspler, J. R. Chiarenzelli, and M. A. Martins-Neto, 2001, Sedimentology and sequence stratigraphy of Neoproterozoic and Cambrian units across a craton-margin hinge zone, southeastern California, and implications for the early evolution of the Cordilleran margin: *Sedimentary Geology*, v. 141-142, p. 501-522.

- Fedo, C. M., K. A. Eriksson, and E. J. Krogstad, 1996a, Geochemistry of shales from Archean (approximately 3.0 Ga) Buhwa greenstone belt, Zimbabwe; implications for provenance and source-area weathering: *Geochimica et Cosmochimica Acta*, v. 60, p. 1751-1763.
- Ferguson, C. A., 1994, Structural geology and stratigraphy of the northern Cariboo Mountains between Isaac Lake and Fraser River, British Columbia: Map thesis, University of Calgary, Calgary.
- Ferri, F., Rees, C. J., Nelson, J. L., & Legun, A. S. 1999. Geology and mineral deposits of the northern Kechika Trough between Gataga River and the 60th parallel. British Columbia Ministry of Energy and Mines Bulletin 107.
- Ferri, F., C. Rees, J. Nelson, A. Legun, M. J. Orchard, B. S. Norford, W. H. Fritz, J. K. Mortensen, and J. E. Gabites, 1999, Geology and mineral deposits of the northern Kechika Trough between Gataga River and the 60th parallel, v. vol.107, Bulletin - British Columbia Ministry of Energy and Mines, Energy and Minerals Division, Geological Survey Branch, 122 p.
- Font, E., A. Nedelec, R. I. F. Trindade, M. Macouin, and A. Charriere, 2006, Chemostratigraphy of the Neoproterozoic Mirassol d'Oeste cap dolostones (Mato Grosso, Brazil); an alternative model for Marinoan cap dolostone formation: *Earth and Planetary Science Letters*, v. 250, p. 89-103.
- Froelich, P. N., G. P. Klinkhammer, M. L. Bender, N. Luedtke, G. R. Heath, D. Cullen, P. Dauphin, D. Hammond, B. Hartman, and V. Maynard, 1979, Early oxidation of organic matter in pelagic sediments of the eastern equatorial Atlantic; suboxic diagenesis: *Geochimica et Cosmochimica Acta*, v. 43, p. 1075-1090.
- Gabrielse, H. & Campbell, R. B. 1991. Upper Proterozoic Assemblages. In: Gabrielse H. & Yorath, C. J. (eds) *Geology of the Cordilleran Orogen*, Geological Survey of Canada, *Geology of Canada*, 4, 125-150.
- Gal, L. P., and E. D. Ghent, 1990, Metamorphism in the Solitude Range, southwestern Rocky Mountains, British Columbia; comparison with adjacent Omineca Belt rocks and tectonometamorphic implications for the Purcell Thrust: *Canadian Journal of Earth Sciences = Revue Canadienne des Sciences de la Terre*, v. 27, p. 1511-1520.
- Gammon, P. R., D. M. McKirdy, and H. D. Smith, 2005, The timing and environment of tepee formation in a Marinoan cap carbonate: *Sedimentary Geology*, v. 177, p. 195-208.
- Gautier, D. L., 1987, Isotopic composition of pyrite; relationship to organic matter type and iron availability in some North American Cretaceous shales, in N. Clauer, and S. Chaudhuri, eds., *Chemical Geology; Isotope Geoscience Section*, v. 65: Amsterdam, Elsevier, p. 293-303.
- Gehrels, G. E., and G. M. Ross, 1998, Detrital zircon geochronology of Neoproterozoic to Permian miogeoclinal strata in British Columbia and Alberta: *Canadian Journal of Earth Sciences = Journal Canadien des Sciences de la Terre*, v. 35, p. 1380-1401.

- Giddings, J. A., and M. W. Wallace, 2009, Facies-dependent delta C-13 variation from a Cryogenian platform margin, South Australia: Evidence for stratified Neoproterozoic oceans?: *Palaeogeography Palaeoclimatology Palaeoecology*, v. 271, p. 196-214.
- Girty, G. H., A. D. Hanson, C. Knaack, and D. Johnson, 1994, Provenance determined by REE, Th, and Sc analyses of metasedimentary rocks, Boyden Cave roof pendant, central Sierra Nevada, California: *Journal of Sedimentary Research, Section B: Stratigraphy and Global Studies*, v. 64, p. 68-73.
- Glover, J. K., and R. A. Price, 1976, Stratigraphy and structure of the Windermere Supergroup, southern Kootenay Arc, British Columbia: *Geological Survey of Canada Paper*, v. 76-1B, p. 21-23.
- Gorjan, P., J. J. Veevers, and M. R. Walter, 2000, Neoproterozoic sulfur-isotope variation in Australia and global implications: *Precambrian Research*, v. 100, p. 151-179.
- Grasby, S. E., 1991, Stratigraphy of the Miette Group and tectonic history of the southern Selwyn Range, western Main Ranges, British Columbia: Master's thesis, McGill University, Montréal, Québec, 121 p.
- Grasby, S. E., and R. L. Brown, 1993, New correlations of the Hadrynian Windermere Supergroup in the northern Selkirk Mountains, British Columbia: *Current Research, Part A, Geological Survey of Canada Paper*, v. 93-1A, p. 199-206.
- Gromet, L. P., R. F. Dymek, L. A. Haskin, and R. L. Korotev, 1984, The "North American shale composite"; its compilation, major and trace element characteristics: *Geochimica et Cosmochimica Acta*, v. 48, p. 2469-2482.
- Grotzinger, J. P., and A. H. Knoll, 1995, Anomalous carbonate precipitates; is the Precambrian the key to the Permian?: *Palaaios*, v. 10, p. 578-596.
- Gussow, W. C. 1973. *Chuar* sp. cf. *C. circularis* Walcott from the Precambrian Hector Formation, Banff National Park, Alberta, Canada. *Journal of Paleontology*, 47, 1108-1112.
- Gussow, W. C., 1956, Lipalian Interval evaluated (Canada): *Geological Society of America Bulletin*, v. 67, p. 1702.
- Gussow, W. C., 1957, Cambrian and Precambrian geology of southern Alberta: *Alberta Society of Petroleum Geologists Guidebook*, v. Seventh Annual Field Conference, p. 7-19.
- Gussow, W. C., 1973, *Chuar* sp. cf. *C. circularis* Walcott from the Precambrian Hector Formation, Banff National Park, Alberta, Canada: *Journal of Paleontology*, v. 47, p. 1108-1112.
- Habicht, K. S., and D. E. Canfield, 2001, Isotope fractionation by sulfate-reducing natural populations and the isotopic composition of sulfide in marine sediments: *Geology*, v. 29, p. 555-558.
- Hallam, A., 1986, Origin of minor limestone-shale cycles; climatically induced or diagenetic?: *Geology*, v. 14, p. 609-612.

- Halverson, G. P., A. C. Maloof, and P. F. Hoffman, 2004, The Marinoan glaciation (Neoproterozoic) in northeast Svalbard: *Basin Research*, v. 16, p. 297-324.
- Halverson, G. P., and M. T. Hurtgen, 2007, Ediacaran growth of the marine sulfate reservoir: *Earth and Planetary Science Letters*, v. 263, p. 32-44.
- Halverson, G. P., P. F. Hoffman, D. P. Schrag, A. C. Maloof, and A. H. N. Rice, 2005, Toward a Neoproterozoic composite carbon-isotope record: *Geological Society of America Bulletin*, v. 117, p. 1181-1207.
- Hammer, O., D. A. T. Harper, and P. D. Ryan, 2001, PAST: Paleontological Statistics Software Package for Education and Data Analysis: *Palaeontologia Electronica*, v. 4, p. 9.
- Hatch, J. R., and J. S. Leventhal, 1992, Relationship between inferred redox potential of the depositional environment and geochemistry of the Upper Pennsylvanian (Missourian) Stark Shale Member of the Dennis Limestone, Wabaunsee County, Kansas, U.S.A, in P. A. Meyers, L. M. Pratt, and B. Nagy, eds., *Chemical Geology*, v. 99, p. 65-82.
- Hayes, J. M., H. Strauss, and A. J. Kaufman, 1999, The abundance of (super 13) C in marine organic matter and isotopic fractionation in the global biogeochemical cycle of carbon during the past 800 Ma: *Chemical Geology*, v. 161, p. 103-125.
- Hayes, J. M., I. R. Kaplan, and K. W. Wedeking, 1983, Precambrian organic geochemistry; preservation of the record, in J. W. Schopf, ed.: Princeton, Princeton Univ. Press.
- Hein, F. J., and M. E. McMechan, 1994, Proterozoic-Lower Cambrian strata of the Western Canada Sedimentary Basin, in G. D. Mossop, and Shetsen, eds., *Geological Atlas of the western Canada Sedimentary Basin*: Calgary, Canadian Society of Petroleum Geologists, p. 57-68.
- Helz, G. R., C. V. Miller, J. M. Charnock, J. F. W. Mosselmans, R. A. D. Pattrick, C. D. Garner, and D. J. Vaughan, 1996, Mechanism of molybdenum removal from the sea and its concentration in black shales: EXAFS evidence: *Geochimica Et Cosmochimica Acta*, v. 60, p. 3631-3642.
- Herron, M. M., 1988, Geochemical classification of terrigenous sands and shales from core or log data: *Journal of Sedimentary Petrology*, v. 58, p. 820-829.
- Hesse, R., H. Rashid, and S. Khodabakhsh, 2004, Fine-grained sediment lofting from meltwater-generated turbidity currents during Heinrich events: *Geology*, v. 32, p. 449-452.
- Higgins, J. A., and D. P. Schrag, 2003, Aftermath of a snowball Earth: *Geochemistry, Geophysics, Geosystems - G (super 3)*, v. 4, p. no.3, 20.
- Hoffman, P. F., 1991, Did the breakout of Laurentia turn Gondwanaland inside-out?: *Science*, v. 252, p. 1409-1412.
- Hoffman, P. F., A. J. Kaufman, G. P. Halverson, and D. P. Schrag, 1998b, A Neoproterozoic snowball earth: *Science*, v. 281, p. 1342-1346.
- Hoffman, P. F., A. J. Kaufman, G. P. Halverson, and S. A. Bowring, 1998a, Neoproterozoic post-glacial cap carbonates; sequence stratigraphical

- perspective from the Otavi Group, Namibia: *Journal of African Earth Sciences* (1994), v. 27, p. 113-115.
- Hoffman, P. F., and D. P. Schrag, 2002, The snowball Earth hypothesis; testing the limits of global change: *Terra Nova*, v. 14, p. 129-155.
- Hoffman, P. F., and G. P. Halverson, submitted, Neoproterozoic glacial record in the Mackenzie Mountains, northern Canadian Cordillera, in E. Arnaud, G. P. Halverson, and G. A. Shields, eds., *The Geological Record of Neoproterozoic Glaciations*, Geological Society of London Special Publication.
- Hoffman, P. F., G. P. Halverson, D. P. Schrag, and Anonymous, 2004, On the consistent sequence of mineralogy and bedforms in post-glacial cap carbonates of Marinoan (ca 635 Ma) age on different paleomargins; steady-state ocean stratification during a post-snowball Earth marine transgression?, *Abstracts with Programs - Geological Society of America*, v. 36, p. 198.
- Hoffman, P. F., G. P. Halverson, E. W. Domack, J. M. Husson, J. A. Higgins, and D. P. Schrag, 2007, Are basal Ediacaran (635 Ma) post-glacial "cap dolostones" diachronous?
- Hoffman, P. F., G. P. Halverson, J. P. Grotzinger, M. J. Kennedy, N. Christie-Blick, and L. E. Sohl, 2002, Are Proterozoic cap carbonates and isotopic excursions a record of gas hydrate destabilization following Earth's coldest intervals?; discussion and reply: *Geology*, v. 30, p. 286-288.
- Hoffmann, K. H., D. J. Condon, S. A. Bowring, and J. L. Crowley, 2004, U-Pb zircon date from the Neoproterozoic Ghaub Formation, Namibia; constraints on Marinoan glaciation: *Geology*, v. 32, p. 817-820.
- Hofmann, H. J. & Mountjoy, E. W. 2001. Namacalathus-Cloudina assemblage in Neoproterozoic Miette Group (Byng Formation), British Columbia; Canada's oldest shelly fossils, *Geology* 13, 819-821.
- Hofmann, H. J., 1971, Precambrian fossils, pseudofossils, and Problematica in Canada: *Bulletin - Geological Survey of Canada*, v. 189, p. 146.
- Hudson, J. D., 1978, Concretions, isotopes, and the diagenetic history of the Oxford Clay (Jurassic) of central England: *Sedimentology*, v. 25, p. 339-367.
- Hurtgen, M. T., G. P. Halverson, M. A. Arthur, and P. F. Hoffman, 2006, Sulfur cycling in the aftermath of a 635-Ma snowball glaciation; evidence for a syn-glacial sulfidic deep ocean: *Earth and Planetary Science Letters*, v. 245, p. 551-570.
- Hurtgen, M. T., M. A. Arthur, and G. P. Halverson, 2005, Neoproterozoic sulfur isotopes, the evolution of microbial sulfur species, and the burial efficiency of sulfide as sedimentary pyrite: *Geology*, v. 33, p. 41-44.
- Hurtgen, M. T., M. A. Arthur, N. S. Suits, and A. J. Kaufman, 2002, The sulfur isotopic composition of Neoproterozoic seawater sulfate; implications for a snowball Earth?: *Earth and Planetary Science Letters*, v. 203, p. 413-429.
- Irwin, H., C. Curtis, and M. Coleman, 1977, Isotopic evidence for source of diagenetic carbonates formed during burial of organic-rich sediments: *Nature*, v. 269, p. 209-213.

- Jacobsen, S. B., and A. J. Kaufman, 1999, The Sr, C and O isotopic evolution of Neoproterozoic seawater: *Chemical Geology*, v. 161, p. 37-57.
- James, N. P., G. M. Narbonne, and T. K. Kyser, 2001, Late Neoproterozoic cap carbonates; Mackenzie Mountains, northwestern Canada; precipitation and global glacial meltdown: *Canadian Journal of Earth Sciences = Revue Canadienne des Sciences de la Terre*, v. 38, p. 1229-1262.
- Jenner, G. A., H. P. Longerich, S. E. Jackson, and B. J. Fryer, 1990, ICP-MS; a powerful tool for high-precision trace-element analysis in earth sciences; evidence from analysis of selected U.S.G.S. reference samples: *Chemical Geology*, v. 83, p. 133-148.
- Jiang, G. Q., A. J. Kaufman, N. Christie-Blick, S. H. Zhang, and H. C. Wu, 2007, Carbon isotope variability across the Ediacaran Yangtze platform in South China: Implications for a large surface-to-deep ocean delta C-13 gradient: *Earth and Planetary Science Letters*, v. 261, p. 303-320.
- Jones, B., and D. A. C. Manning, 1994, Comparison of geochemical indices used for the interpretation of palaeoredox conditions in ancient mudstones: *Chemical Geology*, v. 111, p. 111-129.
- Juniper, S. K., and Y. Fouquet, 1988, Filamentous iron-silica deposits from modern and ancient hydrothermal sites, in T. J. Barrett, and J. L. Jambor, eds., *The Canadian Mineralogist*, vol. 26, Part 3, p. 859-869.
- Karlstrom, K. E., S. S. Harlan, M. L. Williams, J. McLelland, J. W. Geissman, and K.-I. Ahall, 1999, Refining Rodinia; geologic evidence for the Australia-Western U.S. connection in the Proterozoic: *GSA Today*, v. 9, p. 1-7.
- Katz, B. J., 2005, Controlling factors on source rock development; a review of productivity, preservation, and sedimentation rate, in N. B. Harris, ed., *The Deposition of Organic-Carbon-Rich Sediments: Models, Mechanisms, and Consequences*, v. 82, p. 7-16.
- Kendall, B. S., R. A. Creaser, G. M. Ross, and D. Selby, 2004, Constraints on the timing of Marinoan "Snowball Earth" glaciation by ^{187}Re - ^{187}Os dating of a Neoproterozoic, post-glacial black shale in Western Canada: *Earth and Planetary Science Letters*, v. 222, p. 729-740.
- Kennedy, C. B., S. D. Scott, and F. G. Ferris, 2004, Hydrothermal phase stabilization of 2-line ferrihydrite by bacteria: *Chemical Geology*, v. 212, p. 269-277.
- Kennedy, M. J., 1996, Stratigraphy, sedimentology, and isotopic geochemistry of Australian Neoproterozoic postglacial cap dolostones; deglaciation, delta (sub 13) C excursions, and carbonate precipitation: *Journal of Sedimentary Research*, v. 66, p. 1050-1064.
- Kennedy, M. J., B. Runnegar, A. R. Prave, K. H. Hoffmann, and M. A. Arthur, 1998, Two or four Neoproterozoic glaciations?: *Geology*, v. 26, p. 1059-1063.
- Kennedy, M. J., N. Christie-Blick, and A. R. Prave, 2001a, Carbon isotopic composition of Neoproterozoic glacial carbonates as a test of paleoceanographic models for snowball Earth phenomena: *Geology*, v. 29, p. 1135-1138.

- Kennedy, M. J., N. Christie-Blick, and L. E. Sohl, 2001b, Are Proterozoic cap carbonates and isotopic excursions a record of gas hydrate destabilization following Earth's coldest intervals?: *Geology*, v. 29, p. 443-446.
- Kennedy, M., D. Mrofka, and C. von der Borch, 2008, Snowball Earth termination by destabilization of equatorial permafrost methane clathrate: *Nature*, v. 453, p. 642-645.
- Kirschvink, J. L., 1992, Late Proterozoic low-latitude glaciation: the snowball Earth, in J. W. Schopf, and C. Klein, eds., *The Proterozoic Biosphere*, Cambridge University Press, Cambridge, p. 51-52.
- Klein, G. A., and E. W. Mountjoy, 1988, Northern Porcupine Creek anticlinorium and footwall of the Purcell Thrust, Northern Park Ranges, B.C., Current Research, Part E, Geological Survey of Canada Paper, v. 88-1E, p. 163-170.
- Knoll, A. H., J. M. Hayes, A. J. Kaufman, K. Swett, and I. B. Lambert, 1986, Secular variation in carbon isotope ratios from upper Proterozoic successions of Svalbard and East Greenland: *Nature*, v. 321, p. 832-838.
- Knoll, A. H., M. R. Walter, G. M. Narbonne, and N. Christie-Blick, 2004, A new period for the geologic time scale: *Science*, v. 305, p. 621-622.
- Knoll, A. H., M. R. Walter, G. M. Narbonne, and N. Christie-Blick, 2006, The Ediacaran Period: a new addition to the geologic time scale: *Lethaia*, v. 39, p. 13-30.
- Knoll, A. H., R. K. Bambach, D. E. Canfield, and J. P. Grotzinger, 1996, Comparative Earth history and Late Permian mass extinction: *Science*, v. 273, p. 452-457.
- Kronberg, B. I., H. W. Nesbitt, and W. W. Lam, 1986, Upper Pleistocene Amazon deep-sea fan muds reflect intense chemical weathering of their mountainous source lands: *Chemical Geology*, v. 54, p. 283-294.
- Kroopnick, P. M., 1985, The distribution of (super 13) C of Sigma CO (sub 2) in the world oceans: *Deep-Sea Research. Part A: Oceanographic Research Papers*, v. 32, p. 57-84.
- Kubli, T. E., 1986, Stratigraphy and structure of the Hadrynian Horsethief Creek Group in the northern Dogtooth Range south of Grizzly Creek, Purcell Mountains, British Columbia, Current Research, Part A, Geological Survey of Canada Paper, v. 86-1A, p. 553-558.
- Kubli, T. E., 1990, Geology of the Dogtooth Range, northern Purcell Mountains, British Columbia: Doctoral thesis, University of Calgary, Calgary, 324 p.
- Kubli, T. E., and P. S. Simony, 1992, The Dogtooth High, northern Purcell Mountains, British Columbia: *Bulletin of Canadian Petroleum Geology*, v. 40, p. 36-51.
- Kubli, T. E., and P. S. Simony, 1994, The Dogtooth Duplex, a model for the structural development of the northern Purcell Mountains: *Canadian Journal of Earth Sciences = Journal Canadien des Sciences de la Terre*, v. 31, p. 1672-1686.
- Le Guerroue, E., P. A. Allen, A. Cozzi, J. L. Etienne, and M. Fanning, 2006b, 50 Myr recovery from the largest negative delta (super 13) C excursion in the Ediacaran Ocean: *Terra Nova*, v. 18, p. 147-153.

- Le Guerroue, E., P. A. Allen, and A. Cozzi, 2006a, Chemostratigraphic and sedimentological framework of the largest negative carbon isotopic excursion in Earth history; the Neoproterozoic Shuram Formation (Nafun Group, Oman): *Precambrian Research*, v. 146, p. 68-92.
- Leech, G. B. 1954. Canal Flats, British Columbia. Geological Survey of Canada Paper 54-7.
- Lemieux, Y., R. I. Thompson, P. Erdmer, A. Simonetti, and R. A. Creaser, 2007, Detrital zircon geochronology and provenance of late Proterozoic and mid-Paleozoic successions outboard of the miogeocline, southeastern Canadian Cordillera: *Canadian Journal of Earth Sciences = Revue Canadienne des Sciences de la Terre*, v. 44, p. 1675-1693.
- Lewan, M. D., and J. B. Maynard, 1982, Factors controlling enrichment of vanadium and nickel in the bitumen of organic sedimentary rocks: *Geochimica et Cosmochimica Acta*, v. 46, p. 2547-2560.
- Li, Z. X., L. H. Zhang, and C. M. Powell, 1995, South China in Rodinia - Part of the Missing Link between Australia East Antarctica and Laurentia: *Geology*, v. 23, p. 407-410.
- Li, Z. X., X. H. Li, P. D. Kinny, and J. Wang, 1999, The breakup of Rodinia: did it start with a mantle plume beneath South China?: *Earth and Planetary Science Letters*, v. 173, p. 171-181.
- Lickorish, W. H. & Simony, P. S. 1995. Evidence for late rifting of the Cordilleran margin outlined by stratigraphic division of the Lower Cambrian Gog Group, Rocky Mountain main ranges, British Columbia and Alberta. *Canadian Journal of Earth Sciences*, 32, 860-874.
- Link, P. K., Christie-Blick, N., Devlin, W. J., Elston, D. P., Horodyski, R. J., Levy, M., Miller, J. M. G., Pearson, R. C., Prave, A., Stewart, J. H., Winston, D., Wright, L. A., & Wrucke, C. T. 1993. Middle and Late Proterozoic stratified rocks of the western United States Cordillera, Colorado Plateau, and Basin and Range Province. In: Reed, J., Sims, P., Houston, R. S., Rankin, D. W., Link, P. K., Van Schmus, W.R., & Bickford, M. E. (eds) *Precambrian: Conterminous United States*, Geological Society of America *Decade of North American Geology Series*, C-3, 474-690.
- Link, P. K., N. Christie-Blick, W. J. Devlin, D. P. Elston, R. J. Horodyski, M. Levy, J. M. G. Miller, R. C. Pearson, A. Prave, J. H. Stewart, D. Winston, L. A. Wright, and C. T. Wrucke, 1993, Middle and late Proterozoic stratified rocks of the western U.S. Cordillera, Colorado Plateau, and Basin and Range Province, in J. C. Reed, Jr., M. E. Bickford, R. S. Houston, P. K. Link, D. W. Rankin, P. K. Sims, and W. R. Van Schmus, eds., *Precambrian; conterminous U.S.*, v. C-2: Boulder, Geological Society of America, p. 463-595.
- Lis, M. G. & Price, R. A. 1976. Large-scale block faulting during deposition of the Windermere Supergroup (Hadrynian) in southeastern British Columbia. Geological Survey of Canada Paper 76-1A, 135-136.

- Longerich, H. P., G. A. Jenner, B. J. Fryer, and S. E. Jackson, 1990, Inductively coupled plasma-mass spectrometric analysis of geological samples; a critical evaluation based on case studies: *Chemical Geology*, v. 83, p. 105-118.
- Loutit, T. S., J. Hardenbol, P. R. Vail, and G. R. Baum, 1988, Condensed sections; the key to age determination and correlation of continental margin sequences, in C. K. Wilgus, B. S. Hastings, C. A. Ross, H. Posamentier, J. Van Wagoner, and C. G. S. C. Kendall, eds., *Special Publication - Society of Economic Paleontologists and Mineralogists*, vol.42, p. 183-213.
- Loveridge, W. D., Leech, G. B., Stevens, R. D. & Sullivan, R. W. 1981. Zircon and monazite age of a granitic clast in Toby Conglomerate (Windermere Supergroup), Canal Flats, British Columbia. *Geological Survey of Canada Paper 81-1C*, 131-134.
- Lowe, D. R., 1982, Sediment gravity flows; II, Depositional models with special reference to the deposits of high-density turbidity currents: *Journal of Sedimentary Petrology*, v. 52, p. 279-297.
- Lund, K., J. N. Aleinikoff, K. V. Evans, and C. M. Fanning, 2003, SHRIMP U-Pb geochronology of Neoproterozoic Windermere Supergroup, central Idaho; implications for rifting of western Laurentia and synchronicity of Sturtian glacial deposits: *Geological Society of America Bulletin*, v. 115, p. 349-372.
- Lyle, M., 1983, The brown-green color transition in marine sediments; a marker of the Fe(III)-Fe(II) redox boundary: *Limnology and Oceanography*, v. 28, p. 1026-1033.
- Lyons, T. W., and R. A. Berner, 1992, Carbon-sulfur-iron systematics of the uppermost deep-water sediments of the Black Sea: *Chemical Geology*, v. 99, p. 1-27.
- Lyons, T. W., J. P. Werne, D. J. Hollander, and R. W. Murray, 2003, Contrasting sulfur geochemistry and Fe/Al and Mo/Al ratios across the last oxic-to-anoxic transition in the Cariaco Basin, Venezuela: *Chemical Geology*, v. 195, p. 131-157.
- Lyons, T. W., S. Severmann, D. E. Canfield, T. W. Lyons, and J. W. Morse, 2006, A critical look at iron paleoredox proxies; new insights from modern euxinic marine basins: *Geochimica et Cosmochimica Acta*, v. 70, p. 5698-5722.
- Maynard, J. B., 1980, Sulfur isotopes of iron sulfides in Devonian-Mississippian shales of the Appalachian Basin; control by rate of sedimentation: *American Journal of Science*, v. 280, p. 772-786.
- Mazzullo, S. J., 2000, Organogenic dolomitization in peritidal to deep-sea sediments: *Journal of Sedimentary Research*, v. 70, p. 10-23.
- McDonough, M. R., 1989, The structural geology and strain history of the northern Selwyn Range, Rocky Mountains, near Valemount, British Columbia: Doctoral thesis, University of Calgary, Calgary, 290 p.
- McDonough, M. R., and D. C. Murphy, 1994, Geology and structure cross-sections, Valemount, British Columbia (1:50,000-scale): *Geological Survey of Canada*.

- McDonough, M. R., and P. S. Simony, 1988a, Stratigraphy and structure of the late Proterozoic Miette Group, northern Selwyn Range, Rocky Mountains, British Columbia, Current Research, Part D, Geological Survey of Canada Paper, v. 88-1D, p. 105-113.
- McDonough, M. R., and P. S. Simony, 1988b, Structural evolution of basement gneisses and Hadrynian cover, Bulldog Creek area, Rocky Mountains, British Columbia: Canadian Journal of Earth Sciences = Journal Canadien des Sciences de la Terre, v. 25, p. 1687-1702.
- McDonough, M. R., and P. S. Simony, 1989, Valemount strain zone; a dextral oblique-slip thrust system linking the Rocky Mountain and Omineca belts of the southeastern Canadian Cordillera: Geology, v. 17, p. 237-240.
- McDonough, M. R., R. R. Parrish, and G. M. Ross, 1991, Proterozoic gneisses of the Malton Complex, near Valemount, British Columbia; U-Pb ages and Nd isotopic signatures: Canadian Journal of Earth Sciences = Journal Canadien des Sciences de la Terre, v. 28, p. 1202-1216.
- McIlroy, D., T. P. Crimes, and J. C. Pauley, 2005, Fossils and matgrounds from the Neoproterozoic Longmyndian Supergroup, Shropshire, UK: Geological Magazine, v. 142, p. 441-455.
- McKibben, M. A., and L. R. Riciputi, 1998, Sulfur isotopes by ion microprobe: Reviews in Economic Geology, v. 7, p. 121-139.
- McManus, J., W. M. Berelson, S. Severmann, R. L. Poulson, D. E. Hammond, G. P. Klinkhammer, and C. Holm, 2006, Molybdenum and uranium geochemistry in continental margin sediments; paleoproxy potential: Geochimica et Cosmochimica Acta, v. 70, p. 4643-4662.
- McMechan, M. E. & Thompson, R. I. 1985. Geology of southeast Monkman Pass area (93I/SW), British Columbia. Geological Survey of Canada Open File 1150.
- McMechan, M. E. & Thompson, R. I. 1995a. Geology, Ovington Creek, west of sixth meridian, British Columbia. Geological Survey of Canada Map 1873A.
- McMechan, M. E. & Thompson, R. I. 1995b. Geology, Wapiti Pass, west of sixth meridian, British Columbia. Geological Survey of Canada Map 1872A.
- McMechan, M. E. 1987. Stratigraphy and structure of the Mount Selwyn area, Rocky Mountains, northeastern British Columbia. Geological Survey of Canada Paper 85-28.
- McMechan, M. E. 1990. Upper Proterozoic to Middle Cambrian history of the Peace River Arch; evidence from the Rocky Mountains. Bulletin of Canadian Petroleum Geology, 38A, 36-44.
- McMechan, M. E., 1987, Stratigraphy and structure of the Mount Selwyn area, Rocky Mountains, northeastern British Columbia.
- McMechan, M. E., 2000, Vreeland diamictites; Neoproterozoic glaciogenic slope deposits, Rocky Mountains, Northeast British Columbia: Bulletin of Canadian Petroleum Geology, v. 48, p. 246-261.

- McMechan, M. E., and R. A. Price, 1982, Superimposed low-grade metamorphism in the Mount Fisher area, southeastern British Columbia; implications for the East Kootenay Orogeny: *Canadian Journal of Earth Sciences* = *Journal Canadien des Sciences de la Terre*, v. 19, p. 476-489.
- McMechan, M. E., and R. I. Thompson, 1995, *Geology, Ovington Creek, west of sixth meridian, British Columbia*.
- Meyer, L., 2004, Internal architecture of an ancient deep-water, passive margin, basin-floor fan system, upper Kaza Group, Windermere Supergroup, Castle Creek, British Columbia: Master's thesis, University of Calgary, Calgary.
- Mohr, D. W., and R. C. Newton, 1983, Kyanite-staurolite metamorphism in sulfidic schists of the Anakeesta Formation, Great Smoky Mountains, North Carolina: *American Journal of Science*, v. 283, p. 97-134.
- Monger, J. W. H., R. A. Price, and D. J. Tempelman-Kluit, 1982, Tectonic accretion and the origin of the two major metamorphic and plutonic welts in the Canadian Cordillera: *Geology*, v. 10, p. 70-75.
- Moores, E. M., 1991, Southwest U.S.-East Antarctic (SWEAT) connection; a hypothesis: *Geology*, v. 19, p. 425-428.
- Morford, J. L., A. D. Russell, and S. Emerson, 2001, Trace metal evidence for changes in the redox environment associated with the transition from terrigenous clay to diatomaceous sediment, Saanich Inlet, BC: *Marine Geology*, v. 174, p. 355-369.
- Mountjoy, E. W., 1962, Mount Robson (southeast) map-area, Rocky Mountains of Alberta and British Columbia (83 E SE), *Geological Survey of Canada Paper* 61-31, p.??
- Mountjoy, E. W., 1971, Mount Robson Map-area, Alberta and British Columbia, Report of Activities, Part A, *Geological Survey of Canada Paper*, v. 71-1A, p. 227-232.
- Mountjoy, E. W., and J. D. Aitken, 1963, Early Cambrian and Late Precambrian paleocurrents, Banff and Jasper National Parks: *Bulletin of Canadian Petroleum Geology*, v. 11, p. 161-168.
- Mountjoy, E. W., and R. A. Price, 1985, *Geology; Jasper; west of sixth meridian; Alberta (1:50,000)*.
- Mountjoy, E. W., and S. E. Grasby, 1990, Revised stratigraphic and structural interpretation of folded decollements, southern Fraser River Antiform, Selwyn Range, British Columbia, *Current Research, Part E, Geological Survey of Canada Paper*, v. 90-1E, p. 359-367.
- Mulder, T., and P. Cochonat, 1996, Classification of offshore mass movements: *Journal of Sedimentary Research*, v. 66, p. 43-57.
- Murphy, D. C. 1986. Stratigraphy and structure of the east-central Cariboo Mountains, British Columbia, and implications for the geological evolution of the southeastern Canadian Cordillera. Ph.D. thesis, Carleton University.
- Murphy, D. C., 1986, Stratigraphy and structure of the east-central Cariboo Mountains, British Columbia, and implications for the geological evolution of

- the southeastern Canadian Cordillera: Doctoral thesis, Carleton University, Ottawa, 187 p.
- Murphy, D. C., 1987, Kaza Group, eastern Wells Gray Park, British Columbia, Current Research, Part A, Geological Survey of Canada Paper, v. 87-1A, p. 735-742.
- Murphy, D. C., and C. J. Rees, 1983, Structural transition and stratigraphy in the Cariboo Mountains, British Columbia, Current Research, Part A, Geological Survey of Canada Paper, v. 83-1A, p. 245-252.
- Murphy, D. C., R. T. Walker, R. R. Parrish, and G. M. Ross, 1991, Age and geological setting of Gold Creek Gneiss, crystalline basement of the Windermere Supergroup, Cariboo Mountains, British Columbia: Canadian Journal of Earth Sciences = Journal Canadien des Sciences de la Terre, v. 28, p. 1217-1231.
- NACSN, 2005, North American Stratigraphic Code; North American Commission on Stratigraphic Nomenclature: AAPG Bulletin, v. 89, p. 1547-1591.
- Narbonne, G. M., A. J. Kaufman, and A. H. Knoll, 1994, Integrated chemostratigraphy and biostratigraphy of the Windermere Supergroup, northwestern Canada; implications for Neoproterozoic correlations and the early evolution of animals; with Suppl. Data 9434: Geological Society of America Bulletin, v. 106, p. 1281-1292.
- Narbonne, G. M., and H. J. Hofmann, 1987, Ediacaran biota of the Wernecke Mountains, Yukon, Canada: Palaeontology, v. 30, p. 647-676.
- Nedelec, A., P. Affaton, C. France-Lanord, A. Charriere, and J. Alvaro, 2007, Sedimentology and chemostratigraphy of the Bwipe Neoproterozoic cap dolostones (Ghana, Volta Basin); a record of microbial activity in a peritidal environment: Comptes Rendus - Academie des Sciences. Geoscience, v. 339, p. 223-239.
- Nesbitt, H. W., 2003, Petrogenesis of siliciclastic sediments and sedimentary rocks, in D. R. Lentz, ed., Geochemistry of sediments and sedimentary rocks: evolutionary considerations to mineral-deposit forming environments, v. GEOtext 4, Geological Association of Canada, p. 39-52.
- Nesbitt, H. W., and G. M. Young, 1982, Early Proterozoic climates and plate motions inferred from major element chemistry of lutites: Nature, v. 299, p. 715-717.
- Nesbitt, H. W., and G. M. Young, 1984, Prediction of some weathering trends of plutonic and volcanic rocks based on thermodynamic and kinetic considerations: Geochimica et Cosmochimica Acta, v. 48, p. 1523-1534.
- Nesbitt, H. W., and G. M. Young, 1989, Formation and diagenesis of weathering profiles: Journal of Geology, v. 97, p. 129-147.
- Nesbitt, H. W., N. D. MacRae, and B. I. Kronberg, 1990, Amazon deep-sea fan muds; light REE enriched products of extreme chemical weathering: Earth and Planetary Science Letters, v. 100, p. 118-123.

- Normark, W. R., and P. R. Carlson, 2003, Giant submarine canyons; is size any clue to their importance in the rock record?: Special Paper - Geological Society of America, v. 370, p. 175-190.
- Normark, W. R., D. J. W. Piper, and R. N. Hiscott, 1998, Sea level controls on the textural characteristics and depositional architecture of the Hueneme and associated submarine fan systems, Santa Monica Basin, California: *Sedimentology*, v. 45, p. 53-70.
- Oaie, G., 1998, Sedimentological significance of mudstone microclast intervals in upper Proterozoic turbidites, central Dobrogea, Romania: *Sedimentary Geology*, v. 115, p. 289-300.
- O'Cofaigh, C., and J. A. Dowdeswell, 2001, Laminated sediments in glacial marine environments; diagnostic criteria for their interpretation: *Quaternary Science Reviews*, v. 20, p. 1411-1436.
- Park, J. K., 1997, Paleomagnetic evidence for low-latitude glaciation during deposition of the Neoproterozoic Rapitan Group, Mackenzie Mountains, N.W.T., Canada: *Canadian Journal of Earth Sciences = Journal Canadien des Sciences de la Terre*, v. 34, p. 34-49.
- Parrish, R. R., R. J. Scammell, and J. K. Mortensen, 1988, The age of the Mount Copeland syenite gneiss and its metamorphic zircons, Monashee Complex, southeastern British Columbia: *Geological Survey of Canada Paper*, v. 88-2, p. 21-28.
- Pell, J., 1984, Stratigraphy, structure and metamorphism of Hadrynian strata in the southeastern Cariboo Mountains, B.C: Doctoral thesis, University of Calgary, Calgary, ?? p.
- Pell, J., and P. S. Simony, 1981, Stratigraphy, structure, and metamorphism in the southern Cariboo Mountains, British Columbia, Current Research, Part A, *Geological Survey of Canada Paper*, v. 81-1A, p. 227-230.
- Pell, J., and P. S. Simony, 1982, Hadrynian Horsethief Creek Group/Kaza Group correlations in the southern Cariboo Mountains, British Columbia, Current Research, Part A, *Geological Survey of Canada Paper*, v. 82-1A, p. 305-308.
- Pell, J., and P. S. Simony, 1984, Stratigraphy of the Hadrynian Kaza Group between the Azure and North Thompson rivers, Cariboo Mountains, British Columbia, Current Research, Part A, *Geological Survey of Canada Paper*, v. 84-1A, p. 95-98.
- Pell, J., and P. S. Simony, 1987, New correlations of Hadrynian strata, south-central British Columbia: *Canadian Journal of Earth Sciences = Journal Canadien des Sciences de la Terre*, v. 24, p. 302-313.
- Pickering, K. T., 1982a, Middle-fan deposits from the late Precambrian Kongsfjord Formation submarine fan, Northeast Finnmark, Northern Norway: *Sedimentary Geology*, v. 33, p. 79-110.
- Pickering, K. T., 1982b, A Precambrian upper basin-slope and prodelta in Northeast Finnmark, North Norway; a possible ancient upper continental slope: *Journal of Sedimentary Petrology*, v. 52, p. 171-186.

- Pickering, K. T., and J. Corregidor, 2005, Mass-transport complexes (MTCs) and tectonic control on basin-floor submarine fans, middle Eocene, south Spanish Pyrenees: *Journal of Sedimentary Research*, v. 75, p. 761-783.
- Pigage, L. C. & MacNaughton, R. B. 2004. Reconnaissance geology of northern Toobally Lake (95D/8), southeast Yukon. In: Emond, D.S. & Lewis, L. L. (eds) *Yukon Exploration and Geology 2003*, Yukon Geological Survey, 199-219.
- Piper, D. Z., and R. B. Perkins, 2004, A modern vs. Permian black shale; the hydrography, primary productivity, and water-column chemistry of deposition: *Chemical Geology*, v. 206, p. 177-197.
- Piper, D. Z., and W. E. Dean, 2002, Trace-element deposition in the Cariaco Basin, Venezuela Shelf, under sulfate-reducing conditions; a history of the local hydrography and global climate, 20 ka to the present, p. 41.
- Pope, A. 1990. Geology and mineral deposits of the Toby-Horsethief Creek map area, northern Purcell Mountains, southeast British Columbia (82K). Ministry of Energy, Mines and Petroleum Resources, Mineral Resources Division Open File Report 1990-26, 1-53.
- Pope, M. C., and J. W. Sears, 1997, Cassiar Platform, north-central British Columbia; a miogeoclinal fragment from Idaho: *Geology*, v. 25, p. 515-518.
- Porter, S. M., A. H. Knoll, and P. Affaton, 2004, Chemostratigraphy of Neoproterozoic cap carbonates from the Volta Basin, West Africa: *Precambrian Research*, v. 130, p. 99-112.
- Posamentier, H. W., and P. R. Vail, 1988, Eustatic controls on clastic deposition; II, Sequence and systems tract models, in C. K. Wilgus, B. S. Hastings, C. A. Ross, H. W. Posamentier, J. Van Wagoner, and C. G. S. C. Kendall, eds., *Special Publication - Society of Economic Paleontologists and Mineralogists*, vol.42, p. 125-154.
- Posamentier, H. W., M. T. Jervey, and P. R. Vail, 1988, Eustatic controls on clastic deposition; I, Conceptual framework, in C. K. Wilgus, B. S. Hastings, C. A. Ross, H. W. Posamentier, J. Van Wagoner, and C. G. S. C. Kendall, eds., *Special Publication - Society of Economic Paleontologists and Mineralogists*, vol.42, p. 109-124.
- Potter, P. E., J. B. Maynard, and W. A. Pryor, 1980, *Sedimentology of shale; study guide and reference source*, Springer-Verlag, New York, NY, United States (USA), 277 p.
- Poulton, T. P., 1973, Upper Proterozoic 'Limestone Unit', Northern Dogtooth Mountains, British Columbia: *Canadian Journal of Earth Sciences = Revue Canadienne des Sciences de la Terre*, v. 10, p. 292-305.
- Praeg, D., M. S. Stoker, P. M. Shannon, S. Ceramicola, B. O. Hjelstuen, J. S. Laberg, and A. Mathiesen, 2005, Episodic Cenozoic tectonism and the development of the NW European "passive" continental margin: *Marine and Petroleum Geology*, v. 22, p. 1007-1030.

- Prave, A. R., 1999, Two diamictites, two cap carbonates, two delta (super 13) C excursions, two rifts; the Neoproterozoic Kingston Peak Formation, Death Valley, California: *Geology*, v. 27, p. 339-342.
- Price, R. A., D. G. Cook, J. D. Aitken, and E. W. Mountjoy, 1980a, *Geology, Lake Louise (east half), west of fifth meridian, Alberta-British Columbia*.
- Price, R. A., D. G. Cook, J. D. Aitken, E. W. Mountjoy, and D. J. Walter, 1980b, *Geology, Lake Louise (west half), west of fifth meridian, Alberta-British Columbia*.
- Pyle, L. J., and C. R. Barnes, 2003, Lower Paleozoic stratigraphic and biostratigraphic correlations in the Canadian Cordillera; implications for the tectonic evolution of the Laurentian margin: *Canadian Journal of Earth Sciences = Revue Canadienne des Sciences de la Terre*, v. 40, p. 1739-1753.
- Raiswell, R., 1982, Pyrite texture, isotopic composition and the availability of iron: *American Journal of Science*, v. 282, p. 1244-1263.
- Raiswell, R., 1987, Non-steady state microbiological diagenesis and the origin of concretions and nodular limestones: *Geological Society Special Publications*, v. 36, p. 41-54.
- Raiswell, R., 1988, Chemical model for the origin of minor limestone-shale cycles by anaerobic methane oxidation: *Geology*, v. 16, p. 641-644.
- Reading, H. G., and R. G. Walker, 1966, Sedimentation of Eocambrian tillites and associated sediments in Finnmark, northern Norway: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 2, p. 177-212.
- Reesor, J. E., 1957, The Proterozoic of the Cordillera in southeastern British Columbia and southwestern Alberta: *Special Publications - Royal Society of Canada*, v. 2, p. 150-177.
- Reesor, J. E., 1973, *Geology of the Lardeau Map-area, east-half, British Columbia*, Geological Survey of Canada Memoir 369, p. 122.
- Reid, L. F., P. S. Simony, and G. M. Ross, 2002, Dextral strike-slip faulting in the Cariboo Mountains, British Columbia; a natural example of wrench tectonics in relation to Cordilleran tectonics: *Canadian Journal of Earth Sciences = Revue Canadienne des Sciences de la Terre*, v. 39, p. 953-970.
- Ridgwell, A. J., M. J. Kennedy, and K. Caldeira, 2003, Carbonate deposition, climate stability, and Neoproterozoic ice ages: *Science*, v. 302, p. 859-862.
- Rieu, R., P. A. Allen, M. Ploetze, and T. Pettke, 2007, Climatic cycles during a Neoproterozoic "snowball" glacial epoch: *Geology*, v. 35, p. 299-302.
- Rimmer, S. M., 2004, Geochemical paleoredox indicators in Devonian-Mississippian black shales, central Appalachian Basin; USA: *Chemical Geology*, v. 206, p. 373-391.
- Ripperdan, R. L., 2001, Stratigraphic variation in marine carbonate carbon isotope ratios: *Reviews in Mineralogy and Geochemistry*, v. 43, p. 637-662.
- Roddaz, M., J. Viers, S. Brusset, P. Baby, C. Boucayrand, and G. Herail, 2006, Controls on weathering and provenance in the Amazonian foreland basin;

- insights from major and trace element geochemistry of Neogene Amazonian sediments: *Chemical Geology*, v. 226, p. 31-65.
- Roddaz, M., P. Debat, and S. Nikiema, 2007, Geochemistry of upper Birimian sediments (major and trace elements and Nd-Sr isotopes) and implications for weathering and tectonic setting of the late Paleoproterozoic crust: *Precambrian Research*, v. 159, p. 197-211.
- Rodrigues Nogueira, A. C., C. Riccomini, A. Nobrega Sial, C. A. Veloso Moura, and T. R. Fairchild, 2003, Soft-sediment deformation at the base of the Neoproterozoic Puga cap carbonate (southwestern Amazon Craton, Brazil); confirmation of rapid icehouse to greenhouse transition in snowball Earth: *Geology*, v. 31, p. 613-616.
- Root, K. G. 1987. Geology of the Delphine Creek area, southeastern British Columbia: implications for the Proterozoic and Paleozoic development of the Cordilleran divergent margin. Ph.D. thesis, University of Calgary.
- Root, K. G., 1987, Geology of the Delphine Creek area, southeastern British Columbia; implications for the Proterozoic and Paleozoic development of the Cordilleran divergent margin: Map thesis, University of Calgary, Calgary.
- Ross G. M. & Villeneuve, M. E. 2003. Provenance of the Mesoproterozoic (1.45 Ga) Belt basin (western North America): another piece in the pre-Rodinia paleogeographic puzzle, *Geological Society of America Bulletin*, 115, 1191-1217.
- Ross, G. M. & Bowring, S. A. 1990. Detrital zircon geochronology of the Windermere Supergroup and the tectonic assembly of the southern Canadian Cordillera. *Journal of Geology*, 98, 879-893.
- Ross, G. M. & Ferguson, C. R. 2003a. Geology and structure cross-sections, Eddy, British Columbia. Geological Survey of Canada, "A" series map 1967A.
- Ross, G. M. & Ferguson, C. R. 2003b. Geology and structure cross-sections, Lanezi Lake, British Columbia. Geological Survey of Canada, "A" series map 2001A.
- Ross, G. M. & Murphy, D. C. 1988. Transgressive stratigraphy, anoxia, and regional correlations within the late Precambrian Windermere group of the southern Canadian Cordillera. *Geology*, 16, 139-143.
- Ross, G. M. & Villeneuve, M. E. 1997. U-Pb geochronology of stranger stones in Neoproterozoic diamictites, Canadian Cordillera; implications for provenance and ages of deposition. *Geological Survey of Canada Paper* 1997-F, 141-155.
- Ross, G. M. 1991. Tectonic setting of the Windermere Supergroup revisited. *Geology*, 19, 1125-1128.
- Ross, G. M., & Parrish, R. R. 1991. Detrital zircon geochronology of metasedimentary rocks in the southern Omineca Belt, Canadian Cordillera. *Canadian Journal of Earth Sciences*, 28, 1254-1270.
- Ross, G. M., 1991, Tectonic setting of the Windermere Supergroup revisited: *Geology*, v. 19, p. 1125-1128.

- Ross, G. M., 2000, The Neoproterozoic Windermere Supergroup: An on-land continental margin turbidite system, Geological Survey of Canada Open File 3932, p. 2 sheets.
- Ross, G. M., 2003, The Windermere turbidite system; a window into the Neoproterozoic deep-water world, Abstracts with Programs - Geological Society of America, v. 35, p. 472.
- Ross, G. M., and C. A. Ferguson, 2003a, Geology and structure cross-sections, Eddy, British Columbia (1:50,000-scale): Geological Survey of Canada.
- Ross, G. M., and C. A. Ferguson, 2003b, Geology and structure cross-sections, Lanezi Lake, British Columbia (1:50,000-scale): Geological Survey of Canada.
- Ross, G. M., and C. A. Ferguson, 2003c, Geology and structure cross-sections, McBride, British Columbia (1:50,000-scale): Geological Survey of Canada.
- Ross, G. M., and D. C. Murphy, 1988, Transgressive stratigraphy, anoxia, and regional correlations within the late Precambrian Windermere grit of the southern Canadian Cordillera: *Geology*, v. 16, p. 139-143.
- Ross, G. M., and J. A. Thomson, 1990, Late Proterozoic Stratigraphy in the McBride area (British Columbia): Windermere turbidites, condensed intervals and the vanished carbonate platform, in J. D. Aitken, and M. R. McDonough, eds., Late Proterozoic Glaciation, Rifting and Eustasy, as Illustrated by the Windermere Supergroup, Geological Association of Canada Nuna Research Conference Fieldtrip Guidebook, p. 7.1-7.13.
- Ross, G. M., and M. E. Villeneuve, 1997, U-Pb geochronology of stranger stones in Neoproterozoic diamictites, Canadian Cordillera; implications for provenance and ages of deposition: Radiogenic Age and Isotopic Studies, Report 10, Geological Survey of Canada, Current Research 1997-F, p. 141-155.
- Ross, G. M., and R. W. C. Arnett, 2007, Regional geology of the Windermere Supergroup, southern Canadian Cordillera and stratigraphic setting of the Castle Creek study area, Canada, in T. H. Nilsen, R. D. Shew, G. S. Steffens, and J. R. J. Studlick, eds., Atlas of deep-water outcrops: AAPG Studies in Geology 56, v. CD-ROM, p. 16.
- Ross, G. M., and S. A. Bowring, 1990, Detrital zircon geochronology of the Windermere Supergroup and the tectonic assembly of the southern Canadian Cordillera: *Journal of Geology*, v. 98, p. 879-893.
- Ross, G. M., C. Rowe, and C. Augereau, 2001, Stable isotope stratification of Neoproterozoic seawater in a post-Snowball Earth: evidence from deepwater rocks of western Canada.: American Geophysical Union, Fall Meeting, American Geophysical Union., p. Abstract #V31C-09.
- Ross, G. M., G. E. Gehrels, and P. J. Patchett, 1997, Provenance of Triassic strata in the Cordilleran miogeocline, Western Canada: *Bulletin of Canadian Petroleum Geology*, v. 45, p. 461-473.
- Ross, G. M., J. D. Bloch, and H. R. Krouse, 1995, Neoproterozoic strata of the southern Canadian Cordillera and the isotopic evolution of seawater sulfate: *Precambrian Research*, v. 73, p. 71-99.

- Ross, G. M., L. Heaman, and Anonymous, 2005, Provenance of the Neoproterozoic Windermere turbidite system (southern Canadian Cordillera); assessing scales of continental drainage, *Abstracts with Programs - Geological Society of America*, v. 37, p. 220.
- Ross, G. M., M. E. McMechan, and F. J. Hein, 1989a, Proterozoic History: The Birth of the Miogeocline, in B. D. Ricketts, ed., *The Western Canadian Sedimentary Basin*: Calgary, AB, Canadian Society of Petroleum Geologists, p. 79-104.
- Ross, G. M., M. E. Villeneuve, R. R. Parrish, and S. A. Bowring, 1989b, Tectonic subdivision and U-Pb geochronology of the crystalline basement of the Alberta Basin, western Canada, *Geological Survey of Canada Open File*, p. 4X?
- Ross, G. M., M. E. Villeneuve, R. R. Parrish, and S. A. Bowring, 1989, Tectonic subdivision and U-Pb geochronology of the crystalline basement of the Alberta Basin, western Canada, *Geological Survey of Canada Open File*, p. 4X?
- Ross, G. M., R. R. Parrish, and G. M. Ross, 1991, Detrital zircon geochronology of metasedimentary rocks in the southern Omineca Belt, Canadian Cordillera: *Canadian Journal of Earth Sciences = Journal Canadien des Sciences de la Terre*, v. 28, p. 1254-1270.
- Sandberg, P., 1985, Aragonite cements and their occurrence in ancient limestones, in N. Schneidermann, and P. M. Harris, eds., *Special Publication - Society of Economic Paleontologists and Mineralogists*, vol.36, p. 33-57.
- Scheffler, K., D. Buehmann, and L. Schwark, 2006, Analysis of late Palaeozoic glacial to postglacial sedimentary successions in South Africa by geochemical proxies; response to climate evolution and sedimentary environment: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 240, p. 184-203.
- Schidlowski, M., R. Weber, and J. C. Guerrero, 1983, Evolution of photoautotrophy and early atmospheric oxygen levels, in B. Nagy, and M. Schidlowski, eds., *Precambrian Research*, v. 20, p. 319-335.
- Schlager, W., J. J. G. Reijmer, and A. Droxler, 1994, Highstand shedding of carbonate platforms: *Journal of Sedimentary Research, Section B: Stratigraphy and Global Studies*, v. 64, p. 270-281.
- Scott, C., T. W. Lyons, A. Bekker, Y. Shen, S. W. Poulton, X. Chu, and A. D. Anbar, 2008, Tracing the stepwise oxygenation of the Proterozoic ocean: *Nature*, v. 452, p. 456-459.
- Sears, J. W., and R. A. Price, 2003, Tightening the Siberian connection to western Laurentia: *Geological Society of America Bulletin*, v. 115, p. 943-953.
- Sevigny, J. H., 1988, Geochemistry of late Proterozoic amphibolites and ultramafic rocks, southeastern Canadian Cordillera: *Canadian Journal of Earth Sciences = Journal Canadien des Sciences de la Terre*, v. 25, p. 1323-1337.
- Shen, B., S. Xiao, A. J. Kaufman, H. Bao, C. Zhou, and H. Wang, 2008a, Stratification and mixing of a post-glacial Neoproterozoic ocean; evidence from carbon and

- sulfur isotopes in a cap dolostone from northwest China: *Earth and Planetary Science Letters*, v. 265, p. 209-228.
- Shen, Y., A. H. Knoll, and M. R. Walter, 2003, Evidence for low sulphate and anoxia in a mid-Proterozoic marine basin: *Nature*, v. 423, p. 632-635.
- Shen, Y., T. Zhang, and X. Chu, 2005, C-isotopic stratification in a Neoproterozoic postglacial ocean: *Precambrian Research*, v. 137, p. 243-251.
- Shen, Y., Z. Tonggang, and P. F. Hoffman, 2008b, On the coevolution of Ediacaran oceans and animals: *Proceedings of the National Academy of Sciences*, v. 105, p. 7376-7381.
- Shepard, F. P., and R. F. Dill, 1966, Submarine canyons and other sea valleys.
- Shields, G. A., 2005, Neoproterozoic cap carbonates; a critical appraisal of existing models and the plumeworld hypothesis: *Terra Nova*, v. 17, p. 299-310.
- Shields, G. A., H. Kimura, J. Yang, and P. Gammon, 2004, Sulphur isotopic evolution of Neoproterozoic-Cambrian seawater; new francolite-bound sulphate delta (super 34) S data and a critical appraisal of the existing record: *Chemical Geology*, v. 204, p. 163-182.
- Shields, G. A., M. Deynoux, H. Strauss, H. Paquet, and D. Nahon, 2007b, Barite-bearing cap dolostones of the Taoudeni Basin, northwest Africa; sedimentary and isotopic evidence for methane seepage after a Neoproterozoic glaciation: *Precambrian Research*, v. 153, p. 209-235.
- Shields, G. A., M. Deynoux, S. J. Culver, M. D. Brasier, P. Affaton, and D. Vandamme, 2007a, Neoproterozoic glaciomarine and cap dolostone facies of the southwestern Taoudeni Basin (Walidiala Valley, Senegal/Guinea, NW Africa): *Comptes Rendus - Academie des Sciences. Geoscience*, v. 339, p. 186-199.
- Simony, P. S., E. D. Ghent, D. Craw, and W. Mitchell, 1980, Structural and metamorphic evolution of the northeast flank of the Shuswap Complex, southern Canoe River area, British Columbia, in P. J. Coney, ed., *Cordilleran Core Complexes: Geological Society of America Memoir*, v. 153.
- Slind, O. L. & Perkins, G. D. 1966. Lower Paleozoic and Proterozoic sediments of the Rocky Mountains between Jasper, Alberta and Pine River, British Columbia. *Bulletin of Canadian Petroleum Geology*, 14, 442-468.
- Smith, M. D. 2009. Stratigraphic and geochemical evolution of the Old Fort Point Formation, southern Canadian Cordillera: a deep-marine perspective of Neoproterozoic post-glacial palaeoenvironmental change. Ph.D. thesis, University of Ottawa.
- Smith, M. T., G. E. Gehrels, and G. M. Ross, 1991, Detrital zircon geochronology of upper Proterozoic to lower Paleozoic continental margin strata of the Kootenay Arc; implications for the early Paleozoic tectonic development of the eastern Canadian Cordillera, *Canadian Journal of Earth Sciences = Journal Canadien des Sciences de la Terre*, v. 28, p. 1271-1284.
- Stasiuk, L. D., and M. G. Fowler, 2004, Organic facies in Devonian and Mississippian strata of Western Canada sedimentary basin; relation to

- kerogen type, paleoenvironment, and paleogeography: *Bulletin of Canadian Petroleum Geology*, v. 52, p. 234-255.
- Stelck, C. R., Burwash, R. A. & Stelck, D. R. 1978. The Vreeland High; a Cordilleran expression of the Peace River Arch. *Bulletin of Canadian Petroleum Geology*, 26, 87-104.
- Stewart, J. H., 1972, Initial Deposits in the Cordilleran Geosyncline; evidence of a Late Precambrian (<850 m.y.) Continental Separation: *Geological Society of America Bulletin*, v. 83, p. 1345-1360.
- Stow, D. A. V., and A. J. Bowen, 1980, A physical model for the transport and sorting of fine-grained sediment by turbidity currents: *Sedimentology*, v. 27, p. 31-46.
- Stow, D. A. V., and D. J. W. Piper, 1984a, Deep-water fine-grained sediments; facies models, in D. A. V. Stow, and D. J. W. Piper, eds., *Geological Society Special Publications*, vol.15, p. 611-646.
- Stow, D. A. V., and D. J. W. Piper, 1984b, Deep-water fine-grained sediments; history, methodology and terminology, in D. A. V. Stow, and D. J. W. Piper, eds., *Geological Society Special Publications*, vol.15, p. 3-14.
- Stow, D. A. V., and G. Shanmugam, 1980, Sequence of structures in fine-grained turbidites; comparison of Recent deep-sea and ancient flysch sediments: *Sedimentary Geology*, v. 25, p. 23-42.
- Strauss, H., and J. Schieber, 1990, A sulfur isotope study of pyrite genesis; the mid-Proterozoic Newland Formation, Belt Supergroup, Montana: *Geochimica et Cosmochimica Acta*, v. 54, p. 197-204.
- Sylvester, Z., and D. R. Lowe, 2004, Textural trends in turbidites and slurry beds from the Oligocene flysch of the East Carpathians, Romania: *Sedimentology*, v. 51, p. 945-972.
- Taylor, S. R., R. L. Rudnick, S. M. McLennan, and K. A. Eriksson, 1986, Rare-Earth Element Patterns in Archean High-Grade Metasediments and Their Tectonic Significance: *Geochimica Et Cosmochimica Acta*, v. 50, p. 2267-2279.
- Teitz, M. W., and E. W. Mountjoy, 1988, The late Proterozoic Yellowhead carbonate platform west of Jasper, Alberta, in H. H. J. Geldsetzer, N. P. James, and G. E. Tebbutt, eds., *Memoir - Canadian Society of Petroleum Geologists*, vol.13, p. 129-134.
- Terlaky, V., and R. W. C. Arnott, 2008, Stratigraphy and architecture of distal basin-floor strata, Neoproterozoic Middle Kaza Group, British Columbia, Canada, *Abstracts with Programs - Geological Society of America*, v. 40, p. 537.
- Thompson, R. I., P. Glombick, P. Erdmer, L. M. Heaman, Y. Lemieux, and K. Daughtry, 2006, Evolution of the ancestral Pacific margin, southern Canadian Cordillera; insights from new geologic maps, Paleozoic evolution and metallogeny of pericratonic terranes at the ancient Pacific margin of North America, Canadian and Alaskan Cordillera, v. 45, *Special Paper - Geological Association of Canada*, p. 433-482.

- Thomson, J., S. Colley, N. C. Higgs, D. J. Hydes, T. R. S. Wilson, and J. Sorensen, 1987, Geochemical oxidation fronts in NE Atlantic distal turbidites and their effects in the sedimentary record, in P. P. E. Weaver, and J. Thomson, eds., Geological Society Special Publications, vol.31, p. 167-177.
- Tissot, B. P., and D. H. Welte, 1978, Petroleum formation and occurrence; a new approach to oil and gas exploration.
- Tribovillard, N., A. Riboulleau, T. Lyons, and F. Baudin, 2004, Enhanced trapping of molybdenum by sulfurized marine organic matter of marine origin in Mesozoic limestones and shales: *Chemical Geology*, v. 213, p. 385-401.
- Trindade, R. I. F., E. Font, M. S. d'Agrella-Filho, A. C. R. Nogueira, and C. Riccomini, 2003, Low-latitude and multiple geomagnetic reversals in the Neoproterozoic Puga cap carbonate, Amazon Craton: *Terra Nova*, v. 15, p. 441-446.
- Tyson, R. V., 2005, The "productivity versus preservation" controversy; cause, flaws, and resolution, in N. B. Harris, ed., *The Deposition of Organic-Carbon-Rich Sediments: Models, Mechanisms, and Consequences*, v. 82, p. 17-33.
- Valley, J. W., 2001, Stable isotope thermometry at high temperatures: *Reviews in Mineralogy and Geochemistry*, v. 43, p. 365-413.
- Veizer, J., 1983, Trace elements and isotopes in sedimentary carbonates: *Reviews in Mineralogy*, v. 11, p. 265-299.
- Veizer, J., M. A. Arthur, T. F. Anderson, I. R. Kaplan, J. Veizer, and L. S. Land, 1983, Chemical diagenesis of carbonates; theory and application of trace element technique: *SEPM Short Course*, v. 10, p. 3.1-3.100.
- Villeneuve, M. E., G. M. Ross, R. J. Theriault, W. Miles, R. R. Parrish, and J. Broome, 1993, Tectonic subdivision and U-Pb geochronology of the crystalline basement of the Alberta Basin, western Canada, p. 93.
- von der Borch, C. C., R. Smit, and A. E. Grady, 1982, Late Proterozoic submarine canyons of Adelaide Geosyncline, South Australia: *AAPG Bulletin*, v. 66, p. 332-347.
- Vorliceck, T. P., G. R. Helz, and P. A. Candela, 2002, Catalysis by mineral surfaces; implications for Mo geochemistry in anoxic environments: *Geochimica et Cosmochimica Acta*, v. 66, p. 3679-3692.
- Vorliceck, T. P., M. D. Kahn, Y. Kasuya, and G. R. Helz, 2004, Capture of molybdenum in pyrite-forming sediments; role of ligand-induced reduction by polysulfides: *Geochimica et Cosmochimica Acta*, v. 68, p. 547-556.
- Walcott, C. D., 1910, Pre-Cambrian Rocks of the Bow River Valley, Alberta, Canada: *Smithsonian Miscellaneous Collections*, v. 53, p. 423-431.
- Walcott, C. D., 1913, Cambrian Formations of the Robson Peak district, British Columbia and Alberta, Canada: *Smithsonian Miscellaneous Collections*, v. 57, p. 327-343.
- Walker, J. F., 1926, Geology and Mineral Deposits of the Windermere Map-area, British Columbia, Geological Survey of Canada Memoir 148, p.??

- Walter, M. R., and J. Bauld, 1983, The association of sulphate evaporites, stromatolitic carbonates and glacial sediments; examples from the Proterozoic of Australia and the Cainozoic of Antarctica: *Precambrian Research*, v. 21, p. 129-148.
- Warren, J., 2000, Dolomite; occurrence, evolution and economically important associations: *Earth-Science Reviews*, v. 52, p. 1-81.
- Warren, M. J. 1997. Crustal extension and subsequent crustal thickening along the Cordilleran rifted margin of ancestral North America, western Purcell Mountains, southeastern British Columbia. Ph.D. thesis, Queen's University. Available electronically at:
<http://www.collectionscanada.ca/obj/s4/f2/dsk3/ftp04/nq22501.pdf>.
- Warren, M. J., 1996, Geology of the west-central Purcell Mountains, B.C, p. 3.
- Weber, M. E., M. H. Wiedicke, H. R. Kudrass, C. Huebscher, and H. Erlenkeuser, 1997, Active growth of the Bengal Fan during sea-level rise and highstand: *Geology*, v. 25, p. 315-318.
- Weiner, J. L., 1966, The Old Fort Point Formation, Jasper, Alberta: Doctoral thesis, University of Alberta, Edmonton, 188 p.
- Werne, J. P., B. B. Sageman, T. W. Lyons, and D. J. Hollander, 2002, An integrated assessment of a "type euxinic" deposit; evidence for multiple controls on black shale deposition in the Middle Devonian Oatka Creek Formation: *American Journal of Science*, v. 302, p. 110-143.
- Wignall, P. B., 1994, Black Shales: Oxford Monographs on Geology and Geophysics, v. 30, Clarendon Press, Oxford, 127 p.
- Williams, G. E., and V. A. Gostin, 2000, Mantle plume uplift in the sedimentary record; origin of kilometre-deep canyons within late Neoproterozoic successions, South Australia: *Journal of the Geological Society of London*, v. 157, p. 759-768.
- Williams, T. A., S. A. Graham, and K. N. Constenius, 1998, Recognition of a Santonian submarine canyon, Great Valley Group, Sacramento Basin, California; implications for petroleum exploration and sequence stratigraphy of deep-marine strata: *AAPG Bulletin*, v. 82, p. 1575-1595.
- Wilson, T. R. S., J. Thomson, S. Colley, D. J. Hydes, and N. C. Higgs, 1985, Early organic diagenesis; the significance of progressive subsurface oxidation fronts in pelagic sediments: *Geochimica et Cosmochimica Acta*, v. 49, p. 811-822.
- Wingate, M. T. D., S. A. Pisarevsky, and D. A. D. Evans, 2002, Rodinia connection between Australia and Laurentia; no SWEAT, no AUSWUS?: *Terra Nova*, v. 14, p. 121-128.
- Xie, Q., J. Jain, M. Sun, R. Kerrich, and J. Fan, 1994, ICP-MS analysis of basalt BIR-1 for trace elements: *Geostandards Newsletter*, v. 18, p. 53-63.
- Zack, T., H. von Eynatten, and A. Kronz, 2004, Rutile geochemistry and its potential use in quantitative provenance studies: *Sedimentary Geology*, v. 171, p. 37-58.

- Zheng, Y., R. F. Anderson, A. van Geen, and J. Kuwabara, 2000, Authigenic molybdenum formation in marine sediments: A link to pore water sulfide in the Santa Barbara Basin: *Geochimica Et Cosmochimica Acta*, v. 64, p. 4165-4178.
- Zhou, C. M., R. Tucker, S. H. Xiao, Z. X. Peng, X. L. Yuan, and Z. Chen, 2004, New constraints on the ages of neoproterozoic glaciations in south China: *Geology*, v. 32, p. 437-440.

APPENDICES

APPENDIX A: The Record of Neoproterozoic Glaciations in the Windermere Supergroup, southern Canadian Cordillera

Mark D. Smith¹, Emmanuelle Arnaud², R.W.C. (Bill) Arnott¹ and Gerald M. Ross³

¹*Department of Earth Sciences, University of Ottawa, Ottawa, Ontario, K1N 6N5, Canada*

²*Department of Land Resource Science, University of Guelph, Guelph, Ontario, N1G 2W1, Canada (e-mail: earnaud@guelph.ca)*

³*Kupa'a Farm, P.O.Box 458, Kula, Hawai'i, 96790, USA*

A.1 CHAPTER SUMMARY

The Neoproterozoic Windermere Supergroup (WSG) is exposed over an area of 35,000 km² in the southern Canadian Cordillera, and consists primarily of deep-marine meta-sedimentary rocks interpreted to have been deposited during rifting and subsequent post-rift thermal relaxation. The main exposures of the WSG occur within thrust panels and structural culminations of the eastern Cordilleran orogen. Within the thick stratigraphic succession (~9 km) are three units of glacial affinity: Toby, Vreeland and Old Fort Point (OFP) formations. The Toby Formation is composed of up to 2500 m of diamictite, interbedded with conglomerate, sandstone, mudstone, carbonate and mafic volcanic rocks. The Vreeland Formation ranges from 350 m to 2000 m thick and consists of diamictite, interbedded with mudstone, sandstone and conglomerate. The OFP ranges from 60 to 450 m in thickness and consists of a distinctive three-fold stratigraphic package of basal siltstone grading upward into limestone-siltstone rhythmite, organic-rich mudstone and an overlying heterolithic unit of diamictite, breccia, conglomerate, sandstone, siltstone to mudstone and limestone. A locally prominent unconformity marks the

base of the OFP upper member. Both the Toby and Vreeland formations represent remobilized glacially-derived marine sediments deposited by sediment-gravity flows. Deposition of the Toby Formation was fault-controlled during an active tectonic phase (rifting) whereas the Vreeland Formation accumulated during the subsequent quiescent phase (post-rift) with limited structural control. The OFP is interpreted to be a regionally extensive deep-marine post-glacial marker temporally associated with the glacigenic Vreeland Formation. Although direct geochronological ages for WSG units in southwestern Canada are generally absent, high-precision radiometric ages of underlying and overlying igneous events constrain the relative maximum and minimum timing of deposition from ca. 740-728 Ma to ca. 569 Ma. At the base of the WSG succession, the Toby Formation may be as young as ca. 685 Ma based on ages obtained from potential stratigraphic correlatives in the United States. There is no direct age constraint for the deposition of the Vreeland Formation; its minimum timing is based on its stratigraphic relationship with the post-glacial OFP. The middle member of the OFP was precisely dated at 607.8 ± 4.7 Ma using the Re-Os method placing it in the Ediacaran Period. Published geochemical and stable isotopic data are similarly limited for all three units with only some $\delta^{34}\text{S}_{\text{py}}$ values available from one section of the OFP. Recent work has focused on detailed sedimentologic and stratigraphic studies of the Toby and the OFP formations with future efforts being directed towards integrated geochemical and isotopic research. Additional geochronological constraints are needed to refine paleogeographic models and strengthen regional correlations with other North American Cordilleran glacigenic units.

A.2 INTRODUCTION

The record of Neoproterozoic glacigenic sedimentation in the southern Canadian Cordillera (Fig. 1) is preserved in three units within the Windermere Supergroup (WSG): a glacial interval at the base of the succession is inferred from

the diamictite-bearing Toby Formation, with another event higher in the succession inferred from the diamictite-bearing Vreeland Formation (glacial) and Old Fort Point Formation (post-glacial) (Fig. 2) (Ross *et al.* 1989; Ross *et al.* 1995).

A.2.1 Toby Formation

The Toby Formation (also known as the Toby Conglomerate) is best exposed in the Purcell Mountains of southeastern British Columbia. The variability of its lithofacies has precluded the identification of a type section; the formation was named by Walker (1926) after well exposed outcrops located along Toby Creek, west of Invermere, British Columbia (50° 30' N, 116° 02' W) (Fig. 1: A). This area has been extensively modified by Proterozoic, Devonian and Mesozoic deformation and the structural context of these rocks is often complicated (e.g. Root, 1987).

Previous studies of the Toby Formation are relatively few, with primary emphasis on regional mapping relative to Proterozoic- and Mesozoic-age structures (Walker 1926; Leech 1954; Aalto 1971; Reesor 1973; Root 1987; Pope 1990; Warren 1997). The glacial origin of the Toby Formation was first proposed based on a more detailed study of facies types and variability, petrography, as well as trends in clast characteristics in the Toby Formation itself (Aalto 1971). Additional mapping of specific regions have followed including mapping of the Toby Formation and related structures in the Paradise Mine (Atkinson 1975), Delphine Creek (Root 1987), Mount Forster (Bennett 1986), Creston/Salmo (Glover & Price 1976) and Crawford Bay/Columbia Point areas (Lis & Price 1976). Ongoing investigations are focusing on the relationship between Toby Formation facies variability and structural trends as well as isotopic analyses of associated strata.

A.2.2 Vreeland Formation

The Vreeland Formation has received little study (due largely to inaccessibility) despite its impressive exposures and thickness in the Pine and Monkman Pass regions, central British Columbia (from 54° 05' N to 57° 00' N) (Fig.

1). It was originally mapped by Slind & Perkins (1966) as an unnamed Precambrian conglomerate-schist. Later, it was briefly examined by Stelck *et al.* (1978) but was not really described until regional mapping conducted by McMechan (1987) and McMechan & Thompson (1985, 1995a, 1995b). It was initially referred to as a diamictite within the Misinchinka Group or the Mount Vreeland – Paksumo Pass diamictites (McMechan 1990), until Hein and McMechan (1994) referred to it as the Vreeland Formation. McMechan (2000) provided the first detailed stratigraphic description and paleogeographic interpretation in the Monkman Pass area. No type section has been defined for the Vreeland Formation, although the Mount Vreeland sections (54° 35' N, 121° 32' W) in the Snake Indian thrust sheet (Fig. 1: B) and the Paksumo Pass section (54° 20' N, 120° 49' W) in the Wapiti Pass thrust sheet (Fig. 1: C) of the Monkman Pass area are thought to be representative exposures (McMechan 2000).

A.2.3 Old Fort Point Formation

The Old Fort Point Formation (OFP) is the preferred name to describe the unique stratigraphic marker in the WSG that is exposed locally over the entire outcrop region of southwestern Canada (Fig. 1: D - K). Walcott (1910) was the first to describe the OFP from the Lake Louise area of Alberta using its distinctive purple and green colours and lithology (siltstone, limestone, breccia) to separate the Precambrian Corral Creek (lower conglomerate to sandstone) and Hector (upper slate) formations. The name and type section (52° 52' 16" N, 118° 03' 40" W) come from outcrops at a prominent landmark near Jasper, Alberta (Charlesworth *et al.* 1967). A more representative and better exposed section crops out ~15 km west of Jasper along the major highway (52° 52' 21" N, 118° 17' 35" W). The regionally extensive nature of the OFP has led to various names: 1) basal Hector Formation (Walcott 1910) or Mount Temple and Taylor Lake members (e.g. Gussow 1957) in the Lake Louise area, Alberta; 2) Old Fort Point Formation (e.g. Weiner 1966; Charlesworth *et al.* 1967) in the Jasper area, Alberta; 3) Middle Miette Marker (e.g.

McDonough 1989) in the Mount Robson area, British Columbia; 4) Kaza Group marker (e.g. Ross & Murphy 1988) in the Cariboo Mountains, British Columbia; 5) Baird Brook Division (e.g. Kubli 1990) in the Dogtooth Range of the Purcell Mountains, British Columbia; 6) Comedy Creek unit (Grasby & Brown 1993), Selkirk Mountains, British Columbia; and 7) upper and lower markers (e.g. Warren 1997) in the Purcell Mountains, British Columbia (Fig. 1). Although there were early attempts to correlate between certain locations (Charlesworth *et al.* 1967; Aitken 1969), it was Ross & Murphy (1988) who first recognized the basin-wide correlation of the OFP (and equivalents), its palaeogeographic significance and importance in Neoproterozoic event stratigraphy. Subsequent work by Ross *et al.* (1995) examined the sulfur isotopic evolution of the OFP and WSG strata in the Cariboo Mountains, British Columbia (Fig. 1). A regionally comprehensive study of the OFP integrating sedimentology, stratigraphy, geochemistry, and stable isotopes has recently been completed (Smith 2009).

A.3 STRUCTURAL FRAMEWORK AND BASIN SETTING

The WSG forms part of a long arcuate belt of semi-continuous outcrops in western North America that extends from the Yukon-Alaska border region to northwestern Mexico (e.g. Ross *et al.* 1989). In southwestern Canada, exposures crop out over an area of 35,000 km² in a series of thrust sheets in the Main Ranges of the western Fold-and-Thrust Belt and the Omineca Belt of the southern Canadian Cordillera (Fig. 1). Major structures affecting WSG strata in the region include the Southern Rocky Mountain Trench (Fig. 1) and a broad gently north-plunging structure in the Purcell Mountains (the Purcell Anticlinorium). Proterozoic-age structures that affected WSG deposition include regionally significant transfer faults (e.g. Mount Forster and Moyie) and associated uplifted blocks (e.g. Windermere High and Montania; Reesor 1973; Lis & Price 1976; Root 1987; Warren 1997).

All WSG strata were subjected to Mesozoic orogenic deformation that resulted in a wide range of structural complexity and metamorphic grade between different structural panels. Extensive tracts of sub-greenschist to greenschist grade exist in the western Main Ranges of the Rocky Mountains (Lake Louise, Jasper, northern Cariboo Mountains and eastern Purcells Mountains); whereas higher grade metamorphic rocks (biotite to upper amphibolite) are found in the southern Cariboo and western Purcell Mountains, as well as the Shuswap Complex (e.g. Simony *et al.* 1980; Ross *et al.*, 1995). Areas of low metamorphic grade and relatively uncomplicated tectonic deformation show exceptional preservation of primary sedimentary textures and structures. This allowed the development of a consistent internal stratigraphy of the WSG and reconstruction of the Windermere basin in southwestern Canada (Ross and Murphy 1988; Ross *et al.* 1989, 1995; Ross 2000).

The WSG is thought to represent deposition in two tectonic phases (e.g. Stewart 1972; Ross 1991). The first phase was characterized by rifting during the break-up of the supercontinent Rodinia, whereas the second phase occurred during post-rift thermal relaxation. At the base of the WSG, the Toby Formation together with the Irene Formation volcanic rocks, are interpreted to have accumulated during the rifting phase (Aalto 1971; Glover & Price 1976; Root 1987). The variable thickness of the Toby Formation is attributed to syn-sedimentary fault-controlled deposition (Aalto 1971; Root 1987). Based on the nature of Proterozoic-age faults, Root (1987) suggested that the basin underwent two episodes of extension; one trending approximately E-W, resulting in a series of NNE and NNW faults and another trending NW-SE, resulting in a series of NE-SW normal faults.

The Vreeland Formation and OFP both accumulated during the post-rift phase with possible local structural control (McMechan, 2000; Smith 2009). During this later phase, the basin is thought to be an elongate northwest-flowing turbidite system (Ross *et al.* 1989; Ross 1991; Ross *et al.* 1995), based on consistent palaeocurrent data and bimodal pattern (>2.6 Ga and 1.9 to 1.75 Ga) of U-Pb detrital zircon provenance (Ross & Bowring 1990; Ross & Parrish 1991). Basement clasts

from the Vreeland Formation yielded ages between 1865 to 1842 Ma (Ross & Villeneuve 1997) suggesting derivation from a source area to the north and northeast (McMechan 2000).

While there is broad agreement about these two tectonic phases, the exact tectonic setting of the Windermere basin and its evolution remains controversial. Some argue that the upper part of the WSG in the southern Canadian Cordillera accumulated on a continental passive margin with a substantial Proto-Pacific Ocean (Ross 1991; Ross *et al.* 1995; Dalrymple & Narbonne 1996). Others prefer an intracontinental rift and restricted ocean basin setting for the southern WSG, and a late Neoproterozoic-early Cambrian inception for the Proto-Pacific Ocean (Colpron *et al.* 2002). The controversy and uncertainty is in part due to the presence of two intervals of rift-related igneous rocks within the southern Canadian Cordillera (Bond & Kominz 1984; Ross 1991; Colpron *et al.* 2002), diachronous dates for the timing of rifting along the whole of Laurentia's Pacific margin (see discussion in Lund *et al.* 2003), and tectonic deformation that currently precludes certain identification of a western Windermere basin margin.

A.4 STRATIGRAPHY

In the southern Canadian Cordillera, the WSG is a thick (~9 km), unconformity-bounded succession of predominantly coarse-grained deep-marine siliciclastic rocks with subordinate carbonate and mafic volcanic rocks (Fig. 2). Older units associated with the rift phase (e.g. Toby and Irene formations) are more limited in areal extent and tend to show greater lateral facies variations compared with units associated with the post-rift phase (e.g. Ross *et al.* 1989; Ross 1991; Ross *et al.* 1995; Warren 1997). At the base of the WSG, the Toby Formation unconformably overlies shallow-water deposits of the Mount Nelson Formation (Neoproterozoic/Mesoproterozoic?, Root 1987; Ross & Villeneuve 2003) or deep-marine sedimentary rocks of the Mesoproterozoic Purcell Supergroup (Aalto 1971;

Root 1987). The Toby Formation is associated with localized rift-related mafic volcanic rocks of the Irene Formation and a laterally discontinuous carbonate horizon at its top (e.g. Root 1987; Warren, 1997). These basal units of the WSG are largely restricted to the Purcell Mountains region (Fig. 1). Potential high-grade metamorphic equivalents of the Toby (e.g. Simony *et al.* 1980; Murphy *et al.* 1991) and the Irene volcanic rocks (e.g. Simony *et al.* 1980; Sevigny 1988) may exist in the Shuswap Complex and northern Cariboo Mountains, although the stratigraphic control is poor (Fig. 1).

The nomenclature of WSG succession that overlies the Toby Formation in the southern Canadian Cordillera is rather complex: a direct result of correlation challenges across thrust-bound panels with varying levels of metamorphism, general absence of reliable stratigraphic markers and poor geochronological constraints. The Horsethief Creek Group (Purcell Mountains), Kaza and lower/middle Cariboo groups (Cariboo Mountains), Miette Group (Rocky Mountains) and Misinchinka Group (Rocky Mountains) all refer to parts of the same ~5 km deep-marine turbidite system exposed over 35,000 km² (e.g. Ross *et al.* 1989) (Figs. 1, 2). Lithologically, the thick package is dominated by coarse-grained arkosic sandstone and granule conglomerate interbedded with mudstone-dominated intervals or minor carbonate.

The Vreeland Formation of the Misinchinka Group is a local exception, being composed of up to 2000 m of diamictite interbedded with mudstone, sandstone and conglomerate (McMechan 2000). Mapping of the Vreeland Formation has shown that the diamictite units undergo a lateral facies change into typical deep-marine coarse-grained turbidites of the WSG in both a westward (McMechan 1987) and southward direction (McMechan & Thompson 1995a).

Throughout much of the basin, the overall monotony of the thick-bedded, immature turbidites of the Horsethief Creek, Miette and Kaza groups is interrupted by the fine-grained, regionally widespread OFP (and correlative units) (Ross and Murphy 1988; Ross *et al.* 1995). Nowhere is the OFP observed to be contact with

diamictite of the Vreeland Formation, rather the OFP overlies WSG turbiditic strata interpreted as deep-marine lateral equivalents. The OFP is overlain by coarse-grained basin-floor turbidite deposits that form a km-scale shoaling upwards trend to mudstone-dominated upper slope units and shelf platform carbonates (Ross *et al.* 1989). A significant regional unconformity marks the end of WSG deposition and the beginning of a latest Neoproterozoic to Cambrian rift-drift succession with the clastic and volcanic sediments of the upper Cariboo, Hamill and Gog groups.

A.5 GLACIGENIC DEPOSITS AND ASSOCIATED STRATA

A.5.1 Toby Formation

The Toby Formation consists primarily of diamictite interbedded with conglomerate, sandstone, dolomitized or recrystallized limestone and mudstone (Fig. 3) (Aalto 1971). Its thickness is highly variable, ranging from 0 to 2500 m. Lithofacies, in general, and sedimentary characteristics of diamictite, in particular, (including clast concentration, clast size, matrix and clast lithology, lateral continuity and bed thickness) are highly variable over short distances; a fact that has been stressed by all workers in this region. The following descriptions rely heavily upon the regional study of Aalto (1971), with additional observations based on more recent field work by E. Arnaud and K. Root.

Diamictite is predominantly massive, matrix- or clast-supported with subangular to subrounded clasts up to 2 m floating in a muddy sandstone or sandy mudstone matrix. Clast lithology includes quartzite, volcanic greenstone, slate, dolomite and chert derived from the underlying Mount Nelson Formation as well as rare extrabasinal granite (Leech 1954; Reesor 1973; Loveridge *et al.* 1981). The diamictite matrix exhibits a similar lithological variability. Tectonic overprinting typically obscures clast fabric in many outcrops. Where relatively unaltered, clasts show no preferred orientation. Diamictite units vary in thickness from several m to

10s of metres. In outcrops with good lateral exposure, basal contacts are relatively planar, and conformable or erosional.

Conglomerate occurs in lenticular or planar units (cm to m scale) interbedded with diamictite and sandstone. It is distinguished from the diamictite by its coarse sandstone matrix, and consistently high clast concentration (65 to 80%). It is generally unorganized and massive with occasional subtle coarse-tail grading. Sandstone varies from coarse- to fine-grained, moderately to poorly sorted and occurs in planar beds or lenticular units (cm to m scale). It is most commonly massive or laminated, though some sandstone units exhibit ripple cross-lamination, climbing ripples or normal grading. Dolomitized or recrystallized limestone (cm to m scale thick) with varying amounts of quartz grains is also observed within and at the top of the Toby Formation at various sites within the region. These carbonate strata are planar-tabular and can be laterally persistent over 100s' of metres, though their overall distribution is patchy. Lastly, mudstone is relatively common throughout the Toby Formation. It is massive or laminated and occurs in relatively planar tabular units (cm to m scale thick). Outsized clasts are found within these mudstone units and some are seen to depress or puncture underlying laminations (Aalto 1971).

In terms of associated strata, the underlying Mount Nelson and Dutch Creek formations consist of thick packages of carbonate and siliciclastic strata (km scale; Walker 1926; Reesor 1973, Root 1987). Slate predominates in the Dutch Creek Formation, whereas thick packages of white quartzite and dolomite interbedded with intervals of argillite, siltstone and conglomerate characterize the Mount Nelson Formation. In the Purcell Mountains, the Toby Formation is overlain by the Horsethief Creek Group, which consists of a thick package (<100 to 2000+ m) of mudstone, sandstone, conglomerate, calcareous mudstone and dolostone (Walker 1926; Root 1987; Kubli 1990; Warren 1997). Further to the south, the Toby Formation is interbedded and overlain by volcanic greenstone of the Irene

Formation, and coarse- to fine- grained clastic and carbonate lithofacies of the Monk Formation (Aalto 1971).

A.5.2 Vreeland Formation

Description of the Vreeland Formation is based entirely on regional mapping studies in the Pine and Monkman Pass areas (McMechan 1987; McMechan & Thompson 1985, 1995a, 1995b) and geological descriptions from the Snake Indian and Wapiti Pass thrust sheets (Fig. 1) (McMechan 1990, 2000). The Vreeland Formation comprises a thick succession of diamictite interbedded with mudstone, sandstone and conglomerate (Fig. 4). Diamictite units are generally massive (~98%) with a sandstone or siltstone to mudstone matrix and form laterally extensive (up to 2 km) tabular sheets that range from a few metres to >40 m thick. The basal contact of massive diamictite units is sharp and locally erosive. Subtle normal grading is observed locally in diamictite in addition to rare stratified diamictite defined by clast layers, or sandstone/siltstone stringers and lenses. Clasts are lithologically diverse and consist of both intra-basinal (mudstone, sandstone, carbonate) and extra-basinal (felsic or mafic plutonic, volcanic, quartzite) varieties. Differing provenance trends are apparent in the two main areas based on clast lithology.

Interstratified mudstone units are up to 38 m thick with rare sandstone interbeds, and common lonestones. Sandstone units are sharp-based and range from very fine- to very coarse-grained and very thin- to thick-bedded. Sedimentary structures include scours, cross-stratification, graded bedding and intraclast rip-ups. Conglomerate and sandstone units commonly form lenticular channel-like deposits. Conglomerate is matrix- and clast-supported with a sandstone matrix, which contrasts with the typical siltstone to mudstone matrix of the diamictite. Clast lithologies are similarly diverse, rounded to angular and range up to boulder size.

In the Snake Indian thrust sheet, the top of the Vreeland Formation is marked by a pyrite-rich zone up to 30 cm thick and locally the diamictites are overlain by a thin (few metres), parallel laminated limestone. The conformably overlying

Framstead Formation is mudstone-dominated, but locally is composed of sandstone to conglomerate or limestone. Locally, large (up to 650 m long) carbonate olistoliths occur on, or just above the basal contact with the Vreeland Formation, and also near its upper contact. These olistoliths occur as discrete, randomly-oriented blocks that lack internal deformation. Lithologies are predominantly tan-weathered shallow-water carbonates and include: laminated dolomite with rare layers of teepee structures and bladed calcite, stromatolitic dolomite, sandy- to pebbly dolomite, dolomite conglomerate, and quartzose fenestral and vuggy dolomite.

A.5.3 Old Fort Point Formation

The following sedimentological and stratigraphic description stems mostly from a recent detailed regional study (Smith 2009) but also incorporates work of earlier authors (Fig. 1: D to K) (Walcott 1910; Weiner 1966; Charlesworth *et al.* 1967; Aitken 1969; Murphy 1986; Pell and Simony 1987; Ross & Murphy 1988; McDonough 1989; Deschesne 1990; Kubli 1990; Grasby & Brown 1993; Ross *et al.* 1995; Warren 1997; Ross & Ferguson 2003a, 2003b). The OFP comprises three distinctive lithological members, which despite variable metamorphic grade, form a consistent stratigraphic relationship throughout the southern Canadian Cordillera (Fig. 5).

The lower member is a purple, green, grey, or red-brown fine-grained unit that ranges from 50 to 125 m thick. The basal portion is composed of siltstone to mudstone that grades upward into rhythmic couplets of limestone-siltstone. Beds typically range from <1 cm to 10 cm in thickness and exhibit common tractional sedimentary structures including: planar lamination, lenticular bedding, ripple cross-lamination, normal grading and minor scours. Subordinate lithofacies include very fine- to fine-grained sandstone interstratified with uncommon limestone-clast breccia beds. Palaeocurrents measured from 3D current-ripples generally indicate flow toward the southwest to northwest.

The middle member ranges from 2 to 15 m thick and consists of a dark-grey organic-rich mudstone/pelite. The basal contact with the underlying lower member is usually gradational over a few metres. The unit is characterized by alternating siltstone and mudstone laminae with subtle normal grading. Isolated, thin-bedded dark-grey massive or planar-laminated limestone and very fine ripple-stratified sandstone occur locally. This member is regionally extensive. Its fissile nature typically results in poor or covered exposures, although notable exceptions occur (e.g. Ross *et al.* 1995; Kendall *et al.* 2004).

In contrast to the lower two members, the upper member is lithologically diverse and highly variable in thickness (<0.5 to 165 m). The basal contact with underlying strata is always sharp, and locally, it completely erodes the lower two members. Lithologies include diamictite, breccia, conglomerate, mudstone, siltstone, sandstone, quartz arenite, calcareous arenite, arenaceous limestone and limestone. Diamictite and breccia to conglomerate are generally sharp, commonly erosively-based, massive beds with mudstone/siltstone or well-sorted, coarse quartz-rich sandstone matrix. Bed thickness (<0.5 to >10 m), clast-size (cm to m) and clast lithologies are variable. Clasts include fragments of the OFP members and shallow-marine carbonates, some with rare bladed calcite crystals. Mudstone and siltstone exhibit planar laminations, micro-scours, subtle normal grading, large single chlorite flakes and rare scours. This lithofacies is locally thick (~100 m) and monotonous with rare interbeds of diamictite, breccia, conglomerate or sandstone. Sandstone in the upper member consists of a range of textures: fine- to very coarse-grained, poor- to well-sorted and mineralogical maturity (immature to supermature). The well-sorted, mature quartz arenites are interbedded with dark, organic-rich limestone beds and these units can exhibit a range of compositions between the two end members (e.g. calcareous arenites or arenaceous limestones). Sedimentary structures include massive beds, planar lamination, and cross-stratification. Rare palaeocurrent measurements from the upper member are consistently towards the southwest to northwest. Soft-sediment deformation

features such as load structures, convolute or contorted bedding and ductile folding are common in both fine- and coarse-grained facies of the upper member.

A.6 BOUNDARY RELATIONS WITH OVERLYING AND UNDERLYING NON-GLACIAL UNITS

A.6.1 Toby Formation

The Toby Formation rests unconformably on various members of the Mount Nelson Formation or the underlying Dutch Creek Formation. In outcrop, the unconformity is commonly subtle ($<10^\circ$), though a distinctive angular unconformity with tilted underlying Mount Nelson strata is evident in some places. The upper contact of the Toby Formation with the Horsethief Creek Group is conformable and gradational throughout the Purcell Mountains and typically established based on the loss of diamictite. To the west and south of the Purcell Mountains, the Toby Formation is conformably overlain by pillow lavas of the Irene Formation as well as conglomerate and diamictite facies of the lower Monk Formation (Aalto 1971). Considering there are localized lenses of conglomerate and diamictite in the Irene Formation, and that the upper contact of the Toby Formation is defined in the Purcell Mountains with the loss of diamictite facies, the upper contact of the Toby Formation may actually occur several 10's of metres above the Irene volcanic rocks (Aalto 1971).

A.6.2 Vreeland Formation

In the western Snake Indian thrust sheet, the basal contact of the Vreeland Formation is not exposed (McMechan 2000). In the eastern Wapiti Pass thrust sheet, the basal diamictite appears to interfinger with the upper 150 m of the fine-grained facies of the underlying Paksumo Formation (McMechan & Thompson 1995b). The Vreeland Formation is conformably overlain by the Framstead Formation: in the western exposures by a carbonate olistolith bearing unit; whereas in the eastern

exposures by a sandstone unit (McMechan 2000). The carbonate olistolith bearing unit correlates from west to east where it overlies the lowermost Framstead Formation sandstone. This suggests at the western Snake Indian thrust sheet locality that either local erosion of the sandstone unit occurred or it is actually a lateral equivalent of diamictite of the Vreeland Formation (McMechan 1990).

A.6.3 Old Fort Point Formation

The OFP conformably and gradationally overlies deep-marine turbiditic strata of the WSG interpreted to be lateral facies equivalent of the Vreeland Formation diamictite. The contact is commonly marked by a distinctive change in colour (e.g. grey to purple) and lithology (appearance of lower member siltstones). However, at some locations the lower and middle members have been eroded and the upper member forms a sharp unconformity over older WSG strata. The top of the OFP is conformably overlain by younger WSG strata. In many cases the contact is identified by a sharp change in grain-size and/or framework mineralogy (e.g. OFP quartz arenite to WSG arkosic sandstone). The challenge arises where OFP mudstone units are overlain directly by a younger mudstone unit of the WSG. The contact is taken to coincide with the termination of organic-rich limestone beds or the appearance of common sandstone interbeds. Field observations can sometimes be confirmed by a decrease in gamma-ray counts or correlative geochemical trends (e.g. decrease in TOC, Mo) (Smith 2009).

A.7 CHEMOSTRATIGRAPHY

The only published geochemical or isotopic data from the three units is the sulfur isotopic study of Ross *et al.* (1995) on pyrite in the post-rift strata of the WSG, Cariboo Mountains, British Columbia (Fig. 1: E). A total of 170 samples were analysed for $\delta^{34}\text{S}_{\text{py}}$ and these showed a broad range of isotopic values (approximately 50‰) (Ross *et al.* 1995). As part of that study, a suite of 36 samples

were collected from a measured section that includes the OFP. A strong correlation between lithology (and inferred sedimentation rate) and pyrite isotopic composition was reported (Ross *et al.* 1995). For example, the most negative $\delta^{34}\text{S}_{\text{py}}$ values (-31.9‰ to -25.3‰) corresponded to siltstone and mudstone of the OFP whereas the interval in the underlying Kaza Group with the highest sandstone-mudstone ratio were the most positive (around +11.9‰ to +14.5‰) (Ross *et al.* 1995).

New isotopic data ($\delta^{18}\text{O}_{\text{carb}}$, $\delta^{13}\text{C}_{\text{carb}}$, $\delta^{13}\text{C}_{\text{org}}$, $\delta^{34}\text{S}_{\text{py}}$) from OFP sections and lithogeochemical (major-, trace- and rare-earth-element analyses) data from a regional study of WSG mudstones has recently been obtained (Smith 2009). Preliminary analysis shows lower member limestone units exhibiting negative $\delta^{13}\text{C}_{\text{carb}}$ isotopic values and the middle member characterized by distinctive chemical (e.g. TOC, Mo, V/Cr) and isotopic (e.g. $\delta^{13}\text{C}_{\text{org}}$) signatures.

A.8 OTHER CHARACTERISTICS

Economic deposits associated with the glaciogenic strata are limited. Local copper mineralization has been observed below, or in the basal parts of the OFP (Ross 2000; Smith 2009).

The only description of possible Precambrian fossils from glaciogenic strata are some problematic discoid structures at the base of the OFP near Arnica Lake, west of Banff, Alberta (Fig. 1). The structures are ~3 mm in size, lentil-shaped with either hypo- or epirelief, have concentric wrinkles and a 5-point star-like figure inside the concentric pattern (Hofmann 1971; Gussow 1973; Smith 2009). The specimens are attributed to *Chuaria circularis* (Hofmann 1971; Gussow 1973) but they lack any carbonaceous material that would strengthen a biogenic origin and certainly require further detailed work. Ediacaran fauna (including *Namacalathus* and *Cloudina* assemblages similar to those found in the Nama Group of Namibia) have otherwise been reported from the uppermost part of the WSG (Hofmann & Mountjoy 2001 and references therein).

A.9 PALAEO LATITUDE AND PALAEO GEOGRAPHY

There are no published palaeolatitude data for the WSG in southwestern Canada. A near-equatorial palaeogeographic position is based on palaeomagnetic data obtained from broadly correlative WSG strata in the Mackenzie Mountains, northern Canadian Cordillera (Park 1997).

A.10 GEOCHRONOLOGICAL CONSTRAINTS

The predominantly siliciclastic nature of the WSG in the southern Canadian Cordillera has led to a paucity of high-precision geochronological constraints. Currently, the local maximum depositional age of the WSG in the region is constrained by a U-Pb zircon date of $736 \pm 23/-17$ Ma (MSWD 2.36, 4-point TIMS regression) from orthogneiss basement rocks of the Malton Gneiss Complex (McDonough & Parrish, 1991). This age corresponds well with U-Pb zircon dates obtained from WSG basement rocks elsewhere in the Canadian Cordillera, such as 740 ± 36 Ma (Parrish & Scammell 1988) and $728 \pm 8/-7$ Ma (Evenchick *et al.* 1984; see Ross *et al.* 1995 for a full review). A U-Pb zircon age of 569.6 ± 5.3 Ma (3-point $^{207}\text{Pb}/^{206}\text{Pb}$ weighted average) from syn-rift felsic volcanic rocks of the Hamill Group that unconformably overlie the WSG constrains the minimum timing of deposition (Colpron *et al.* 2002).

No direct ages have been obtained from the Toby Formation or Irene volcanic rocks in southern British Columbia. Mafic metavolcanic rocks of the Huckleberry Formation in northeastern Washington, interpreted to be Irene Formation correlatives were imprecisely dated with a preliminary age of 762 ± 44 Ma (MSWD 0.06) from a three-point Sm-Nd isochron of one whole-rock and two pyroxene separates (Devlin *et al.* 1988). Other possible treatments of the Sm-Nd data produced even larger error estimates: 795 ± 115 Ma (MSWD 6.71) from all the data excluding one pyroxene separate; 674 ± 212 Ma (MSWD 1.0) from a seven point

whole-rock isochron; and 719 ± 200 Ma (MSWD 1.0) from two whole-rock and two pyroxene separates (Devlin *et al.* 1988). More recent work on possible correlative rift-related volcanic rock units in Idaho have obtained precise SHRIMP U-Pb zircon ages, of 685 ± 7 Ma, 684 ± 4 Ma (Lund *et al.* 2003), and 709 ± 5 Ma (Fanning & Link 2004). A comparable U-Pb zircon age of $688.9 +9.5/-6.2$ Ma was obtained from syn-rift felsic volcanoclastics of the Gataga Volcanics, northern British Columbia (Ferri *et al.* 1999).

No absolute age constraints are available for the Vreeland Formation: its relative age is based on regional mapping and lithostratigraphic correlations within the WSG (McMechan 1987, 1990, 2000). Kendall *et al.* (2004) obtained two comparable 5-point Re-Os isochron ages from organic-rich black mudstone of the OFP middle member in the Jasper area, Alberta (Fig. 1): an imprecise 634 ± 57 Ma (MSWD 65) using the conventional inverse aqua regia digestion method; and a more precise 607.8 ± 4.7 Ma (MSWD 1.2) using the $\text{CrO}_3\text{-H}_2\text{SO}_4$ digestion technique that is thought to best reflect depositional age of the OFP.

A.11 DISCUSSION

A.11.1 Toby Formation

The variable level of erosion below the sub-Toby unconformity suggests a period of significant erosion and uplift preceded WSG sedimentation. The depositional setting of the Toby Formation itself has been controversial, specifically in regards to the extent of glacial influence on deposition. Most lithologies record remobilization of sediment by sediment-gravity flows. Some authors have favoured a glacial setting for these reworked deposits based on the regional extent of the Toby Formation, the presence (albeit localized) of extrabasinal clasts, striated clasts, clast clusters within diamictites and outsized clasts interpreted as far-travelled and ice rafted glacial debris (Aalto 1971; Warren 1997). Others favoured the resedimentation of locally derived material formed along a fault-bounded margin

undergoing extension with limited or no glacial influence (Walker 1926; Reesor 1973; Root 1987). The predominance of intrabasinal clasts, the mounting evidence for structural controls on facies type and variability (ongoing research), in addition to the localized and rare occurrence of glacial indicators suggest that tectonic activity imparted a primary control on deposition with localized glacial influence.

Carbonate strata within, and at the top of the Toby Formation have received limited attention to-date. Preliminary results from ongoing work suggest that primary carbonate was accumulating on topographic highs while coarse-grained clastics accumulated in fault-bounded basins. Stable isotopic analyses of these carbonates have so far yielded limited information with current research focused on assessing the effects of metamorphism on isotopic signatures.

A.11.2 Vreeland Formation

The Vreeland Formation is interpreted to have been deposited in a mid-slope, glacially-influenced marine setting (McMechan 2000). The diamictite units are interpreted to be resedimented sediment-gravity flow deposits (e.g. unconfined debris flows) of glacial debris or the result of “rain-out” processes from fine-grained suspended sediment plumes and ice-rafted debris (McMechan 2000). The argument for a glacial origin is based on large, sub-angular extrabasinal basement clasts in the diamictite and the occurrence of limestones interpreted as dropstones in the mudstone units of the Snake Indian thrust sheet (McMechan 2000). The absence of dropstones in the Wapiti Pass thrust sheet Vreeland sediments suggests that there was little to no ice-rafted material at this palaeogeographic location (McMechan 2000). The considerable strike length (~400 km) of diamictite suggests glacial erosion over a large area, whereas its thickness (~2000 m) suggests active subsidence accompanied by local faulting (McMechan 2000).

In the Snake Indian thrust sheet, diamictite units are overlain locally by a discontinuous thin-laminated grey limestone (cap carbonate?) deposited during post-glacial sea-level rise and concomitant shutdown of coarse clastic sediment flux

to the basin (McMechan 1990, 2000). The large shallow-marine carbonate olistoliths in the Framstead Formation suggest continued uplift or faulting causing instability and downslope movement of parts of the carbonate shelf edge (McMechan 2000), although simple highstand shedding during post-glacial eustatic rise could also be a potential delivery mechanism.

A.11.3 Old Fort Point Formation

The OFP was deposited along a deep-marine basin-slope to basin-floor transect and overlies coarse-grained turbidites of the WSG. The OFP is interpreted to be related to an Ediacaran-aged post-glacial eustatic rise and a shutdown of the supply of coarse, immature siliciclastic sediment into the basin (Ross & Murphy 1988). Fine-grained, mostly turbiditic strata of the lower and middle members are regionally uniform in thickness and lithofacies suggesting synchronous, basin-wide deep-marine deposition during transgression and highstand (Ross and Murphy 1988; Ross *et al.* 1995; Smith 2009).

Conversely, the variable lithology and thickness of the upper member appears to be controlled by a combination of more local factors including: palaeogeographic location, topography along the slope, erosional mass wasting, structural activity and/or relative sea-level changes (Smith 2009). Deposition of the upper member is interpreted to have coincided with a fall of a relative sea-level caused at least in part, by regional uplift (Smith 2009). In western North America, other Ediacaran-aged uplift or erosion features have been observed suggesting some type of renewed extensional activity during the post-rift phase (e.g. Warren 1997; Fedo & Cooper 2001; Clapham & Corsetti 2005). Where observable, the locally sharp, basal contact is interpreted as a sequence boundary (possibly overprinting the basal surface of forced regression) within OFP (Smith 2009). Related erosional mass wasting, submarine canyon incision and/or syn-sedimentary growth faults controlled initial sediment transport fairways (lowstand) that were subsequently filled during a renewed relative sea-level rise (transgression and highstand) (Smith

2009). The quartz-rich lithologies of the upper member compared to the arkosic sandstone of other WSG turbidites reflect winnowing and maturation from residence on the shelf during the earlier transgression and highstand (Ross 2000; Smith 2009).

A.11.4 Regional Correlations

The Toby, Vreeland and OFP formations have been correlated with other units along the North American Cordillera based on lithostratigraphic similarities (see Lund *et al.* 2003 or Colpron *et al.* 2002 for most recent reviews). The Toby Formation has been correlated with the Kingston Peak Formation (Death Valley), the Edwardsburg and Pocatello formations (Idaho), the Shedroof Conglomerate (NW Washington) and the Sayunei and Shezal formations (Mackenzie Mountains, NW Canada) (Gabrielse & Campbell 1991; Link *et al.* 1993; Ross *et al.* 1995). The Vreeland Formation has been correlated to the similar diamictite-bearing Toobally (Pigage & MacNaughton 2004) and Icebrook (Aitken 1991; James *et al.* 2001) formations in the northern Canadian Cordillera. The Mount Lloyd George diamictite in north-central British Columbia (Eisbacher 1981a, 1981b) is of uncertain age and may correlate with either the Toby or the Vreeland formations.

The OFP overlies turbidites of the WSG that are interpreted to be correlative with the Vreeland Formation (McMechan 1990, 2000; Ross *et al.* 1995). The OFP lower member rhythmic limestone-siltstone couplets are interpreted as a deep-marine equivalent of the thin limestone overlying the Vreeland Formation (McMechan 2000) and of the cap carbonate succession overlying the Ice Brook Formation (Aitken 1991; James *et al.* 2001). The organic-rich OFP middle member potentially correlates with the pyrite-rich horizon at the top of the Vreeland Formation (McMechan 2000) and represents maximum flooding conditions and anoxic (?) bottom-water conditions during earliest post-glacial highstand. The correlative link between the glacial Ice Brook/Vreeland formations and the post-glacial OFP is based primarily on stratigraphic relationships and on the consistent

stratigraphic presence of associated carbonates and carbonate olistoliths possessing distinctive bladed calcite crystals (Ross *et al.* 1995).

The basal glacigenic event in the southern Canadian Cordillera is represented by deposition of the Toby Formation, which is thought to be younger than ~740 to 728 Ma (see Ross *et al.* 1995 for full review). Various data treatments of the Sm-Nd ages (~795 to 674 Ma) from correlative volcanic rocks (Devlin *et al.* 1988) are considered too imprecise to be useful. Current precise ages from potentially equivalent strata in Idaho provide better absolute timing constraints on the glacial episodes because they were obtained from volcanic rocks intercalated with diamictite units, as opposed to unconformably underlying basement rocks. However, further geochronological studies are needed to determine the synchronicity between glacial conditions in Idaho and the southern Canadian Cordillera. The disparity in radiometric age constraints for rift-related magmatic rocks along the Cordilleran margin suggests a diachronous, protracted history of crustal extension and magmatism and thus underscores the need for caution when correlating Cordilleran glacial deposits without precise geochronological constraints (Lund *et al.* 2003; Fanning & Link 2004). The timing of the younger glacigenic event is constrained by the ~608 Ma OFP (Kendall *et al.* 2004) which provides a relative minimum age for Vreeland diamictite deposition based on current regional stratigraphic correlations.

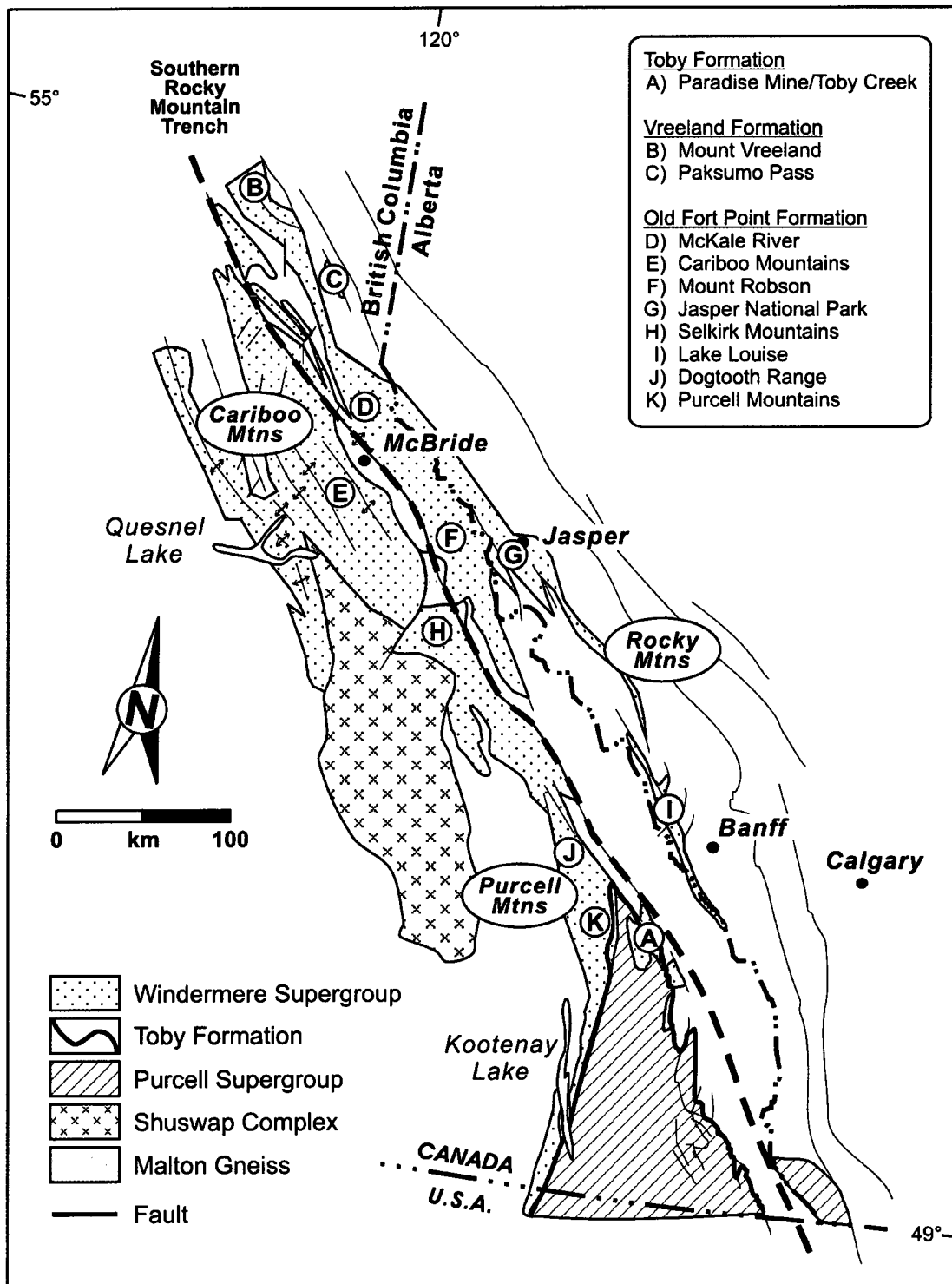


Fig. A.1: Generalized geological map showing outcrop distribution of Windermere Supergroup in western Canada and specific outcrop localities (A - K) discussed in the text (modified from Ross *et al.* 1995). A comprehensive list of outcrop locations for the Toby Formation can be found in Aalto (1971) and Reesor (1973). Outcrop localities for the Vreeland Formation are from McMechan (2000) and for the OFP from Ross & Murphy (1988) and Smith (2009).

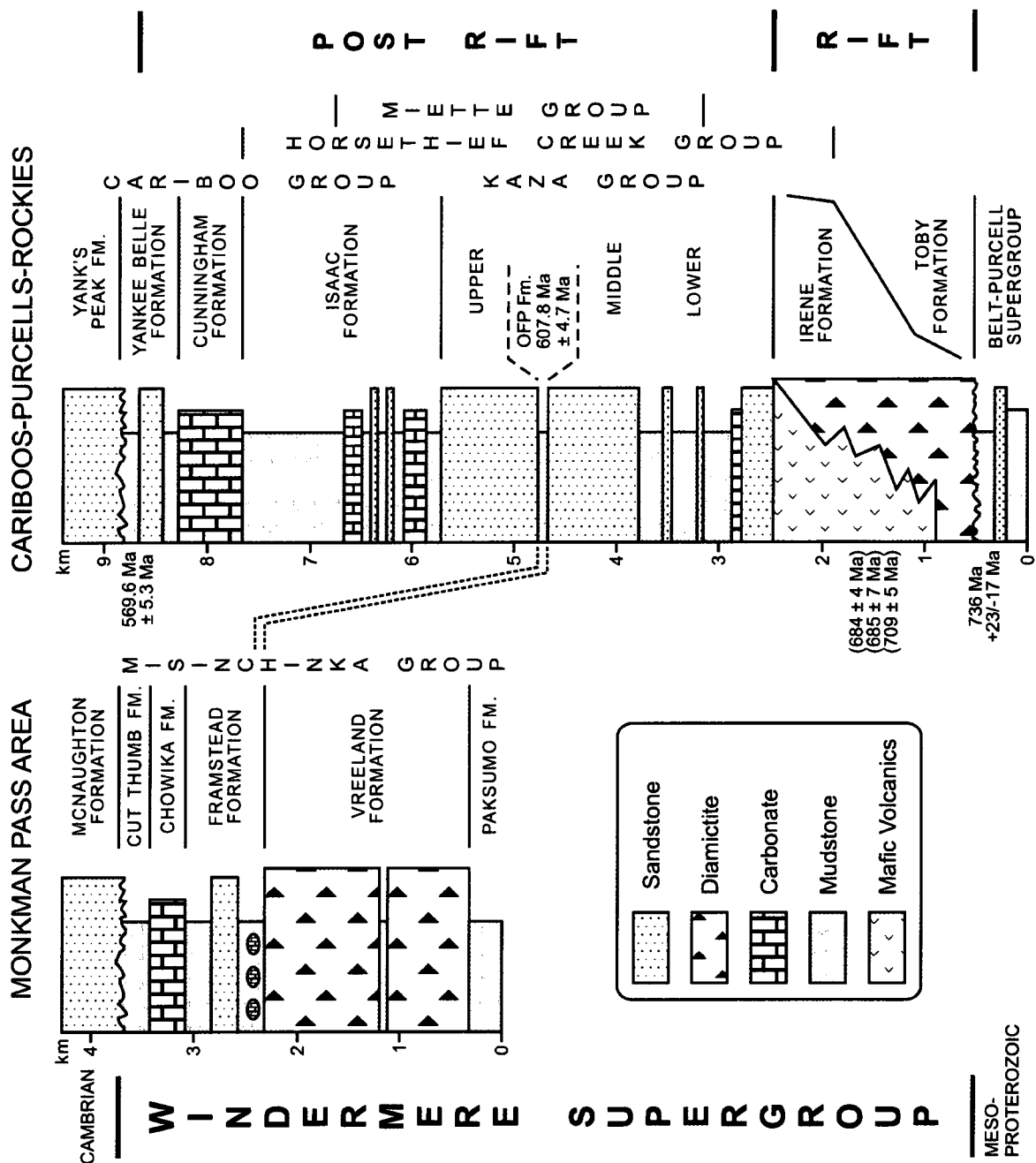
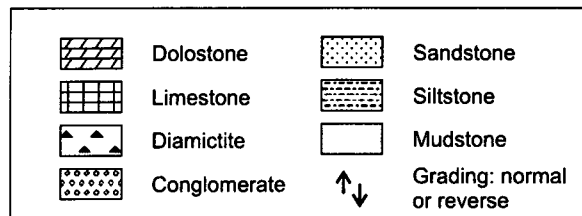
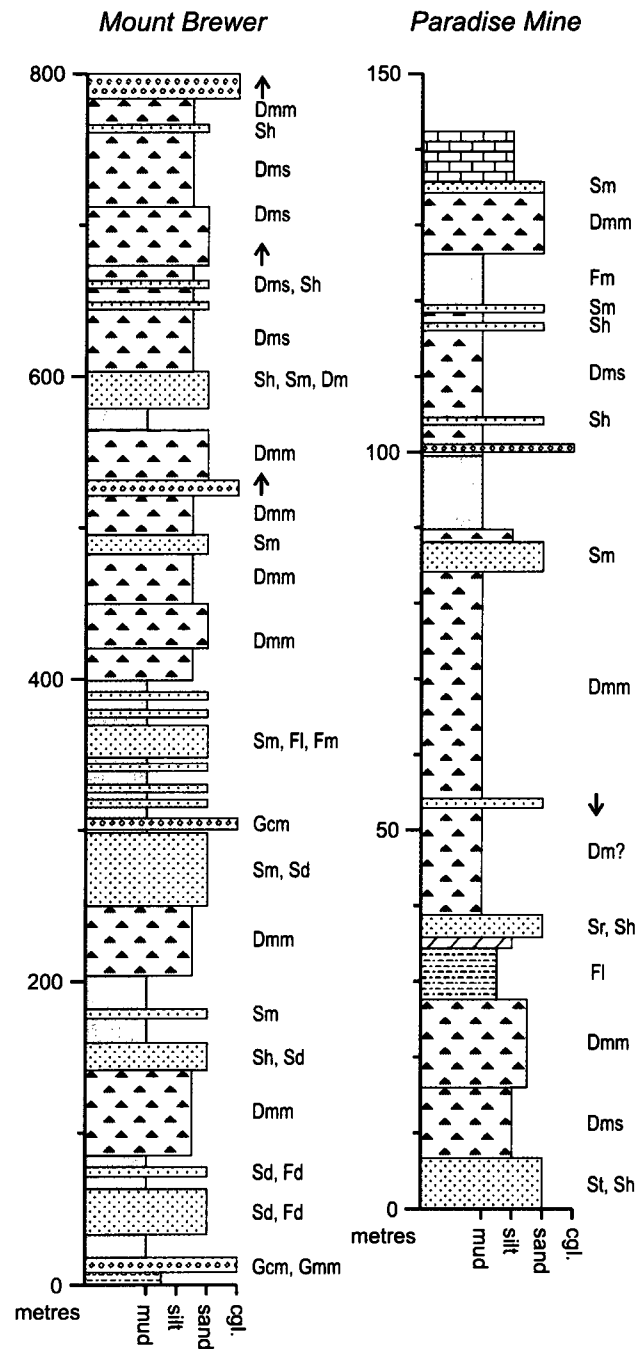


Fig. A.2: Comparative stratigraphic columns for the Windermere Supergroup from the Monkman Pass area and the Cariboo-Purcell-Rocky Mountains (modified from Ross et al. 1995). Nomenclature of rift and post-rift strata (Kaza-Cariboo, Horsethief Creek and Miette groups refer to similar strata, depending on location within the region), relative stratigraphic position of the glacigenic Toby, Vreeland and Old Fort Point formations and proposed correlation between the basal Framstead and Old Fort Point formations are shown. Ages shown are discussed in the text and in stratigraphic order, are: Malton Gneiss (McDonough & Parrish 1991); rift-related volcanic rocks from Idaho (Lund et al. 2003; Fanning & Link 2004); Old Fort Point Formation (Kendall et al. 2004); and Hamill Group volcanic rocks (Colpron et al. 2002). Bracketed ages indicate that the ages are not from rocks of the southern Canadian Cordillera, but rather interpreted correlatives of the Irene Formation.

Fig. A.3: Stratigraphic columns of the Toby Formation from the Mount Brewer and Paradise Mine localities ($\sim 50^{\circ} 28' \text{ N}$, $116^{\circ} 18' \text{ W}$) with lithofacies representative of other outcrops; however, their lateral continuity, stratigraphic thickness and stratigraphic distribution vary widely across the Purcell Mountains. Note the different scales used in each log. Facies codes used: first letter corresponds to D-diamictite, G-Conglomerate, S-sandstone, F-fine-grained facies; second letter in diamictite and conglomerate refers to the following: m-matrix supported, c-clast-supported. Third letter in code refers to sedimentary structure as follows: m-massive, l-laminated, d-deformed, r-rippled, h-horizontally-bedded, s-stratified.

Toby Formation



Vreeland Formation

Mount Vreeland *Paksumo Pass*
Snake Indian thrust sheet *Wapiti Pass thrust sheet*

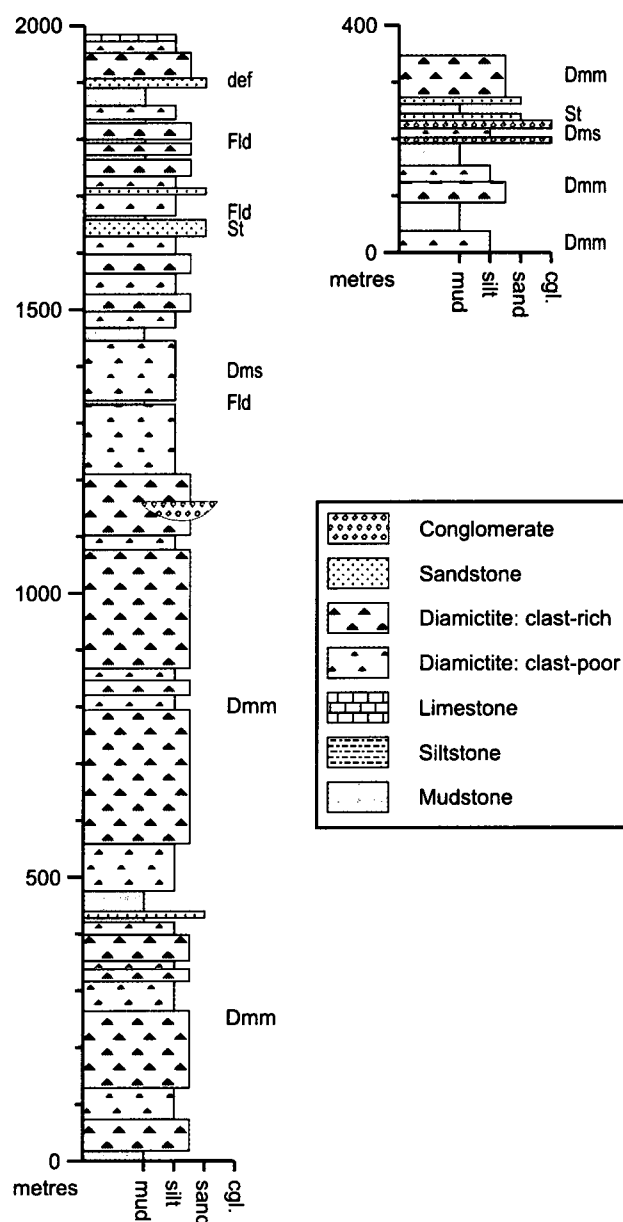


Fig. A.4: Stratigraphic columns of the Vreeland Formation near Mount Vreeland in the Snake Indian thrust sheet, and Paksumo Pass in the Wapiti thrust sheet, modified from McMechan (2000). St-cross-trough bedded sandstone; Fld-laminated fine-grained facies with lonestones. See Fig. 3 for other facies codes.

Old Fort Point Formation

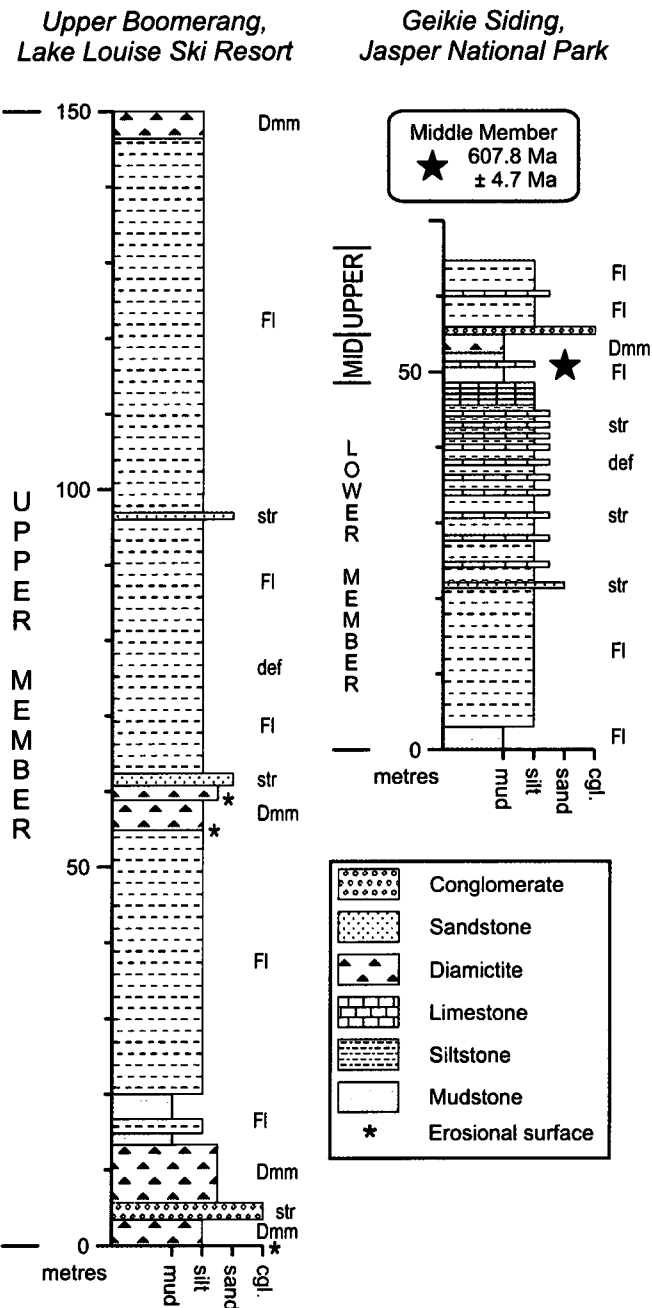


Fig. A.5: Stratigraphic columns of the Old Fort Point Formation, simplified from Smith (2009). At the Geikie Siding section in Jasper National Park, the regionally widespread lower two members are exposed and overlain sharply by a thinly developed upper member. The Re-Os isochron age was obtained from the middle member at this section (Kendall *et al.* 2004). At the Upper Boomerang section on the Lake Louise Ski Resort, only a thickly developed Upper Member is exposed with complete erosion of the lower two members. Str-stratified (ripple cross-laminated and cross-bedded). See Fig. 3 for other facies codes.

APPENDIX B: List of outcrop and sample locations from the southern Canadian Cordillera.

Regional Area	Section	Code	Zone	Easting	Northing
<u>Alberta</u>					
Lake Louise area	Temple Lake	LL1	11	557379	5690015
	Railway/Bath Creek	LL2	11	551641	5701337
	Redoubt SW Spur	LL3	11	562261	5700626
	Upper Boomerang	LL4	11	559666	5702403
	Wolverine Bowl	LL5	11	563943	5698491
	Taylor Lake	LL6	11	563860	5682541
	Icefields Parkway	LL7	11	549902	5709796
	Arnica Lake	LL8	11	570447	5674427
	Icefields Turnoff	LL9	11	555798	5698844
Jasper National Park	Geikie Siding	JP1	11	412974	5858644
	Athabasca River	JP2	11	428416	5857171
	OFP Landmark	JP3	11	428577	5858240
	Marmot Ski Road	JP4	11	430208	5848258
	Yellowhead 0.7 km	JP5	11	425494	5857331
	Yellowhead 8.7 km	JP6	11	417300	5857279
	Yellowhead 27.1 km	JP7	11	402219	5859909
<u>British Columbia</u>					
Mt. Robson Prov. Park	Vista Glacier	MR1	11	400911	5847859
	The Comb	MR2	11	374335	5861575
	Highway Big Hill	MR3	11	373911	6545597
McKale River area	McKale River	MK1	10	692091	5929423
Purcell Mountains	Frances Creek	PM1	11	525658	5613170
	North Jumbo Creek	PM2	11	526350	5586200
Cariboo Mountains	Eagle Valley	CM1	10	678846	5887412
	Mount Quanstrom	CM2	10	693512	5867836
	Castle Creek	CM3	10	672020	5880850
Monkman Pass area	Mount Vreeland	MP1	10	594790	6049200
	Paksumo Pass	MP2	10	641965	6022591

Note: UTM coordinates in grid system NAD27.

APPENDIX C: Complete sample listing and descriptions.

Sample name	Sxn.	Grp./Fm.	Unit/Fcs.	Sample description
<i>MDS 2003 samples</i>				
MDS03-001	CM1	Kaza	Middle	Green pelite/mudstone
MDS03-002	CM1	OFP	TLM-2	Carbonate-cemented sandstone - siltstone
MDS03-003	CM1	OFP	TLM-1	Green siltstone
MDS03-004	CM1	OFP	TLM-2	Carbonate-cemented sandstone - siltstone
MDS03-005	CM1	OFP	TLM-1	Green siltstone
MDS03-006	CM1	OFP	TLM-2	Carbonate-cemented sandstone - siltstone
MDS03-007	CM1	OFP	TLM-1	Grey siltstone
MDS03-008	CM1	OFP	TLM-2	Carbonate-cemented sandstone - siltstone
MDS03-009A	CM1	OFP	TLM-2	Parallel planar marker sandstone
MDS03-009B	CM1	OFP	TLM-2	Parallel planar marker sandstone
MDS03-010	CM1	OFP	TLM-3	Grey limestone
MDS03-011	CM1	OFP	TLM-3	Grey sandy limestone
MDS03-012	CM1	OFP	TLM-3	Grey sandy limestone
MDS03-013	CM1	OFP	TLM-3	Grey siltstone
MDS03-014	CM1	OFP	GSM-1	Dark grey limestone
MDS03-015	CM1	OFP	GSM-1	Parallel planar laminated dark grey limestone
MDS03-016	CM1	OFP	GSM-1	Blue-grey pelite/mudstone
MDS03-017	CM1	OFP	GSM-1	Dark grey limestone
MDS03-018	CM1	OFP	GSM-1	Dark grey limestone
MDS03-019	CM1	OFP	GSM-1	Black pelite/mudstone
MDS03-020	CM1	OFP	GSM-1	Carbonate-cemented sandstone - siltstone
MDS03-021A	CM1	OFP	GSM-1	Dark grey limestone - bottom
MDS03-021B	CM1	OFP	GSM-1	Dark grey limestone - middle
MDS03-021C	CM1	OFP	GSM-1	Dark grey limestone - top
MDS03-022	CM1	OFP	GSM-1	Carbonate-cemented sandstone - siltstone
MDS03-023	CM1	OFP	WMM-2	Dark grey carbonate-rich siltstone
MDS03-024	CM1	OFP	WMM-5	Carbonate-cemented sandstone
MDS03-025	CM1	OFP	WMM-4	Carbonate-cemented sandstone
MDS03-026	CM1	OFP	WMM-2	Pyritic grey mudstone
MDS03-027	CM1	OFP	WMM-4	Carbonate-cemented sandstone
MDS03-028	CM1	OFP	WMM-6	Cone-in-cone carbonate structures
MDS03-029	CM1	OFP	WMM-6	Carbonate-cemented contact zone
MDS03-030	CM1	Kaza	Upper	Grey pyritic mudstone

Sample name	Sxn.	Grp./Fm.	Unit/Fcs.	Sample description
<i>MDS 2004 samples</i>				
MDS04-001	JP1	OFF	TLM-1	Purple siltstone
MDS04-002	JP1	OFF	TLM-2	Pink dolomite-cemented sandstone
MDS04-003	JP1	OFF	TLM-3	Pink limestone
MDS04-004	JP1	OFF	TLM-3	Grey pyritic limestone
MDS04-005	JP1	OFF	TLM-3	Pyrite cubes, 1-2 mm in size
MDS04-006	JP1	OFF	GSM-1	Dark grey limestone
MDS04-007	JP1	OFF	GSM-1	Black mudstone
MDS04-008	JP1	OFF	GSM-1	Black pyritic mudstone
MDS04-009	JP1	OFF	GSM-1	Dark grey limestone
MDS04-010	JP1	OFF	GSM-1	Black mudstone
MDS04-011	JP1	OFF	GSM-2	Black mudstone clast (breccia)
MDS04-012	JP1	OFF	WMM-8	Quartz-matrix breccia, limestone clast
MDS04-013	JP1	OFF	WMM-3	Green carbonate
MDS04-014	JP3	OFF	WMM-2	Blue-grey siltstones
MDS04-015	JP3	OFF	WMM-2	Green-grey siltstones
MDS04-016	JP3	OFF	WMM-1	Carbonate clast (breccia)
MDS04-017A	JP3	OFF	WMM-1	Brown sandy dolomite clast (breccia)
MDS04-017B	JP3	OFF	WMM-1	Grey carbonate clast (breccia)
MDS04-017C	JP3	OFF	WMM-1	Grey carbonate clast (breccia)
MDS04-018	JP3	OFF	WMM-3	Grey carbonate-cemented sandstone
MDS04-019	JP4	OFF	TLM-3	Pink limestone
MDS04-020	JP4	OFF	TLM-3	Grey limestone
MDS04-021	LL8	Miette	Corral Ck.	Grey siltstone - mudstone
MDS04-022	LL2	Miette	Corral Ck.	Ooid carbonate clast (breccia)
MDS04-023	LL4	Miette	Corral Ck.	Grey siltstone - mudstone
MDS04-024	LL4	Miette	Corral Ck.	Grey siltstone - mudstone
MDS04-025	LL4	Miette	Corral Ck.	Brown sandy dolomite clast (breccia)
MDS04-026	LL4	OFF	WMM-1	Grey limestone clast (green breccia)
MDS04-027	LL4	OFF	WMM-1	Pink limestone clast (purple breccia)
MDS04-028A	LL4	OFF	WMM-8	Dolomitized microbial-mat clast (breccia)
MDS04-028B	LL4	OFF	WMM-8	Carbonate-cemented breccia
MDS04-028C	LL4	OFF	WMM-8	Pink limestone clast (breccia)
MDS04-028D	LL4	OFF	WMM-8	Brown sandy dolomite clast (breccia)
MDS04-028E	LL4	OFF	WMM-8	Pink limestone clast (breccia)
MDS04-029	LL4	OFF	WMM-2	Blue-green mudstone
MDS04-030	LL4	OFF	WMM-2	Purple siltstone
MDS04-031	LL4	OFF	WMM-2	Purple-green siltstone transition
MDS04-032A	LL4	OFF	WMM-1	Pink limestone clast (purple breccia)
MDS04-032B	LL4	OFF	WMM-1	Pink limestone clast (purple breccia)
MDS04-032C	LL4	OFF	WMM-1	Pink limestone clast (purple breccia)
MDS04-033A	LL4	OFF	WMM-1	Carbonate clast (green breccia)
MDS04-033B	LL4	OFF	WMM-1	Carbonate clast (green breccia)
MDS04-034	LL4	OFF	WMM-8	Brown sandy carbonate-cemented breccia
MDS04-035	LL4	OFF	WMM-3	Brown carbonate-cemented sandstone

Sample name	Sxn.	Grp./Fm.	Unit/Fcs.	Sample description
MDS04-036	LL4	OFp	WMM-3	Brown carbonate-cemented sandstone
MDS04-037	LL4	OFp	WMM-2	Green siltstone
MDS04-038A	LL4	OFp	WMM-2	Purple siltstone
MDS04-038B	LL4	OFp	WMM-2	Purple siltstone
MDS04-039	LL4	OFp	WMM-2	Green siltstone
MDS04-040A	LL4	OFp	WMM-3	Brown carbonate-cemented sandstone
MDS04-040B	LL4	OFp	WMM-3	Brown carbonate-cemented sandstone
MDS04-041	LL4	OFp	WMM-2	Green siltstone
MDS04-042	LL4	OFp	WMM-2	Grey siltstone
MDS04-043	LL4	Miette	Hector	Grey siltstone - mudstone
MDS04-044	LL4	Miette	Hector	Grey siltstone - mudstone
MDS04-045	LL4	Miette	Hector	Grey siltstone - mudstone
MDS04-046A	LL4	OFp	WMM-8	Pink limestone clast (breccia)
MDS04-046B	LL4	OFp	WMM-8	Dark grey limestone clast (breccia)
MDS04-046C	LL4	OFp	WMM-8	Dark grey limestone clast (breccia)
MDS04-046D	LL4	OFp	WMM-8	Dark grey limestone clast (breccia)
MDS04-047A	LL4	OFp	WMM-8	Grey limestone clast (breccia)
MDS04-047B	LL4	OFp	WMM-8	Grey limestone clast (breccia)
MDS04-048	LL1	OFp	TLM-1	Purple siltstone
MDS04-049A	LL1	OFp	TLM-2	Purple dolomite-cemented sandstone
MDS04-049B	LL1	OFp	TLM-2	Purple dolomite-cemented sandstone
MDS04-050	LL1	OFp	TLM-1	Purple siltstone
MDS04-051	LL1	OFp	TLM-1	Purple siltstone
MDS04-052	LL1	OFp	TLM-3	Pink limestone
MDS04-053	LL1	OFp	TLM-3	Pink limestone
MDS04-054	LL1	OFp	TLM-3	Pink limestone
MDS04-055	LL1	OFp	TLM-3	Pink limestone
MDS04-056	LL1	OFp	TLM-3	Pink limestone
MDS04-057	LL1	OFp	TLM-1	Pink limestone
MDS04-058	LL1	OFp	TLM-3	Pink limestone
MDS04-059	LL1	OFp	TLM-3	Pink limestone
MDS04-060A	LL1	OFp	TLM-4	Pink limestone clast (breccia)
MDS04-060B	LL1	OFp	TLM-4	Pink limestone
MDS04-061	LL1	OFp	TLM-3	Pink limestone
MDS04-062	LL1	OFp	TLM-4	Pink limestone clast (breccia)
MDS04-063	LL1	OFp	TLM-3	Pink limestone
MDS04-064	LL1	OFp	TLM-3	Pink limestone
MDS04-065	LL1	OFp	TLM-1	Purple siltstone
MDS04-066	LL1	OFp	TLM-4	Pink limestone clast (breccia)
MDS04-067	LL1	OFp	TLM-3	Pink sandy carbonate
MDS04-068	LL1	OFp	TLM-4	Pink limestone clast (breccia)
MDS04-069	LL1	OFp	TLM-3	Pink limestone
MDS04-070A	LL1	OFp	TLM-3	Pink limestone
MDS04-070B	LL1	OFp	TLM-3	Purple siltstone
MDS04-070C	LL1	OFp	TLM-3	Purple siltstone
MDS04-071	LL1	OFp	TLM-3	Pink limestone

Sample name	Sxn.	Grp./Fm.	Unit/Fcs.	Sample description
MDS04-072	LL1	OFP	TLM-3	Pink limestone
MDS04-073	LL1	OFP	TLM-3	Pink limestone
MDS04-074	LL1	OFP	TLM-3	Pink limestone
MDS04-075	LL1	OFP	TLM-3	Pink limestone
MDS04-076	LL1	OFP	TLM-3	Pink limestone
MDS04-077	LL1	OFP	TLM-3	Pink limestone
MDS04-078	LL1	OFP	TLM-3	Pink limestone
MDS04-079	LL1	OFP	TLM-3	Pink limestone
MDS04-080	LL1	OFP	TLM-3	Pink limestone
MDS04-081	LL1	OFP	TLM-3	Pink limestone
MDS04-082	LL1	OFP	TLM-3	Pink limestone
MDS04-083	LL1	OFP	TLM-3	Pink limestone
MDS04-084	LL1	OFP	TLM-3	Pink limestone
MDS04-085	LL1	OFP	TLM-3	Pink limestone
MDS04-086	LL1	OFP	TLM-3	Pink limestone
MDS04-087	LL1	OFP	TLM-3	Pink limestone
MDS04-088	LL1	OFP	TLM-4	Pink limestone clast (breccia)
MDS04-089	LL1	OFP	TLM-3	Purple siltstone
MDS04-090	LL1	OFP	TLM-3	Pink limestone
MDS04-091	LL1	OFP	TLM-3	Pink limestone
MDS04-092	LL1	OFP	TLM-3	Pink limestone
MDS04-093	LL1	OFP	TLM-3	Pink limestone
MDS04-094	LL1	OFP	TLM-3	Pink limestone
MDS04-095	LL1	OFP	TLM-3	Pink limestone
MDS04-096	LL1	OFP	TLM-3	Pink limestone
MDS04-097	LL1	OFP	TLM-3	Pink limestone
MDS04-098	LL1	OFP	TLM-3	Grey limestone
MDS04-099	LL1	OFP	TLM-3	Grey limestone
MDS04-100	LL1	OFP	TLM-3	Grey limestone
MDS04-101	LL1	OFP	TLM-3	Grey limestone
MDS04-102	LL1	OFP	TLM-3	Grey limestone
MDS04-103	LL1	OFP	TLM-3	Grey limestone
MDS04-104	LL1	OFP	TLM-3	Grey limestone
MDS04-105	LL1	OFP	TLM-3	Grey siltstone
MDS04-106	LL1	OFP	TLM-3	Grey limestone
MDS04-107	LL1	OFP	TLM-3	Grey limestone
MDS04-108	LL1	OFP	TLM-3	Grey limestone
MDS04-109	LL1	OFP	GSM-1	Dark grey limestone
MDS04-110	LL1	OFP	GSM-1	Dark grey limestone
MDS04-111	LL1	OFP	GSM-1	Black rusty weathered mudstone
MDS04-112	LL1	OFP	GSM-1	Black mudstone
MDS04-113A	LL5	Miette	Corral Ck.	Brown sandy dolomite clast (conglomerate)
MDS04-113B	LL5	Miette	Corral Ck.	Black phosphate clast (conglomerate)
MDS04-114A	LL5	Miette	Corral Ck.	Brown sandy dolomite clast (conglomerate)
MDS04-114B	LL5	Miette	Corral Ck.	Dark grey mudstone clast (conglomerate)
MDS04-114C	LL5	Miette	Corral Ck.	Dark grey mudstone clast (conglomerate)

Sample name	Sxn.	Grp./Fm.	Unit/Fcs.	Sample description
MDS04-115	LL5	Miette	Corral Ck.	Grey siltstone - mudstone
MDS04-116	LL5	Miette	Corral Ck.	Grey siltstone - mudstone
MDS04-117	LL5	OFP	TLM-1	Purple siltstone
MDS04-118	LL5	OFP	TLM-1	Purple siltstone
MDS04-119	LL5	OFP	TLM-1	Purple siltstone
MDS04-120	LL5	OFP	TLM-1	Purple siltstone
MDS04-121	LL5	OFP	TLM-1	Purple siltstone
MDS04-122	LL5	OFP	TLM-4	Pink limestone clast (breccia)
MDS04-123	LL5	OFP	TLM-2	Pink sandy carbonate
MDS04-124	LL5	OFP	TLM-1	Purple siltstone
MDS04-125	LL5	OFP	TLM-3	Pink sandy limestone
MDS04-126	LL5	OFP	TLM-3	Pink sandy limestone
MDS04-127	LL5	OFP	TLM-3	Pink sandy limestone
MDS04-128	LL5	OFP	TLM-3	Pink sandy limestone
MDS04-129	LL5	OFP	TLM-3	Pink sandy limestone
MDS04-130	LL5	OFP	TLM-3	Pink sandy limestone
MDS04-131	LL5	OFP	TLM-3	Pink sandy limestone
MDS04-132A	LL5	OFP	TLM-4	Pink limestone clast (breccia)
MDS04-132B	LL5	OFP	TLM-4	Pink limestone clast (breccia)
MDS04-133	LL5	OFP	TLM-1	Purple siltstone
MDS04-134	LL5	OFP	TLM-3	Pink sandy limestone
MDS04-135	LL5	OFP	TLM-4	Pink limestone clast (breccia)
MDS04-136A	LL5	OFP	TLM-4	Pink limestone clast (breccia)
MDS04-136B	LL5	OFP	TLM-4	Pink limestone clast (breccia)
MDS04-137	LL5	OFP	TLM-4	Pink limestone clast (breccia)
MDS04-138	LL5	OFP	TLM-3	Pink limestone
MDS04-139A	LL5	OFP	TLM-4	Pink limestone clast (breccia)
MDS04-139B	LL5	OFP	TLM-4	Pink limestone clast (breccia)
MDS04-140A	LL5	OFP	TLM-3	Pink limestone
MDS04-140B	LL5	OFP	TLM-3	Pink limestone
MDS04-141	LL5	OFP	TLM-3	Grey limestone
MDS04-142	LL5	OFP	TLM-3	Grey limestone
MDS04-143	LL5	OFP	TLM-3	Pink limestone
MDS04-144	LL5	OFP	TLM-3	Pink limestone
MDS04-145	LL5	OFP	TLM-3	Grey sandy limestone
MDS04-146	LL5	OFP	TLM-3	Grey limestone
MDS04-147	LL5	OFP	TLM-3	Grey limestone
MDS04-148	LL5	OFP	TLM-3	Grey limestone
MDS04-149	LL5	OFP	TLM-3	Grey limestone
MDS04-150	LL5	OFP	TLM-3	Grey limestone
MDS04-151	LL5	OFP	TLM-3	Grey limestone
MDS04-152	LL5	OFP	TLM-3	Grey limestone
MDS04-153	LL5	OFP	TLM-4	Grey limestone clast (breccia)
MDS04-154	LL5	OFP	TLM-3	Grey limestone
MDS04-155	LL5	OFP	TLM-3	Grey limestone
MDS04-156A	LL5	OFP	TLM-3	Grey limestone

Sample name	Sxn.	Grp./Fm.	Unit/Fcs.	Sample description
MDS04-156B	LL5	OFF	TLM-3	Grey limestone
MDS04-156C	LL5	OFF	TLM-3	Grey limestone
MDS04-157	LL5	OFF	TLM-3	Grey limestone
MDS04-158	LL5	OFF	TLM-3	Grey limestone
MDS04-159	LL5	OFF	TLM-3	Grey limestone
MDS04-160	LL5	OFF	TLM-3	Grey limestone
MDS04-161	LL5	OFF	TLM-3	Grey limestone
MDS04-162	LL5	OFF	TLM-3	Grey limestone
MDS04-163	LL5	OFF	TLM-3	Grey limestone
MDS04-164	LL5	OFF	GSM-1	Grey limestone
MDS04-165	LL5	OFF	GSM-1	Dark grey limestone
MDS04-166	LL5	Miette	Hector	Grey mudstone - siltstone
MDS04-167	LL5	Miette	Hector	Grey mudstone - siltstone
MDS04-168	LL5	Miette	Hector	Grey mudstone - siltstone
MDS04-169	LL4	Miette	Hector	Grey mudstone - siltstone
MDS04-170	LL5	Miette	Hector	Carbonate diagenetic nodule
MDS04-171	LL5	OFF	TLM-1	Green reduction halo in purple siltstone
MDS04-172	MR1	Miette	Middle	Grey siltstone - mudstone
MDS04-173	MR1	Miette	Middle	Grey siltstone - mudstone
MDS04-174	MR1	Miette	Middle	Grey siltstone - mudstone
MDS04-175	MR1	Miette	Middle	Grey-green siltstone - mudstone
MDS04-176	MR1	OFF	TLM-1	Green siltstone
MDS04-177A	MR1	OFF	TLM-1	Green sandstone
MDS04-177B	MR1	OFF	TLM-1	Green siltstone
MDS04-178	MR1	OFF	TLM-2	Pyrite-rich green sandstone
MDS04-179	MR1	OFF	TLM-1	Pyrite cubes
MDS04-180	MR1	OFF	TLM-1	Pyrite cubes
MDS04-181	MR1	OFF	TLM-1	Pyrite cubes
MDS04-182	MR1	OFF	TLM-1	Pyrite-rich green sandstone
MDS04-183	MR1	OFF	TLM-1	Green siltstone
MDS04-184	MR1	OFF	TLM-2	Pyrite-rich green sandstone
MDS04-185	MR1	OFF	TLM-2	Pyrite-rich green sandstone
MDS04-186	MR1	OFF	TLM-1	Green siltstone
MDS04-187	MR1	OFF	TLM-2	White sandstone
MDS04-188A	MR1	OFF	TLM-2	Brown dolomitic sandstone
MDS04-188B	MR1	OFF	TLM-1	Brown dolomitic siltstone
MDS04-189	MR1	OFF	TLM-1	Pyrite cubes
MDS04-190	MR1	OFF	TLM-2	Pyrite cubes
MDS04-191A	MR1	OFF	TLM-1	Pyrite cubes
MDS04-191B	MR1	OFF	TLM-1	Pyrite cubes
MDS04-192	MR1	OFF	TLM-1	Pyrite cubes
MDS04-193	MR1	OFF	TLM-1	Pyrite-rich brown dolomitic siltstone
MDS04-194	MR1	OFF	TLM-3	White pyritic limestone
MDS04-195	MR1	OFF	TLM-4	White limestone clast (breccia)
MDS04-196	MR1	OFF	TLM-3	White limestone
MDS04-197	MR1	OFF	TLM-3	White limestone

Sample name	Sxn.	Grp./Fm.	Unit/Fcs.	Sample description
MDS04-198	MR1	OFP	TLM-3	White limestone
MDS04-199	MR1	OFP	TLM-3	White limestone
MDS04-200	MR1	OFP	TLM-3	White limestone
MDS04-201	MR1	OFP	TLM-3	White limestone
MDS04-202	MR1	OFP	TLM-3	Brown dolomitic siltstone
MDS04-203	MR1	OFP	TLM-3	White limestone
MDS04-204	MR1	OFP	TLM-3	White limestone
MDS04-205	MR1	OFP	TLM-3	White pyritic limestone
MDS04-206	MR1	OFP	TLM-3	White limestone
MDS04-207	MR1	OFP	TLM-3	White limestone
MDS04-208	MR1	OFP	GSM-1	Black shaly mudstone
MDS04-209	MR1	OFP	GSM-1	Black shaly mudstone
MDS04-210	MR1	Miette	Middle	Grey siltstone - mudstone
MDS04-211	MR1	Miette	Middle	Grey siltstone - mudstone
MDS04-212	CM1	Kaza	Middle	Green pelite/mudstone
MDS04-213	CM1	OFP	TLM-1	Carbonate-cemented sandstone
MDS04-214	CM1	OFP	TLM-2	Carbonate-cemented sandstone
MDS04-215	CM1	OFP	TLM-2	Carbonate-cemented sandstone
MDS04-216	CM1	OFP	TLM-2	Carbonate-cemented sandstone
MDS04-217	CM1	OFP	TLM-2	Carbonate-cemented sandstone
MDS04-218	CM1	OFP	TLM-2	Carbonate-cemented sandstone
MDS04-219	CM1	OFP	TLM-2	Grey siltstone
MDS04-220	CM1	OFP	TLM-2	Grey limestone
MDS04-221	CM1	OFP	TLM-3	Grey limestone
MDS04-222	CM1	OFP	TLM-3	Grey limestone
MDS04-223	CM1	OFP	TLM-3	Grey limestone
MDS04-224	CM1	OFP	TLM-3	Grey limestone
MDS04-225	CM1	OFP	TLM-3	Grey limestone
MDS04-226	CM1	OFP	TLM-3	Grey limestone
MDS04-227	CM1	OFP	TLM-3	Grey limestone
MDS04-228	CM1	OFP	TLM-3	Grey limestone
MDS04-229	CM1	OFP	TLM-3	Grey limestone
MDS04-230	CM1	OFP	TLM-3	Grey limestone
MDS04-231	CM1	OFP	TLM-3	Grey limestone
MDS04-232	CM1	OFP	TLM-3	Grey limestone
MDS04-233	CM1	OFP	GSM-1	Boudin dark grey limestone
MDS04-234A	CM1	OFP	GSM-1	Boudin dark grey limestone
MDS04-234B	CM1	OFP	GSM-1	Blue-grey pelite/mudstone
MDS04-235	CM1	OFP	GSM-1	Dark grey limestone
MDS04-236	CM1	OFP	GSM-1	Black pelite/mudstone
MDS04-237	CM1	OFP	WMM-6	Grey limestone
MDS04-238	CM1	OFP	WMM-6	Grey limestone
MDS04-239	CM1	OFP	WMM-6	Grey limestone
MDS04-240	CM1	OFP	WMM-5	Calcareous sandstone
MDS04-241	CM1	OFP	WMM-8	Grey limestone
MDS04-242	CM1	OFP	WMM-6	Grey limestone

Sample name	Sxn.	Grp./Fm.	Unit/Fcs.	Sample description
MDS04-243	CM1	OFF	WMM-2	Carbonate-cemented siltstone-mudstone
MDS04-244	CM1	OFF	WMM-4	Carbonate-cemented sandstone
MDS04-245	CM1	OFF	WMM-5	Carbonate-cemented sandstone
MDS04-246	CM1	OFF	WMM-6	Cone-in-cone carbonate structures
MDS04-247	CM1	OFF	WMM-4	Pyrite cubes
MDS04-248	CM1	OFF	WMM-5	Carbonate-cemented sandstone
MDS04-249A	CM1	OFF	WMM-6	Dark grey limestone
MDS04-249B	CM1	OFF	WMM-6	Dark grey limestone
MDS04-250	CM1	Kaza	Upper	Grey mudstone

MDS 2005 samples

MDS05-001	LL2	Miette	Corral Ck.	Black pyritic mudstone
MDS05-002	LL2	Miette	Corral Ck.	Black pyritic mudstone
MDS05-003	LL2	Miette	Corral Ck.	Black pyritic mudstone
MDS05-004	LL2	OFF	WMM-2	Blue-green mudstone
MDS05-005	LL2	OFF	WMM-2	Green siltstone near purple-green transition
MDS05-006	LL5	OFF	TLM-1	Purple siltstone
MDS05-007	LL5	OFF	GSM-1	Black mudstone
MDS05-008	LL5	OFF	GSM-1	Black mudstone
MDS05-009	LL5	OFF	GSM-1	Black mudstone
MDS05-010	LL5	OFF	GSM-1	Black mudstone
MDS05-011	LL5	Miette	Hector	Black siltstone - mudstone
MDS05-012	LL6	OFF	GSM-1	Black mudstone
MDS05-013	LL6	OFF	GSM-1	Black mudstone
MDS05-014	LL6	Miette	Hector	Black mudstone
MDS05-015	LL6	Miette	Hector	Black mudstone
MDS05-016	LL8	OFF	TLM-1	Purple mudstone, discoid structures
MDS05-017	LL7	OFF	WMM-2	Purple-green siltstone transition
MDS05-018	LL7	OFF	WMM-2	Green siltstone
MDS05-019	LL7	OFF	WMM-2	Purple siltstone
MDS05-020	CM2	OFF	TLM-3	Grey limestone
MDS05-021	CM2	OFF	GSM-1	Blue-grey pelite/mudstone
MDS05-022	CM2	OFF	GSM-1	Dark grey limestone
MDS05-023	CM2	OFF	GSM-1	Black pelite/mudstone
MDS05-024	CM2	OFF	GSM-1	Dark grey limestone
MDS05-025	CM2	OFF	GSM-1	Black pelite/mudstone
MDS05-026	CM2	Kaza	Middle	Grey mudstone, non-pyritic
MDS05-027	CM2	Kaza	Middle	Grey mudstone, pyritic
MDS05-028	CM2	Kaza	Middle	Grey mudstone, non-pyritic
MDS05-029	CM2	Kaza	Middle	Grey mudstone, pyritic
MDS05-030	CM2	Kaza	Middle	Grey mudstone, pyritic
MDS05-031	CM2	Kaza	Middle	Grey mudstone, pyritic
MDS05-032	CM2	Kaza	Middle	Grey mudstone, pyritic
MDS05-033	CM2	Kaza	Middle	Grey mudstone, pyritic
MDS05-034	CM2	Kaza	Middle	Grey mudstone, pyritic

Sample name	Sxn.	Grp./Fm.	Unit/Fcs.	Sample description
MDS05-035	CM2	Kaza	Middle	Grey mudstone, pyritic
MDS05-036	CM2	Kaza	Middle	Grey mudstone, pyrite-poor
MDS05-037	CM2	Kaza	Middle	Green mudstone, pyritic
MDS05-038	CM2	Kaza	Middle	Green mudstone, ankeritic
MDS05-039	CM2	Kaza	Middle	Grey mudstone, pyritic
MDS05-040	CM2	Kaza	Middle	Green mudstone
MDS05-041	CM2	Kaza	Middle	Green mudstone
MDS05-042	CM2	Kaza	Middle	Green mudstone
MDS05-043	CM2	Kaza	Middle	Green mudstone
MDS05-044	PM1A	HTC	Lwr Pelite	Grey siltstone - mudstone
MDS05-045	PM1A	HTC	Lwr Pelite	Grey siltstone - mudstone
MDS05-046	PM1A	HTC	Lwr Pelite	Grey pyritic siltstone - mudstone
MDS05-047	PM1A	HTC	Lwr Pelite	Grey pyritic siltstone - mudstone
MDS05-048	PM1A	HTC	Lwr Pelite	Grey pyritic siltstone - mudstone
MDS05-049	PM1A	HTC	Lwr Pelite	Grey siltstone - mudstone
MDS05-050	PM1A	OFF	TLM-2	Brown carbonate-cemented sandstone
MDS05-051	PM1A	OFF	TLM-2	Brown carbonate-cemented sandstone
MDS05-052	PM1A	OFF	TLM-2	Brown carbonate-cemented sandstone
MDS05-053	PM1A	OFF	TLM-2	Brown pyrite-rich sandstone
MDS05-054	PM1A	OFF	TLM-2	Brown dolomitic sandstone
MDS05-055	PM1A	OFF	TLM-2	Brown dolomitic siltstone
MDS05-056	PM1A	-	-	Secondary quartz-calcite vein
MDS05-057	PM1A	OFF	TLM-3	White limestone
MDS05-058	PM1A	OFF	TLM-3	White limestone
MDS05-059	PM1A	OFF	TLM-3	White limestone
MDS05-060	PM1A	OFF	TLM-3	White limestone
MDS05-061	PM1A	OFF	TLM-3	White limestone
MDS05-062	PM1A	OFF	TLM-3	White limestone
MDS05-063	PM1A	OFF	TLM-3	White limestone
MDS05-064	PM1A	OFF	TLM-3	White limestone
MDS05-065	PM1A	OFF	TLM-3	Pyrite vein at brown-green transition
MDS05-066	PM1B	OFF	TLM-2	Pyrite-rich green siltstone
MDS05-067	PM1B	OFF	GSM-1	Dark grey siltstone-mudstone
MDS05-068	PM1B	OFF	GSM-1	Dark grey siltstone-mudstone
MDS05-069	PM1B	OFF	GSM-1	Dark grey siltstone-mudstone
MDS05-070	PM1B	OFF	GSM-1	Dark grey siltstone-mudstone
MDS05-071	PM1B	OFF	GSM-1	Dark grey siltstone-mudstone
MDS05-072	PM1B	OFF	GSM-1	Dark grey siltstone-mudstone
MDS05-073	PM1B	OFF	GSM-1	Dark grey siltstone-mudstone
MDS05-074	PM1B	OFF	GSM-1	Dark grey siltstone-mudstone
MDS05-075	PM1B	OFF	GSM-1	Brown carbonate-cemented sandstone
MDS05-076	PM1B	OFF	GSM-1	Dark grey siltstone-mudstone
MDS05-077	PM1B	OFF	GSM-1	Dark grey siltstone-mudstone
MDS05-078	PM1B	OFF	GSM-1	Dark grey sandstone-siltstone
MDS05-079	PM1B	OFF	WMM-2	Bright green siltstones
MDS05-080	PM1B	OFF	WMM-6	Pink limestone

Sample name	Sxn.	Grp./Fm.	Unit/Fcs.	Sample description
MDS05-081	PM1B	OFP	WMM-2	Grey pyrite-rich siltstone
MDS05-082	PM1B	OFP	WMM-2	Grey pyrite-rich siltstone
MDS05-083	PM1C	OFP	WMM-7	Black pelite/mudstone
MDS05-084	PM1C	OFP	WMM-7	Black pelite/mudstone
MDS05-085	PM1C	OFP	WMM-3	Carbonate-cemented sandstone
MDS05-086	PM1C	OFP	WMM-6	Dark grey carbonate
MDS05-087	PM1C	OFP	WMM-7	Black pelite/mudstone
MDS05-088	PM1C	OFP	WMM-6	Dark grey carbonate
MDS05-089	PM1C	OFP	WMM-6	Dark grey carbonate
MDS05-090	PM1C	OFP	WMM-7	Black pelite/mudstone
MDS05-091	PM1C	OFP	WMM-6	Dark grey carbonate
MDS05-092	PM1C	OFP	WMM-7	Black pelite/mudstone
MDS05-093	PM1C	OFP	WMM-6	Dark grey limestone
MDS05-094	PM1C	OFP	WMM-6	Dark grey limestone
MDS05-095	PM1C	OFP	WMM-5	Dark sandy limestone
MDS05-096A	PM1C	OFP	WMM-5	Dark sandy limestone
MDS05-096B	PM1C	OFP	WMM-7	Calcareous dark grey mudstone
MDS05-097	PM1C	OFP	WMM-6	Dark grey limestone
MDS05-098	PM1C	OFP	WMM-6	Dark grey limestone
MDS05-099	PM1C	OFP	WMM-7	Calcareous dark grey mudstone
MDS05-100	PM1C	OFP	WMM-6	Dark grey limestone
MDS05-101	PM1C	OFP	WMM-6	Dark grey limestone
MDS05-102	PM1C	OFP	WMM-6	Dark grey limestone
MDS05-103A	PM1C	OFP	WMM-6	Dark grey limestone
MDS05-103B	PM1C	OFP	WMM-6	Dark grey limestone
MDS05-103C	PM1C	OFP	WMM-6	Dark grey limestone
MDS05-103D	PM1C	OFP	WMM-6	Dark grey limestone
MDS05-104	PM1C	OFP	WMM-7	Calcareous dark grey mudstone
MDS05-105	PM1C	OFP	WMM-6	Dark grey limestone
MDS05-106	PM1C	OFP	WMM-5	Dark sandy limestone
MDS05-107A	PM1C	OFP	WMM-5	Dark sandy limestone
MDS05-107B	PM1C	OFP	WMM-5	Dark grey limestone
MDS05-108	PM1C	OFP	WMM-5	Sandy limestone
MDS05-109	PM1C	OFP	WMM-6	Dark grey limestone
MDS05-110	PM1C	OFP	WMM-6	Dark grey limestone
MDS05-111A	PM1C	OFP	WMM-8	Dark grey limestone clast (breccia)
MDS05-111B	PM1C	OFP	WMM-8	Black mudstone clast (breccia)
MDS05-112	PM1C	OFP	WMM-3	Black rusty-weathered mudstone
MDS05-113	PM1C	OFP	WMM-8	Dark grey limestone clast (breccia)
MDS05-114	PM1C	HTC	Upper Grit	Pyrite-rich grey mudstones
MDS05-115	PM1C	HTC	Upper Grit	Grey mudstone - siltstone
MDS05-116	PM1C	HTC	Upper Grit	Grey mudstone - siltstone
MDS05-117	JP3	OFP	WMM-1	Carbonate-clast green-grey breccia
MDS05-118	JP1	OFP	TLM-2	Pink sandy carbonate
MDS05-119	JP1	OFP	TLM-3	Pink limestone
MDS05-120	JP1	OFP	TLM-3	Pink limestone

Sample name	Sxn.	Grp./Fm.	Unit/Fcs.	Sample description
MDS05-121	JP1	OFF	TLM-3	Pink limestone
MDS05-122	JP1	OFF	TLM-3	Purple-green contact transition
MDS05-123	MR2	OFF	TLM-1	Green siltstone
MDS05-124	MR2	OFF	TLM-1	Pyrite cubes from green-brown transition
MDS05-125	MR2	OFF	TLM-1	Brown pyritic siltstone
MDS05-126	MR2	OFF	TLM-3	White limestone
MDS05-127	MR2	OFF	TLM-3	White limestone
MDS05-128A	MR2	OFF	GSM-1	Black shaly mudstone
MDS05-128B	MR2	OFF	GSM-1	Black shaly mudstone
MDS05-129	MR2	OFF	WMM-2	Grey mudstone, pyrite-rich
MDS05-130A	MR2	OFF	WMM-8	Dark limestone clast (breccia)
MDS05-130B	MR2	OFF	WMM-8	Dark limestone clast (breccia)
MDS05-130C	MR2	OFF	WMM-8	Brown sandy dolomite clast (breccia)
MDS05-131	MK1	Miette	Middle	Blue-grey siltstone - mudstone
MDS05-132	MK1	Miette	Middle	Dark grey mudstone
MDS05-133A	MK1	OFF	WMM-8	Coarse-sand breccia matrix
MDS05-133B	MK1	OFF	WMM-8	Rusty brown dolomite clast (breccia)
MDS05-133C	MK1	OFF	WMM-8	Dark grey limestone clast (breccia)
MDS05-133D	MK1	OFF	WMM-8	Laminated beige dolomite clast (breccia)
MDS05-133E	MK1	OFF	WMM-8	Ooid-rich carbonate clast (breccia)
MDS05-133F	MK1	OFF	WMM-8	Quartz sandstone clast (breccia)
MDS05-133G	MK1	OFF	WMM-8	Rusty fine sandstone clast (breccia)
MDS05-134	MK1	OFF	WMM-7	Black mudstone
MDS05-135	MK1	OFF	WMM-7	Black mudstone
MDS05-136	MK1	OFF	WMM-7	Black calcareous mudstone
MDS05-137	MK1	OFF	WMM-6	Dark grey limestone
MDS05-138	MK1	OFF	WMM-6	Dark grey limestone
MDS05-139	MK1	OFF	WMM-6	Dark grey limestone
MDS05-140	MK1	OFF	WMM-6	Dark grey limestone
MDS05-141	MK1	OFF	WMM-5	Dark grey sandy limestone
MDS05-142	MK1	OFF	WMM-7	Dark grey mudstone
MDS05-143	MK1	OFF	WMM-7	Black calcareous mudstone
MDS05-144	MK1	OFF	WMM-5	Dark grey sandy limestone
MDS05-145	MK1	OFF	WMM-4	Coarse arenaceous sandstone
MDS05-146	MK1	OFF	WMM-5	Carbonate-cemented sandstone
MDS05-147	MK1	OFF	WMM-6	Dark grey limestone
MDS05-148	MK1	-	-	Secondary quartz-calcite vein
MDS05-149	MK1	OFF	WMM-6	Dark grey limestone
MDS05-150A	MK1	OFF	WMM-6	Dark grey limestone
MDS05-150B	MK1	OFF	WMM-2	Dark grey mudstone
MDS05-151	MK1	OFF	WMM-5	Dark grey sandy limestone
MDS05-152	MK1	Miette	Middle	Grey siltstone - mudstone
MDS05-153	MK1	Miette	Middle	Grey siltstone - mudstone
MDS05-154	LL1	OFF	GSM-1	Black mudstone
MDS05-155	LL1	Miette	Hector	Black siltstone - mudstone
MDS05-156	LL1	Miette	Hector	Black siltstone - mudstone

Sample name	Sxn.	Grp./Fm.	Unit/Fcs.	Sample description
MDS05-157	LL1	Miette	Hector	Black siltstone - mudstone
MDS05-158	LL1	Miette	Hector	Grey siltstone - mudstone
MDS05-159	LL1	Miette	Hector	Grey siltstone - mudstone
MDS05-160	LL1	Miette	Hector	Grey siltstone - mudstone
MDS05-161	LL1	Miette	Hector	Grey siltstone - mudstone
MDS05-162	LL1	Miette	Hector	Grey siltstone - mudstone
MDS05-163	LL4	Miette	Corral Ck.	Grey siltstone - mudstone
MDS05-164	LL4	Miette	Hector	Grey siltstone - mudstone
MDS05-165	LL4	Miette	Hector	Grey siltstone - mudstone
MDS05-166	LL4	Miette	Hector	Grey siltstone - mudstone
MDS05-167	LL4	Miette	Hector	Grey siltstone - mudstone

Other samples 1987, 2001, 2003, 2006

S87-31	CM1	OFF	GSM-1	Black mudstone/pelite
RAR-01-06	MR3	Miette	Upper	Black mudstone/pelite
RAR-01-07	JP5	Miette	Wynd	Grey siltstone - mudstone
RAR-01-08	JP5	Miette	Wynd	Grey siltstone - mudstone
RAR-01-09	JP5	Miette	Wynd	Grey siltstone - mudstone
RAR-01-11	JP7	Miette	Wynd	Grey siltstone - mudstone
RAR-01-12	JP7	Miette	Wynd	Grey siltstone - mudstone
RAR-01-13	JP7	Miette	Wynd	Grey siltstone - mudstone
RAR-01-14	JP7	Miette	Wynd	Grey siltstone - mudstone
RAR-01-17	JP7	Miette	Wynd	Grey siltstone - mudstone
RAR-01-22	JP1	OFF	TLM-1	Green mudstone
RAR-01-23	JP1	OFF	TLM-1	Purple siltstone
RAR-01-24	JP1	OFF	TLM-1	Purple siltstone
RAR-01-25A	JP1	OFF	TLM-2	Pink dolomite-cemented sandstone
RAR-01-25B	JP1	OFF	TLM-2	Pink dolomite-cemented sandstone
RAR-01-25C	JP1	OFF	TLM-2	Pink dolomite-cemented sandstone
RAR-01-25D	JP1	OFF	TLM-2	Pink dolomite-cemented sandstone
RAR-01-25E	JP1	OFF	TLM-2	Pink dolomite-cemented sandstone
RAR-01-25F	JP1	OFF	TLM-2	Pink dolomite-cemented sandstone
RAR-01-25G	JP1	OFF	TLM-2	Pink dolomite-cemented sandstone
RAR-01-25H	JP1	OFF	TLM-4	Pink sandy dolostone clast (breccia)
RAR-01-25I	JP1	OFF	TLM-2	Pink limestone
RAR-01-25J	JP1	OFF	TLM-3	Pink limestone
RAR-01-25K	JP1	OFF	TLM-4	Pink limestone clast (breccia)
RAR-01-25L	JP1	OFF	TLM-3	Pink limestone
RAR-01-25M	JP1	OFF	TLM-4	Pink limestone clast (breccia)
RAR-01-25N	JP1	OFF	TLM-3	Pink limestone
RAR-01-25O	JP1	OFF	TLM-3	Pink limestone
RAR-01-25P	JP1	OFF	TLM-3	Pink limestone, purple-green contact
RAR-01-25Q	JP1	OFF	TLM-3	Grey limestone
RAR-01-25R	JP1	OFF	TLM-3	Grey limestone
RAR-01-25S	JP1	OFF	TLM-3	Grey limestone

Sample name	Sxn.	Grp./Fm.	Unit/Fcs.	Sample description
RAR-01-25T	JP1	OFF	TLM-3	Grey limestone
RAR-01-25U	JP1	OFF	TLM-3	Grey limestone
RAR-01-25V	JP1	OFF	TLM-3	Grey limestone
RAR-01-25W	JP1	OFF	TLM-3	Grey limestone
RAR-01-25X	JP1	OFF	TLM-3	Grey limestone
RAR-01-25Y	JP1	OFF	GSM-1	Grey limestone
RAR-01-25Z	JP1	OFF	GSM-1	Lenoid, grey limestone
RAR-01-25AA	JP1	OFF	GSM-1	Black mudstone
RAR-01-25BB	JP1	OFF	GSM-1	Black mudstone
RAR-01-25CC	JP1	OFF	GSM-1	Black mudstone, shaly, pyritic
RAR-01-25DD	JP1	OFF	GSM-1	Black mudstone
RAR-01-25EE	JP1	OFF	GSM-1	Dark grey limestone
RAR-01-25FF	JP1	OFF	GSM-2	Black mudstone clast (breccia)
RAR-01-25GG	JP1	OFF	GSM-2	Black mudstone clast (breccia)
RAR-01-25HH	JP1	OFF	WMM-8	Dark grey limestone clast(s) (breccia)
RAR-01-25II	JP1	OFF	WMM-2	Green carbonate
RAR-01-25JJ	JP1	OFF	WMM-2	Green carbonate
RAR-01-25KK	JP1	OFF	WMM-2	Pyritic siltstone, gamma "hot-zone"
RAR-01-27	JP1	OFF	TLM-2	Purple carbonate-rich siltstone
RAR-01-28	JP1	OFF	TLM-2	Green carbonate-rich siltstone
RAR-01-29	JP1	OFF	GSM-1	Black pyritic mudstone
RAR-01-30	JP1	OFF	WMM-2	Grey-green siltstone
RAR-01-31	JP1	OFF	WMM-2	Grey-green siltstone
RAR-01-32	JP6	Miette	Wynd	Grey siltstone - mudstone
RAR-01-33	JP6	Miette	Wynd	Grey siltstone - mudstone
RAR-01-34	JP6	Miette	Wynd	Grey siltstone - mudstone
RAR-01-38	MR3	Miette	Upper	Grey siltstone - mudstone
RAR-01-39	MR3	Miette	Upper	Grey siltstone - mudstone
RAR-R01-12P	MR3	Miette	Upper	Grey siltstone - mudstone
RAR-R01-12S	MR3	Miette	Upper	Grey siltstone - mudstone
RAR-R01-12X	MR3	Miette	Upper	Grey siltstone - mudstone
RAR-R01-12Y	MR3	Miette	Upper	Grey siltstone - mudstone
RAR-R01-17	CM3	Kaza	Upper	Grey siltstone - mudstone
RAR-R01-21	CM3	Kaza	Upper	Grey siltstone - mudstone
RAR-R01-42	CM3	Kaza	Upper	Grey siltstone - mudstone
RAR-R01-43	CM3	Kaza	Upper	Grey siltstone - mudstone
RAR-R014-K	CM3	Isaac	base	Blue-grey siltstone - mudstone
RAR-R014-Q	CM3	Isaac	base	Blue-grey siltstone - mudstone
RAR-R014-Z	CM3	Isaac	C1	Blue-grey siltstone - mudstone
RAR-R014-DD	CM3	Isaac	C2	Blue-grey siltstone - mudstone
RAR-R01-54	CM3	Kaza	Upper	Grey siltstone - mudstone
RAR-R01-62	CM3	Kaza	Upper	Grey siltstone - mudstone
RAR-R01-120E	LL9	Miette	Corral Ck.	Grey siltstone - mudstone
RAR03-01A	CM1	Kaza	Upper	Grey limestone
RAR03-01B	CM1	Kaza	Upper	Grey limestone
RAR03-01C	CM1	Kaza	Upper	Grey limestone

Sample name	Sxn.	Grp./Fm.	Unit/Fcs.	Sample description
RAR03-01D	CM1	Kaza	Upper	Grey limestone
RAR03-01E	CM1	Kaza	Upper	Grey limestone
RAR03-01F	CM1	Kaza	Upper	Grey limestone
RAR03-01G	CM1	Kaza	Upper	Grey limestone
RAR03-01H	CM1	Kaza	Upper	Grey limestone
RAR03-01I	CM1	Kaza	Upper	Grey limestone
HT04019	CM3	Isaac	C1 top	Black pelite/mudstone
HT04024	CM3	Isaac	C3 top	Black pelite/mudstone
HT04028	CM3	Isaac	C5 base	Black pelite/mudstone
HT04030	CM3	Isaac	C5 top	Carbonate-rich black pelite/mudstone
JS06-019	PM2	OFP	GSM-1	Black mudstone, pyritic, magnetic

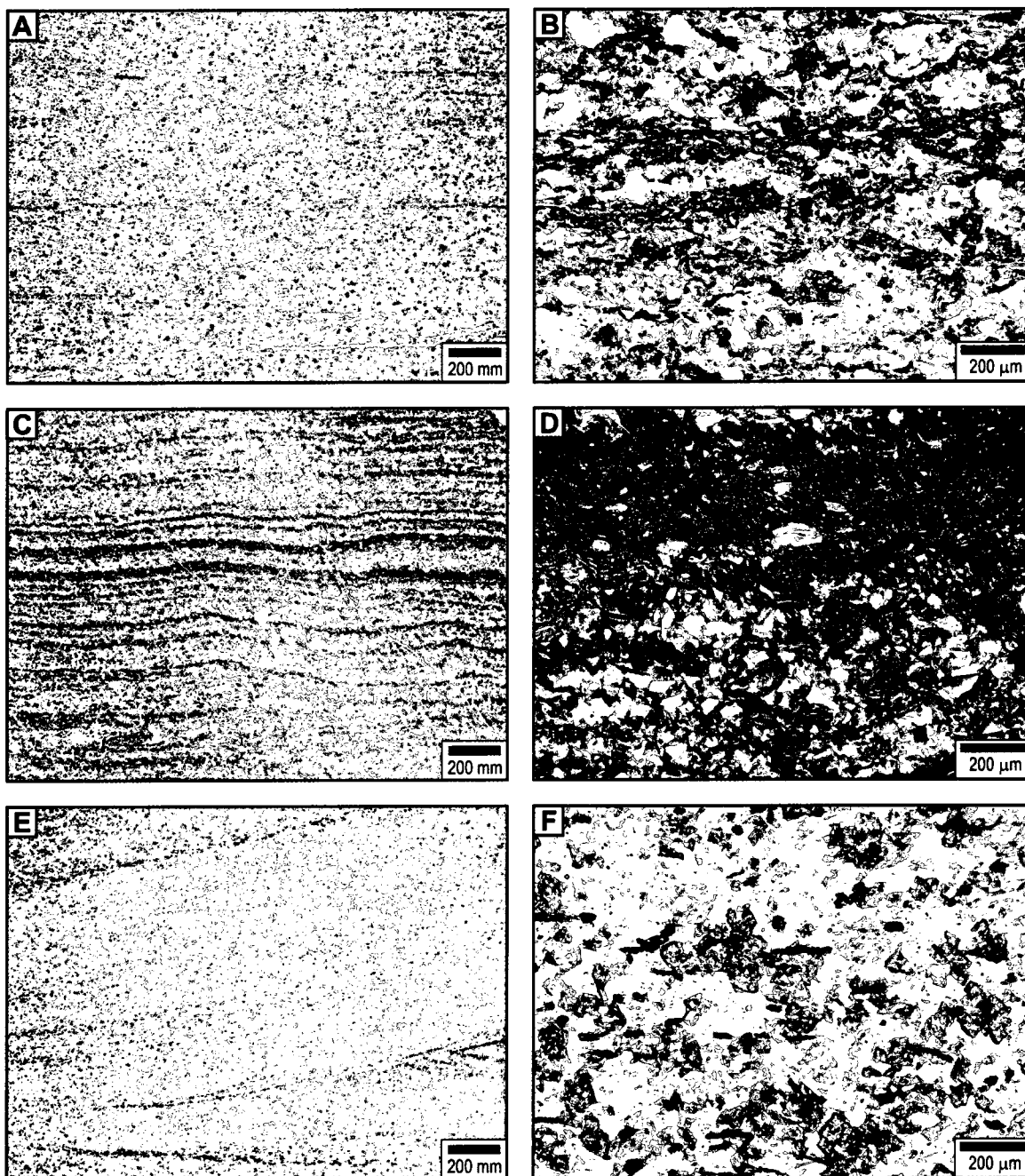
APPENDIX D: Stratigraphic section measurements and data from the Old Fort Point Formation, southern Canadian Cordillera.

See attached DVD for pdf files of individual stratigraphic sections.

APPENDIX E: Outcrop gamma-radiation measurements from the Old Fort Point Formation, southern Canadian Cordillera.

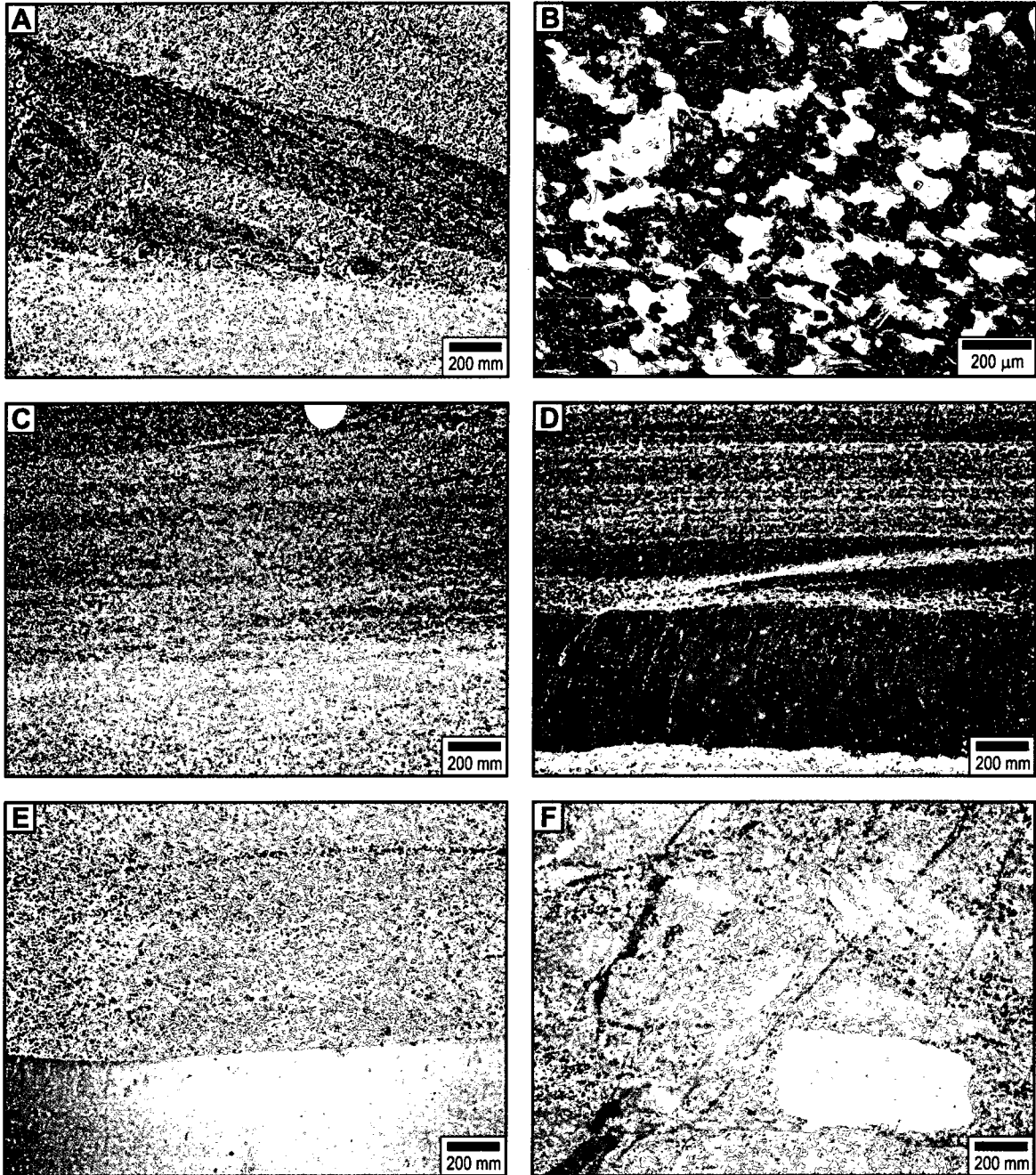
See attached DVD for pdf files of individual stratigraphic sections.

APPENDIX F: Representative thin section photomicrographs of lithofacies from the three members of the Old Fort Point Formation and results of modal mineralogy point-counting of carbonate and fine-grained rocks.



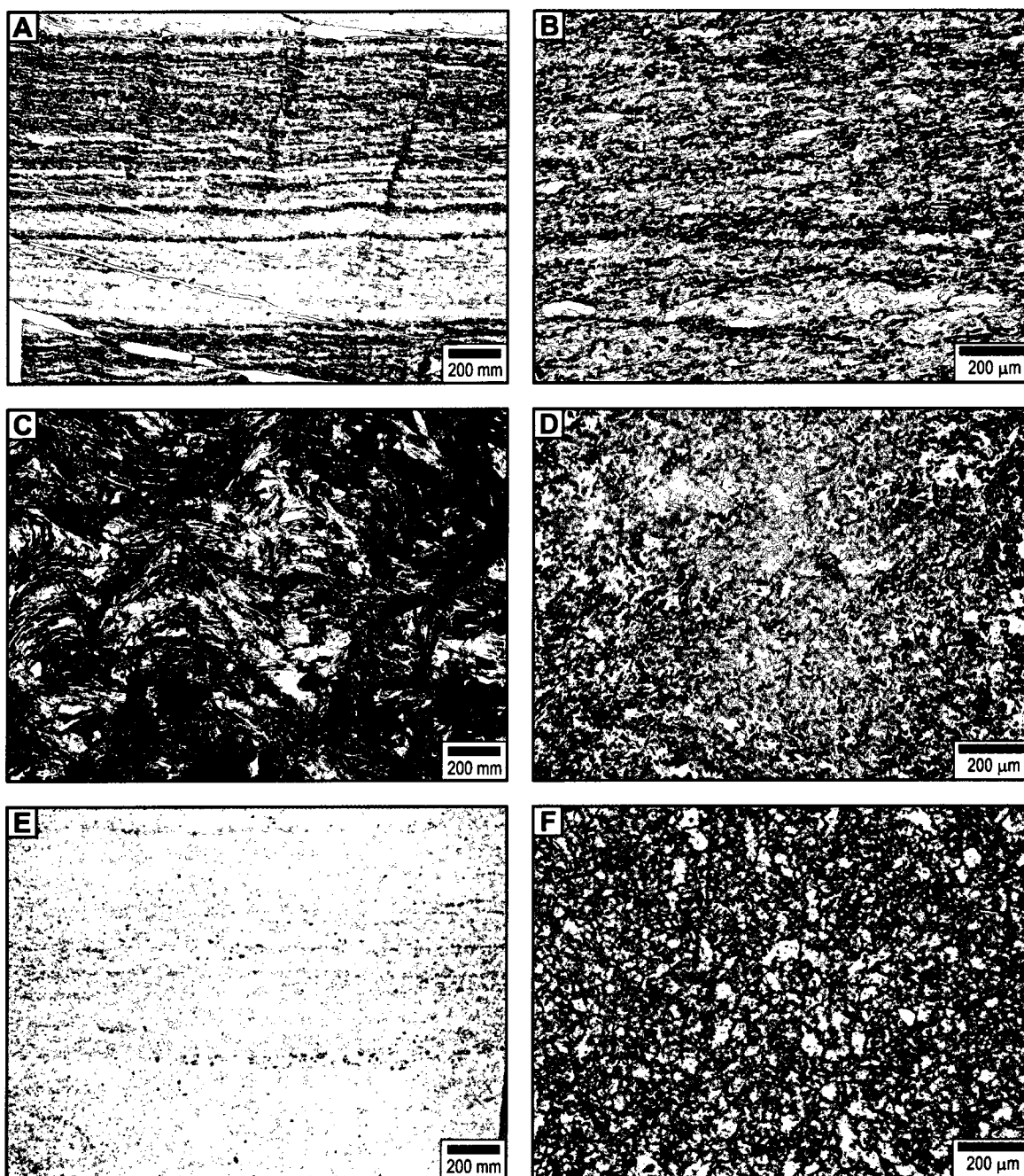
Temple Lake Member (TLM) thin section photomicrographs

A) and B) JP1: TLM-1 (MDS04-001). C) and D) LL5: TLM-1 (MDS04-120). E) and F) LL1: TLM-2 (MDS04-049B). Photomicrographs are in plane-polarized light (ppl).



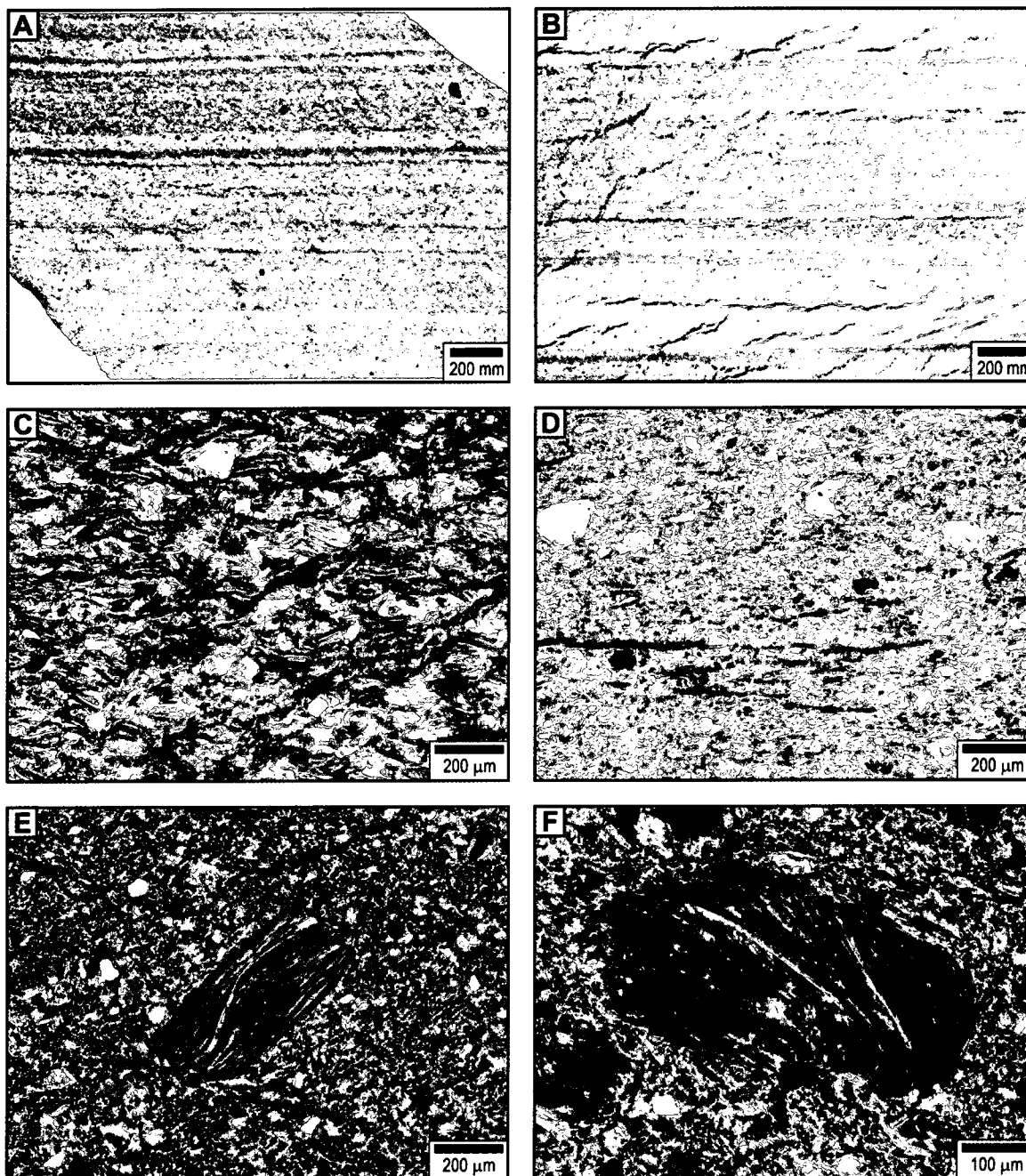
Temple Lake Member (TLM) thin section photomicrographs

A) and B) JP1: TLM-3 (MDS05-122). C) MR1: TLM-3 (MDS04-202). D) PM1: TLM-3 (MDS05-058). E) LL5: TLM-3 (MDS04-155). F) LL1: TLM-4 (MDS04-088). Photomicrographs are in plane-polarized light (ppl).



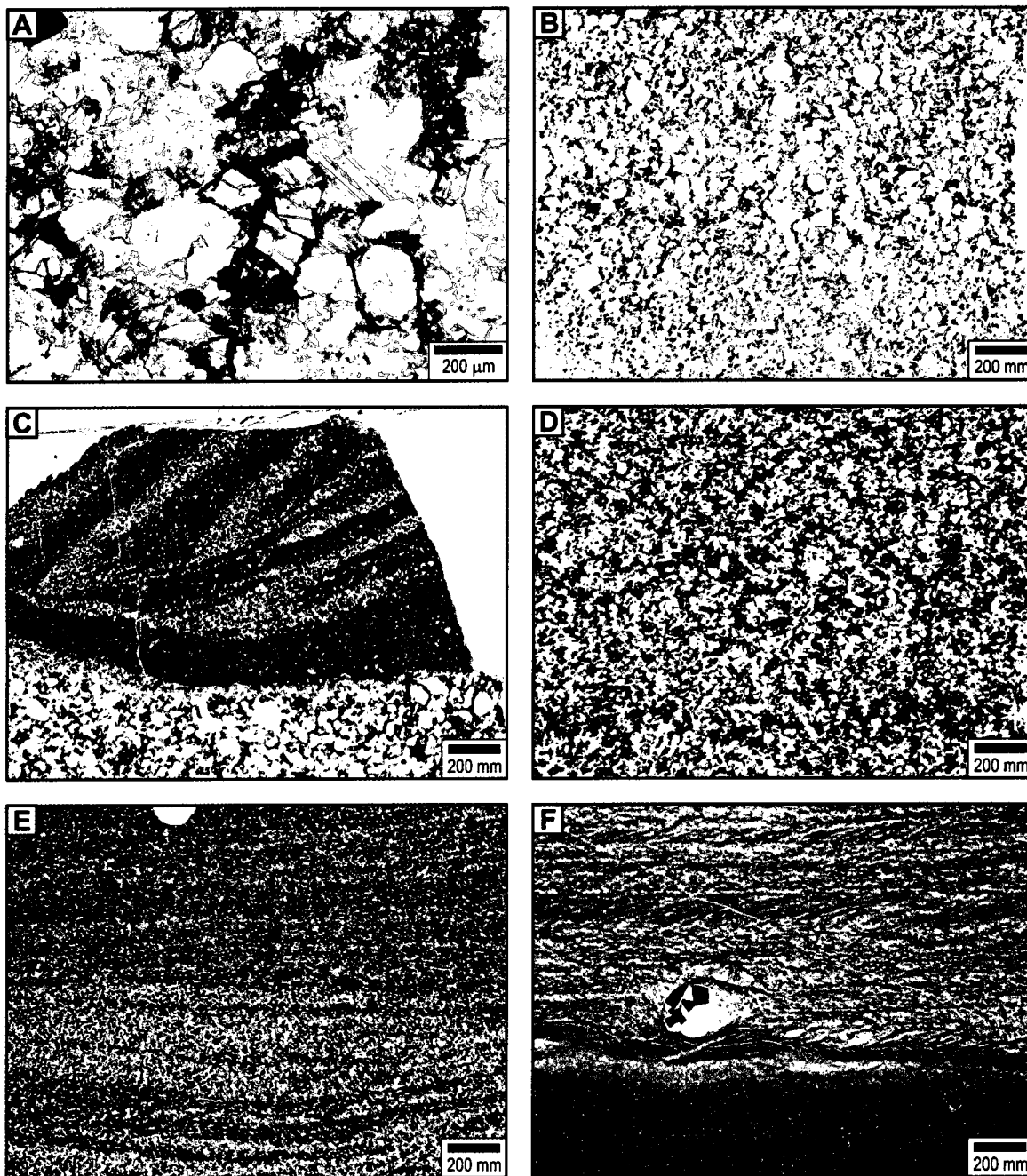
Geikie Siding Member (GSM) thin section photomicrographs

A) and B) JP1: GSM-1 mudstone (MDS04-007). C) and D) CM1: GSM-1 mudstone (MDS03-019). E) and F) JP1: GSM-1 limestone (MDS04-009). Photomicrographs are in plane-polarized light (ppl).



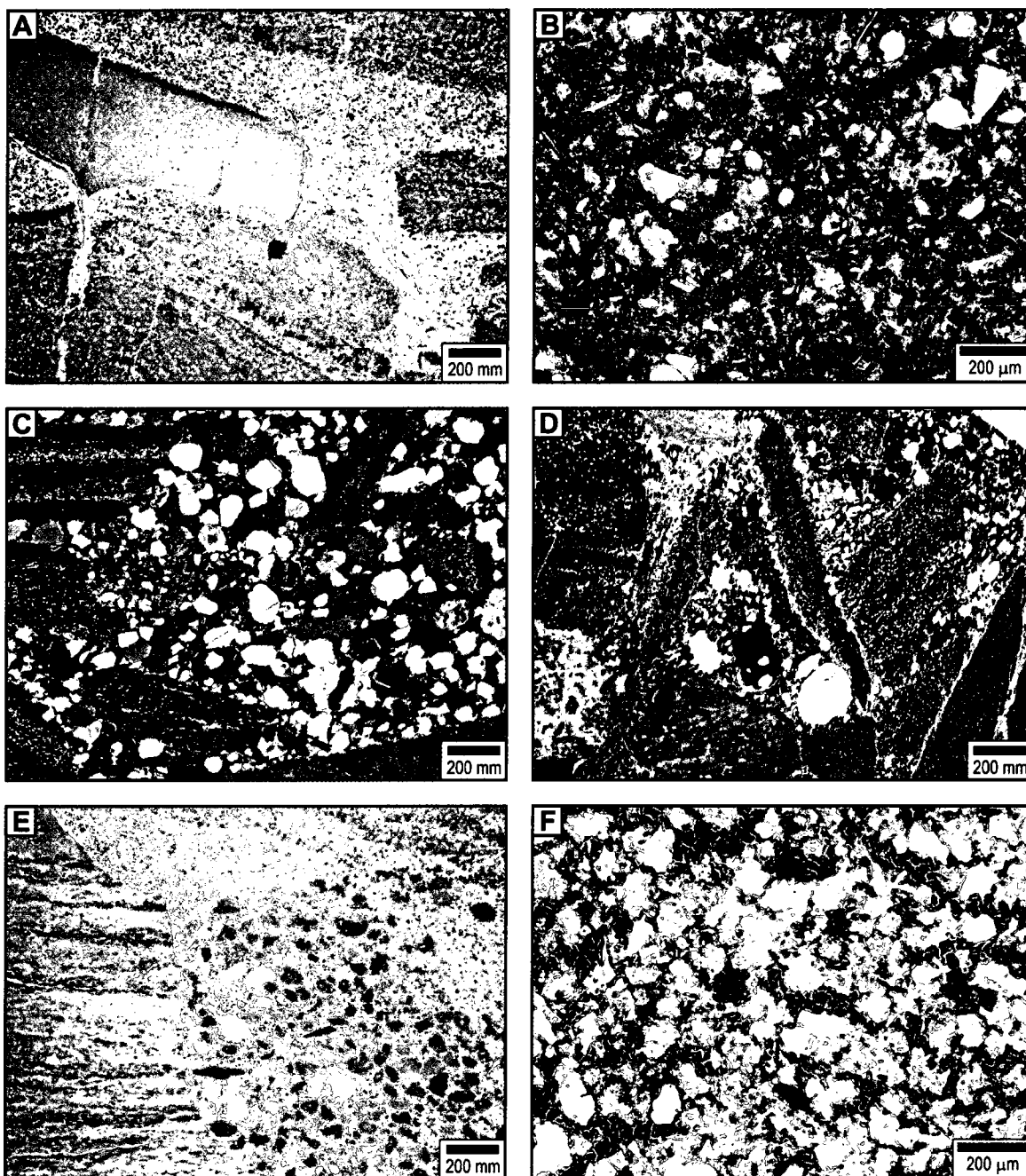
Whitehorn Mountain Member (WMM) thin section photomicrographs

A) LL4: WMM-1 (MDS04-030). B) LL4: WMM-1 (MDS04-038A). C) JP3: WMM-1 (MDS04-018). D) LL7: WMM-1 (MDS05-017). Photomicrographs are in plane-polarized light (ppl). E) LL4: WMM-1, detrital chlorite grain (MDS04-042). F) JP3: WMM-1, detrital chlorite grain (MDS04-016). Photomicrographs are in cross-polarized light (xpl).



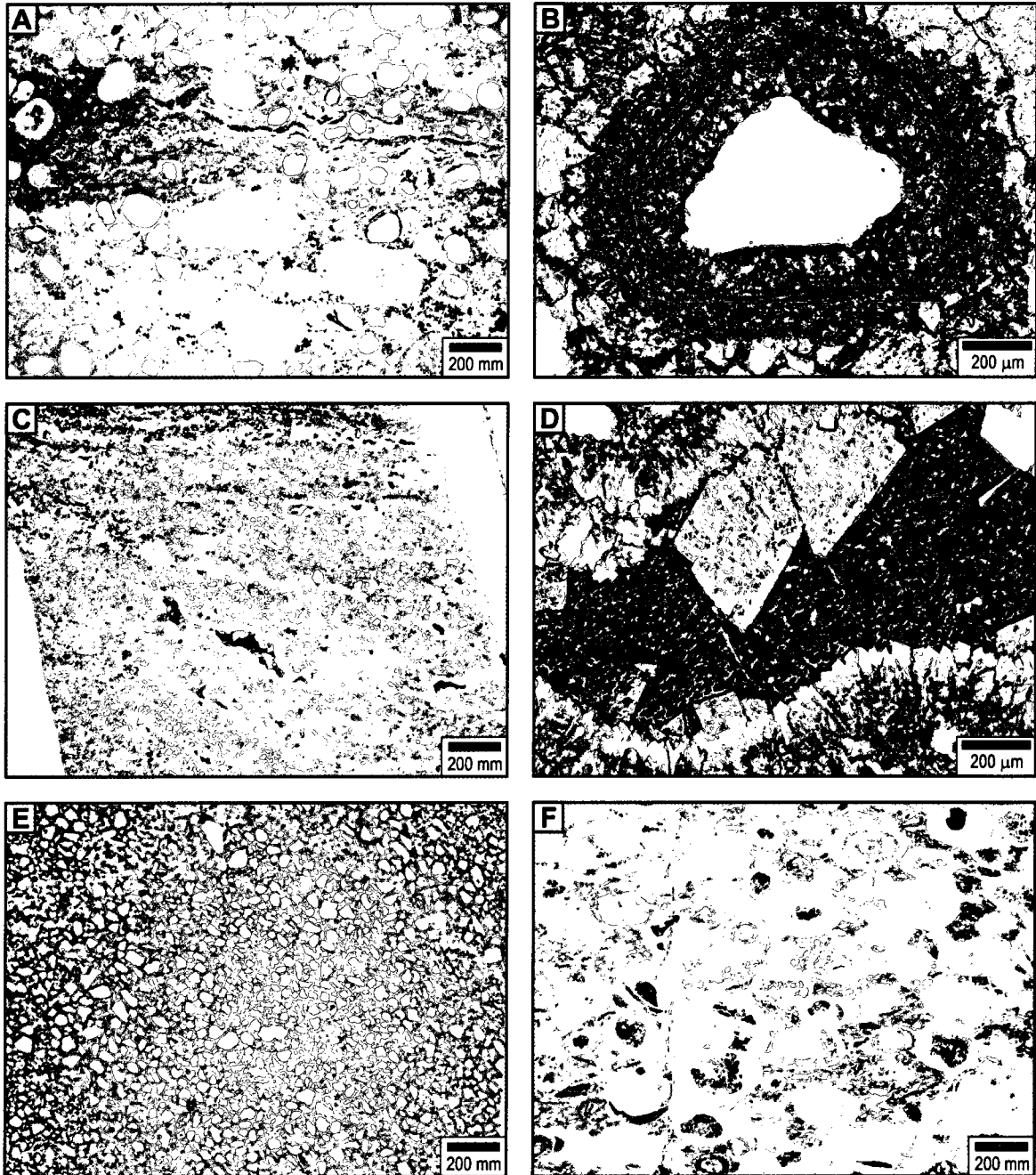
Whitehorn Mountain Member (WMM) thin section photomicrographs

A) LL4: WMM-3 (MDS04-035). B) CM1: WMM-4 (MDS03-024). C) PM1: WMM-4 and WMM-5 (MDS05-111A). D) MK1: WMM-5 (MDS05-146). E) CM1: WMM-5 and WMM-6 (MDS04-249B). F) CM1: WMM-6 and WMM-7 (MDS05-100). Photomicrographs are in plane-polarized light (ppl).



Whitehorn Mountain Member (WMM) thin section photomicrographs

A) and B) LL4: WMM-8 (MDS04-033A). C) JP1: WMM-8 (MDS04-012). D) MK1: WMM-8 (MDS05-133A). E) LL4: WMM-8 (MDS04-047A). F) LL4: WMM-8 (MDS04-028A). Photomicrographs are in plane-polarized light (ppl).



Shallow-marine carbonate (SMC) clasts thin section photomicrographs

A) and B) LL4: Corral Creek Formation, Middle Miette Group (MDS04-022). C and D) LL4: WMM-8 (MDS04-028A). E) LL4: WMM-8 (MDS04-025). F) MK1: WMM-8 (MDS05-133E). Photomicrographs are in plane-polarized light (ppl).

Mineral Abbreviations used in tables

Cc.	Calcite
Dol.	Dolomite
Qtz.	Quartz
Fld.	Feldspar (undifferentiated plagioclase and potassium feldspar)
Chl.	Chlorite (detrital grains)
Mu.	Muscovite (detrital grains)
Opq.	Opaque minerals (e.g. hematite, ilmenite, rutile, oxides)
Oth.	Other minerals (undifferentiated in carbonate samples)
Hvy.	Heavy minerals (e.g. apatite, titanite, tourmaline, zircon)
Org.	Organic matter
Py.	Pyrite
A/S.	Ankerite or siderite (undifferentiated)
Mtx "Cl"	Matrix clay-sized crystals (metamorphic muscovite and chlorite)

Carbonate Sample	Sxn	OFP Unit	Grain Size (µm)		Cement (µm)		Modal Point Counts (300)										Modal Percent (%)							
			Max.	Min.	Max.	Min.	Detrital					Cement					Detrital							
							Qtz.	Fld.	Chl.	Mu.	Opq.	Oth.	Cc.	Dol.	Qtz.	Fld.	Chl.	Mu.	Opq.	Oth.	Cc.	Dol.		
Temple Lake Member																								
MDS03-012	CM1	TLM-3	125	60	100	40	108	3		12	1	1	1	175			36.0	1.0	0.0	4.0	0.3	0.3	58.3	0.0
MDS04-004	JP1	TLM-3	120	20	50	10	31	2	3	1	1			262			10.3	0.7	1.0	0.3	0.3	0.0	87.3	0.0
MDS04-052-2	LL1	TLM-3	120	40	140	10	36	14	1		4			237	8		12.0	4.7	0.3	0.0	1.3	0.0	79.0	2.7
MDS04-054	LL1	TLM-3	120	30	80	10	25	15	3		8	3		236	10		8.3	5.0	1.0	0.0	2.7	1.0	78.7	3.3
MDS04-060B	LL1	TLM-3	180	30	120	10	22	16		2	2			256	2		7.3	5.3	0.0	0.7	0.7	0.0	85.3	0.7
MDS04-063	LL1	TLM-3	120	30	60	10	21	12	1		11			254	1		7.0	4.0	0.3	0.0	3.7	0.0	84.7	0.3
MDS04-072	LL1	TLM-3	120	20	60	10	24	9		1	3			263			8.0	3.0	0.0	0.3	1.0	0.0	87.7	0.0
MDS04-076	LL1	TLM-3	100	30	60	10	23	8		2	8	2		257			7.7	2.7	0.0	0.7	2.7	0.7	85.7	0.0
MDS04-077	LL1	TLM-3	180	40	50	10	42	12		1	7			238			14.0	4.0	0.0	0.3	2.3	0.0	79.3	0.0
MDS04-084	LL1	TLM-3	180	30	80	10	37	13	1	1	3			245			12.3	4.3	0.3	0.3	1.0	0.0	81.7	0.0
MDS04-091	LL1	TLM-3	120	40	60	10	33	8		2	5			252			11.0	2.7	0.0	0.7	1.7	0.0	84.0	0.0
MDS04-093	LL1	TLM-3	100	40	90	10	22	10	1	1	1	1		264			7.3	3.3	0.3	0.3	0.3	0.3	88.0	0.0
MDS04-103	LL1	TLM-3	60	10	40	10	6	2		1	1			290			2.0	0.7	0.0	0.3	0.3	0.0	96.7	0.0
MDS04-108	LL1	TLM-3	60	10	60	10	9	3		1	7			279	2		3.0	1.0	0.0	0.0	2.3	0.0	93.0	0.7
MDS04-148	LL5	TLM-3	40	10	80	10	10	2		1	1			286			3.3	0.7	0.0	0.3	0.3	0.0	95.3	0.0
MDS04-155-3	LL5	TLM-3	40	10	30	10	7	3		1	1	1		287			2.3	1.0	0.0	0.3	0.3	0.3	95.7	0.0
MDS04-161	LL5	TLM-3	30	10	80	20	5	2		3	4	1		285			1.7	0.7	0.0	1.0	1.3	0.3	95.0	0.0
MDS04-196	MR1	TLM-3	60	20	60	10	39	4		5	3	1		248			13.0	1.3	0.0	1.7	1.0	0.3	82.7	0.0
MDS04-206	MR1	TLM-3	100	20	50	10	17	1		8	1	3		270			5.7	0.3	0.0	2.7	0.3	1.0	90.0	0.0
MDS05-058	PM1	TLM-3	40	10	50	20	26	3		12	1			258			8.7	1.0	0.0	4.0	0.3	0.0	86.0	0.0
MDS05-059-1	PM1	TLM-3	30	10	60	10	10	10		44	1			245			3.3	0.0	0.0	14.7	0.3	0.0	81.7	0.0
MDS05-120	JP1	TLM-3	100	20	40	10	63	7		6	1			223			21.0	2.3	0.0	2.0	0.3	0.0	74.3	0.0
MDS05-121	JP1	TLM-3	120	40	40	10	50	10		1	3			236			16.7	3.3	0.0	0.3	1.0	0.0	78.7	0.0
MDS05-122-1	JP1	TLM-3	180	40	80	10	80	13	6	2	3			187	9		26.7	4.3	2.0	0.7	1.0	0.0	62.3	3.0
MDS05-127	MR2	TLM-3	60	30	100	10	17	1		6		1		275			5.7	0.3	0.0	2.0	0.0	0.3	91.7	0.0
Geikie Siding Member																								
MDS03-014	CM1	GSM-1	60	20	50	20	16	1		12	3			268			5.3	0.3	0.0	4.0	1.0	0.0	89.3	0.0
MDS03-015	CM1	GSM-1	90	20	60	20	19	3		16	1			261			6.3	1.0	0.0	5.3	0.3	0.0	87.0	0.0
MDS04-009	JP1	GSM-1	50	10	60	10	1		1	1	5			292			0.3	0.0	0.3	0.3	1.7	0.0	97.3	0.0
Whitehorn Mountain Member																								
MDS04-249B	CM1	WMM-6	60	20	80	40	47	1		8	1			243			15.7	0.3	0.0	2.7	0.3	0.0	81.0	0.0
MDS05-100-1	PM1	WMM-6	20	10	10	5?	6			6	1			287			2.0	0.0	0.0	2.0	0.3	0.0	95.7	0.0
MDS05-101	PM1	WMM-6	60	20	40	20	12	1		6	1			280			4.0	0.3	0.0	2.0	0.3	0.0	93.3	0.0
MDS05-140	MK1	WMM-6	40	20	60	10	12	1		3	3			281			4.0	0.3	0.0	1.0	1.0	0.0	93.7	0.0
MDS04-046B	LL4	WMM-cl	50	20	120	20	10	4			10			276			3.3	1.3	0.0	0.0	3.3	0.0	92.0	0.0

Fine-grained Sample	Sxn	Unit	OFP	Overall		Grain		Modal Points Counts (300)										Modal Percent (%)																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
				Range (µm)	Size (µm)	Detrital					Accessories					Mtx	Cement	Detrital					Accessories					Mtx	Cement																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																										
						Max.	Min.	Qtz.	Fld.	Chl.	Mu.	Opq.	Hvy.	Org.	Py.			A/S	"Cl"	Cc.	Dol.	Qtz.	Fld.	Chl.	Mu.	Opq.	Hvy.			Org.	Py.	A/S	"Cl"	Cc.	Dol.																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
Temple Lake Member																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																							
MDS03-002-1	CM1	TLM-1	>200	clay	80	20	66	6	6	3	3	166	59	220	20	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00

Fine-grained Sample	Sxn	OFP Unit	Overall		Grain Size (µm)	Modal Points Counts (300)										Modal Percent (%)														
			Range (µm)	Max. Min.		Detrital					Accessories					Mtx	Cement	Detrital					Accessories					Mtx	Cement	
						Qtz.	Fld.	Chl.	Mu.	Opq.	Hvy.	Org.	Py.	A/S	Cc.			Dol.	Qtz.	Fld.	Chl.	Mu.	Opq.	Hvy.	Org.	Py.	A/S			Cc.
Geikie Siding Member																														
MDS03-016	CM1	GSM-1	80	clay	60	20	43	1				6	3		238	3	6	14.3	0.3	0.0	0.0	0.0	0.0	2.0	1.0	0.0	79.3	1.0	2.0	
MDS03-019	CM1	GSM-1	200	clay	30	clay	16	1				29			200	52	2	5.3	0.3	0.0	0.0	0.0	0.0	9.7	0.0	0.0	66.7	17.3	0.7	
MDS04-007-1	JP1	GSM-1	120	clay	40	20	21	1	4		1	1			268	2	2	7.0	0.3	1.3	0.0	0.3	0.3	0.7	0.0	0.0	89.3	0.0	1.0	
MDS04-007-2	JP1	GSM-1	100	clay	60	20	25	3				10			259	3	3	8.3	1.0	0.0	0.0	0.0	0.0	3.3	0.0	0.0	86.3	0.0	1.0	
MDS04-234B	CM1	GSM-1	>300	clay	80	10	26	3			1	1			176	85	85	8.7	1.0	0.0	0.0	0.3	0.3	2.7	0.0	0.0	58.7	0.0	28.3	
MDS05-075	PM1	GSM-1	>120	clay	50	30	60	15			5				81	91	91	48	20.0	5.0	0.0	0.0	1.7	0.0	0.0	0.0	27.0	30.3	16.0	
MDS05-076	PM1	GSM-1	>120	clay	60	20	50	11			12	6			198	23	23	16.7	3.7	0.0	0.0	4.0	2.0	0.0	0.0	0.0	66.0	0.0	7.7	
Whitehorn Mountain Member																														
MDS04-016	JP3	WMM-1	100	clay	60	20	26	3	3	1	4				257	10	10	8.7	0.0	1.0	0.0	1.3	0.0	0.0	0.0	0.0	85.7	0.0	3.3	
MDS04-026	LL4	WMM-1	100	clay	100	30	46	3	3	1	10				13	218	6	15.3	1.0	1.0	0.3	3.3	0.0	0.0	0.0	4.3	72.7	2.0	0.0	
MDS04-027	LL4	WMM-1	180	clay	80	30	53	4	1	5	12				15	202	8	17.7	1.3	0.3	1.7	4.0	0.0	0.0	0.0	5.0	67.3	2.7	0.0	
MDS04-032C	LL4	WMM-1	120	clay	60	20	46	17	2	8	12	8			203	4	4	15.3	5.7	0.7	2.7	4.0	0.0	0.0	0.0	0.0	67.7	1.3	0.0	
MDS04-033A	LL4	WMM-1	120	clay	40	20	43	17	4	3	8	4			186	21	14	14.3	5.7	1.3	1.0	2.7	1.3	0.0	0.0	0.0	62.0	7.0	4.7	
MDS04-033B	LL4	WMM-1	150	clay	60	40	52	7	1	2	5	6			4	196	27	17.3	2.3	0.3	0.7	1.7	2.0	0.0	0.0	1.3	65.3	0.0	9.0	
MDS04-018-2	JP3	WMM-2	>200	clay	20	20	45	18	2	2	3				212	20	20	15.0	0.0	6.0	0.7	1.0	0.0	0.0	0.0	0.0	70.7	0.0	6.7	
MDS04-030	LL4	WMM-2	80	clay	40	20	35	5	9		6	8			232	4	4	11.7	1.7	3.0	0.0	2.3	2.7	0.0	0.0	0.0	77.3	0.0	1.3	
MDS04-031	LL4	WMM-2	80	clay	60	20	29	6	1	1	1				251	6	6	9.7	2.0	0.3	0.3	2.0	0.0	0.0	0.0	0.0	83.7	0.0	2.0	
MDS04-037	LL4	WMM-2	80	clay	60	20	38	4	4	1	1				249	3	3	12.7	1.3	1.3	0.3	0.3	0.0	0.0	0.0	0.0	83.0	0.0	1.0	
MDS04-038A	LL4	WMM-2	80	clay	60	20	35	8	2	5	3				244	3	11.7	2.7	0.0	0.7	1.7	1.0	0.0	0.0	0.0	0.0	81.3	0.0	1.0	
MDS04-038B	LL4	WMM-2	80	clay	50	20	42	4	1	1	5				242	5	14.0	1.3	0.3	0.3	1.7	0.0	0.0	0.0	0.0	0.0	80.7	0.0	1.7	
MDS04-039	LL4	WMM-2	80	clay	80	20	46	15	1	1	3	1			222	12	15.3	5.0	0.0	0.3	1.0	0.3	0.0	0.0	0.0	0.0	74.0	0.0	4.0	
MDS04-041	LL4	WMM-2	80	clay	40	20	42	8	4	2	4	2			224	14	14.0	2.7	1.3	0.7	1.3	0.7	0.0	0.0	0.0	0.0	74.7	0.0	4.7	
MDS04-042	LL4	WMM-2	250	clay	80	40	58	11	19	5	3	1			194	9	19.3	3.7	6.3	1.7	1.0	0.3	0.0	0.0	0.0	0.0	64.7	0.0	3.0	
MDS05-004	LL2	WMM-2	120	clay	60	10	55	7	92	2	3	1			132	8	18.3	2.3	30.7	0.7	1.0	0.3	0.0	0.0	0.0	0.0	44.0	0.0	2.7	
MDS05-005	LL2	WMM-2	100	clay	80	40	60	34	40	3	3	3			54	102	4	20.0	11.3	13.3	0.0	1.0	0.0	0.0	0.0	0.0	18.0	34.0	1.3	
MDS05-017-1	LL8	WMM-2	>200	clay	40	10	35	8	26		9	6			206	10	11.7	2.7	8.7	0.0	3.0	2.0	0.0	0.0	0.0	0.0	68.7	0.0	3.3	
MDS05-018	LL8	WMM-2	>150	clay	40	10	44	5	12		5	4			220	3	10	14.7	1.7	4.0	0.0	1.7	1.3	0.0	0.0	0.0	73.3	0.0	3.3	
MDS05-019	LL8	WMM-2	>200	clay	40	10	47	8	20		12				201	12	15.7	2.7	6.7	0.0	4.0	0.0	0.0	0.0	0.0	0.0	67.0	0.0	4.0	
MDS04-018-1	JP3	WMM-3	120	clay	60	20	74	8	2	1	7				137	71	24.7	2.7	0.7	0.3	2.3	0.0	0.0	0.0	0.0	0.0	45.7	0.0	23.7	
MDS04-035	LL4	WMM-3	200	clay	120	85	23	4	3	13	4				42	92	54	28.3	7.7	0.0	0.0	1.3	0.0	0.0	0.0	0.0	14.0	30.7	0.0	18.0
MDS04-036	LL4	WMM-3	120	clay	90	50	104	13	4	3	11	5			31	95	37	34.7	4.3	1.3	1.0	4.3	0.0	0.0	0.0	0.0	10.3	31.7	0.0	12.3
MDS04-040A	LL4	WMM-3	120	clay	90	20	99	28	9	1	11	3			2	131	32	33.0	9.3	3.0	0.3	3.7	1.7	0.0	0.0	0.0	38.3	0.0	10.7	
MDS04-040B	LL4	WMM-3	120	clay	90	20	82	28		3					47	27.3	9.3	0.0	1.0	1.3	1.0	0.0	0.0	0.0	0.0	0.7	43.7	0.0	15.7	
MDS05-085	PM1	WMM-4	120	clay	120	40	186	8	1	1	1				33	84	8	62.0	2.7	0.0	0.0	0.3	0.0	0.0	0.0	0.0	11.0	28.0	2.7	
MDS05-100-2	PM1	WMM-5	80	clay	40	20	34	1	1	1	1				251	6	6	11.3	0.3	0.0	0.0	0.3	0.3	0.0	0.0	0.0	83.7	2.0	2.0	
MDS03-023	CM1	WMM-7	250	clay	70	30	41	6			1	1			30	213	6	13.7	2.0	0.0	0.0	0.3	0.3	0.0	0.0	0.0	10.0	71.0	2.0	0.7
MDS03-026	CM1	WMM-7	250	clay	60	20	42	1			1	1			251	3	3	14.0	0.3	0.0	0.0	0.3	0.3	0.0	0.0	0.3	0.0	83.7	1.0	0.0
MDS05-151	MK1	WMM-7	100	clay	90	40	115	10	6		3	1			11	155	38.3	3.3	0.0	2.0	1.0	0.0	0.0	0.0	0.0	0.0	3.7	51.7	0.0	
MDS04-028B	LL4	WMM-8	100	clay	100	30	82	59			3	1			73	83	27.3	19.7	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	24.3	27.7	0.0	
MDS04-034	LL4	WMM-8	180	clay	120	60	86	9	1		6	1			84	54	4	28.7	3.0	0.3	0.0	2.0	0.3	0.0	0.0	0.0	28.0	18.0	18.3	1.3
Other WSG samples																														
MDS05-049	PM1	HTC	100	clay	60	clay	30				6				227	37	10.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	75.7	12.3	0.0	0.0
MDS03-001	CM1	MK	100	clay	40	clay	47	6			3				243	15.7	2.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.3	0.0	81.0	0.0	0.0
MDS04-173	MR1	MM	180	clay	80	clay	24	3							273	8.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	91.0	0.0	0.0

APPENDIX G: List of paleocurrent measurements.

Lithofacies	Section	Sed. Structure	(Drct.°)
TLM-2	LL1	3D ripples	308
TLM-2	LL1	3D ripples	222
TLM-2	LL1	3D ripple trough	266
TLM-2	LL1	3D ripples	290
TLM-2	LL1	3D ripples	290
TLM-2	LL1	3D ripples	320
TLM-2	LL1	3D ripples	288
TLM-2	LL1	3D ripples	278
TLM-2	LL1	3D ripples	298
TLM-2	LL1	3D ripples	236
TLM-2	LL1	3D ripples	210
TLM-2	LL1	3D ripples	180
TLM-2	LL1	3D ripples	220
TLM-2	LL1	3D ripples	272
TLM-2	LL5	3D ripple	076
TLM-2	LL5	3D ripple	330
TLM-2	LL5	3D ripple	328
TLM-2	LL5	3D ripple	326
TLM-2	LL5	3D ripple	332
TLM-2	LL5	3D ripple	334
TLM-2	LL5	3D ripple	332
TLM-2	LL5	3D ripple	354
TLM-2	LL5	3D ripple	188
TLM-2	LL5	3D ripple	172
TLM-2	LL5	3D ripple	258
TLM-2	MR1	3D ripple	220
TLM-3	LL1	3D ripples	238
TLM-3	LL1	3D ripples	240
TLM-3	LL1	3D ripples	218
TLM-3	LL1	3D ripples	218
TLM-3	LL1	3D ripples	204
TLM-3	LL1	3D ripples	208
TLM-3	LL1	3D ripples	230
TLM-3	LL5	3D ripple	050
TLM-3	LL5	3D ripple	052
TLM-3	LL5	3D ripple	280
WMM-2	LL4	Parting lineation	140-320
WMM-3	LL4	3D ripple trough	220
WMM-3	LL4	3D ripples	340
WMM-5	MK1	3D ripple	310
Miette Grp.	LL4	3D ripples	300

APPENDIX H: Major, trace and rare-earth element lithogeochemical analyses from fine-grained meta-sedimentary rocks of the Windermere Supergroup, southern Canadian Cordillera.

Grp/Fm	Old Fort Point Formation (OFP)							
Unit	TLM	TLM	TLM	TLM	TLM	TLM	TLM	TLM
Type	siltstone	siltstone	siltstone	siltstone	siltstone	siltstone	siltstone	siltstone
Sxn	CM1	CM1	CM1	CM1	JP1	JP1	JP1	LL1
ID#	MDS03-003	MDS03-005	MDS03-007	MDS03-013	MDS04-001	MDS04-002	MDS04-003	MDS04-048
SiO ₂	61.32	62.18	61.72	62.75	65.64	67.61	52.62	58.89
TiO ₂	0.79	0.77	0.80	0.71	0.71	0.64	0.65	0.72
Al ₂ O ₃	18.77	18.00	17.97	19.29	15.52	7.90	12.94	21.06
Fe ₂ O ₃	7.85	7.37	7.16	5.52	5.51	4.57	6.21	8.76
MnO	0.131	0.171	0.211	0.074	0.152	0.344	0.114	0.155
MgO	3.04	3.28	2.97	3.24	2.35	4.60	3.90	3.46
CaO	1.91	2.30	3.56	2.48	4.03	9.83	19.59	0.92
Na ₂ O	1.02	0.63	1.58	0.86	2.41	3.53	1.20	1.22
K ₂ O	4.78	4.91	3.64	4.75	3.29	0.57	2.29	4.47
P ₂ O ₅	0.16	0.16	0.17	0.12	0.18	0.22	0.22	0.14
LOI	5.5	5.9	6.5	6.5	6.9	12.3	16.3	4.9
Li	57.06	53.46	59.53	58.27	17.42	4.12	79.84	112.45
Sc	24.33	20.54	22.14	19.37	19.27	13.05	20.33	25.05
V	86.39	85.18	82.23	150.30	72.62	19.37	54.13	72.98
Rb	183.77	194.98	127.69	151.93	89.08	24.80	84.13	197.89
Sr	106.49	206.72	182.36	110.61	86.50	128.56	156.83	102.35
Y	26.22	23.31	27.39	21.61	28.34	40.45	21.58	35.19
Zr	196.70	187.48	255.71	151.29	339.04	627.51	331.15	156.59
Nb	18.69	16.39	19.28	14.10	16.05	13.38	14.04	18.99
Mo			0.99	17.77	0.51	0.45	0.47	0.34
Cs	7.61	8.51	3.99	5.06	5.15	0.91	2.71	7.57
Ba	802.18	791.56	915.71	740.09	721.12	126.03	1279.70	668.43
Hf	5.67	5.56	7.26	4.45	8.82	16.60	8.50	4.88
Ta	1.29	1.16	1.36	1.05	1.13	0.99	0.98	1.53
Tl	1.09	1.07	0.71	0.81	0.73	0.12	0.42	1.12
Pb	7.37	6.12	11.50	8.79	14.70	13.02	8.11	26.35
Bi	0.20	0.15	0.09	0.19	0.25	0.13	0.03	0.54
Th	21.83	20.31	23.71	17.95	22.65	30.92	17.71	23.54
U	1.87	2.05	2.84	5.99	2.41	4.12	2.60	3.63
Cr	115.69	106.18	103.08	100.21	63.52	32.60	60.57	131.53
Co	21.54	19.84	15.57	12.09	11.66	14.50	14.43	23.56
Ni	70.25	54.51	49.70	35.05	34.44	10.20	32.36	77.93
Cu	1.42	2.18	7.69	37.60	6.76	14.79	2.89	3.26
Zn	111.55	119.16	119.20	97.00	70.23	70.13	84.38	127.47
As	0.26		2.20	2.46	2.32	1.82	0.67	7.43
Ge	1.74	2.05	1.39	1.25	1.28	0.80	1.19	1.98
Ag								
Cd						0.55	0.83	
Sn	3.64	3.53	3.40	3.37	3.24	1.89	2.76	4.58
Sb	1.94	2.54	0.41	1.34	0.39	0.28	0.12	0.53
Re								
Ga					20.25	4.99	17.13	29.23
La	56.31	47.60	60.58	50.30	53.31	49.46	42.84	79.41
Ce	118.72	101.35	127.95	91.58	114.77	119.80	89.17	153.82
Pr	13.11	11.29	14.48	10.74	12.14	14.60	9.49	18.85
Nd	46.34	39.74	52.17	36.18	42.86	59.23	32.40	64.34
Sm	8.20	7.43	9.39	5.82	7.07	14.19	5.18	10.92
Eu	1.58	1.30	1.74	1.22	1.14	1.97	0.84	1.62
Gd	7.43	6.43	8.11	5.72	6.35	10.72	4.39	8.54
Tb	0.98	0.87	1.06	0.78	0.86	1.24	0.59	1.16
Dy	5.98	5.24	6.37	4.93	5.19	7.39	3.73	7.04
Ho	1.20	1.06	1.24	0.99	1.06	1.46	0.77	1.37
Er	3.54	3.02	3.57	2.96	3.10	4.17	2.30	4.05
Tm	0.48	0.42	0.50	0.40	0.46	0.61	0.33	0.58
Yb	3.21	2.81	3.41	2.73	2.95	4.08	2.29	3.81
Lu	0.43	0.38	0.48	0.36	0.41	0.58	0.31	0.52
Eu/Eu*	0.62	0.58	0.61	0.65	0.52	0.49	0.54	0.52

Grp/Fm	Old Fort Point Formation (OFP)							
Unit	TLM	TLM	TLM	TLM	TLM	TLM	TLM	TLM
Type	siltstone	siltstone	carbonate	carbonate	siltstone	siltstone	siltstone	siltstone
Sxn	LL1	LL1	LL1	LL1	LL1	LL5	LL5	LL5
ID#	MDS04-065	MDS04-089	MDS04-091	MDS04-103	MDS04-105	MDS04-118	MDS04-128	MDS04-133
SiO ₂	63.46	63.14	31.43	10.46	53.19	60.61	64.35	66.41
TiO ₂	0.73	0.73	0.30	0.08	0.55	0.77	0.35	0.68
Al ₂ O ₃	15.99	17.34	5.91	2.10	12.90	19.96	9.98	14.17
Fe ₂ O ₃	5.96	6.95	1.55	1.39	6.13	8.23	1.52	5.01
MnO	0.175	0.051	0.448	0.509	0.191	0.106	0.603	0.173
MgO	2.54	3.66	0.96	1.20	1.94	3.25	0.57	1.88
CaO	5.00	2.19	56.13	83.33	20.57	0.73	17.08	5.90
Na ₂ O	1.80	0.68	2.38	0.55	0.97	2.07	4.76	2.88
K ₂ O	3.92	4.85	0.64	0.23	3.17	3.92	0.51	2.53
P ₂ O ₅	0.17	0.18	0.11	0.08	0.19	0.17	0.13	0.18
LOI	6.4	5.0	30.0	38.3	18.4	4.2	12.2	6.1
Li	59.54	81.44	6.30	8.82	24.78	82.42	12.57	32.97
Sc	17.29	16.97	17.70	9.80	18.37	22.18	11.73	16.53
V	73.82	93.42	12.32	6.77	46.87	75.98	172.24	53.71
Rb	148.45	184.95	14.71	6.58	105.99	157.85	28.31	111.00
Sr	90.88	26.26	238.44	238.31	104.53	70.57	163.61	70.92
Y	25.69	18.23	16.11	11.69	18.98	35.44	29.67	32.22
Zr	268.73	247.37	123.11	9.81	220.10	185.50	302.32	490.21
Nb	16.06	15.60	4.53	0.95	11.53	18.41	9.25	13.82
Mo	0.58	0.62	0.29	0.23	0.78	0.83	0.66	0.87
Cs	4.87	6.30	0.45	0.15	1.86	5.95	0.68	3.40
Ba	965.92	1148.27	319.38	104.61	793.82	589.36	523.74	536.60
Hf	7.51	7.13	3.33	0.24	5.85	5.65	8.26	13.54
Ta	1.16	1.15	0.30	0.06	0.85	1.39	0.68	1.16
Tl	0.80	1.07	0.06		0.57	0.89	0.12	0.59
Pb	23.95	8.89	21.38	13.21	6.77	27.04	12.03	16.13
Bi	0.32	0.26	0.06	0.04	0.15	0.43	0.06	0.22
Th	19.69	20.72	5.30	0.97	15.26	23.21	15.15	24.08
U	2.90	2.90	1.08	2.43	8.15	4.25	16.57	3.56
Cr	86.37	68.31	13.20	3.97	52.40	117.49	58.48	54.28
Co	17.01	20.63	3.37	2.83	10.34	19.94	6.00	13.25
Ni	46.32	58.47	8.88	7.73	25.02	65.09	13.43	32.67
Cu	23.14	122.89	9.33	7.19	22.66	8.87	5.50	5.40
Zn	90.10	109.54	26.71	21.52	50.38	115.39	39.47	76.90
As	5.64	2.32	1.20	1.77	16.90	7.53	2.82	3.54
Ge	1.70	1.64	0.31	0.19	0.84	1.75	0.91	1.33
Ag		0.08						
Cd			1.23				0.74	0.23
Sn	3.41	3.54	0.75	0.33	2.56	5.19	2.02	2.72
Sb	0.50	0.57			0.24	0.42	0.13	0.37
Re								
Ga	19.88	23.89	3.54	1.80	17.03	26.52	8.70	17.34
La	51.74	50.73	18.62	9.56	48.17	72.20	30.33	54.03
Ce	110.79	109.78	40.04	21.98	97.94	146.77	76.76	120.87
Pr	12.46	11.94	4.63	2.33	11.04	17.34	9.28	13.92
Nd	43.05	41.15	17.23	8.88	37.29	60.23	36.78	50.23
Sm	7.85	7.21	3.40	2.04	5.96	10.71	9.08	9.55
Eu	1.26	1.09	0.60	0.47	1.10	1.49	1.44	1.44
Gd	6.46	5.43	3.18	2.10	4.99	8.73	8.08	7.95
Tb	0.85	0.66	0.47	0.32	0.62	1.22	1.08	1.06
Dy	5.02	3.68	2.88	1.86	3.64	7.52	6.06	6.38
Ho	0.98	0.70	0.56	0.36	0.70	1.48	1.12	1.26
Er	2.86	2.10	1.54	1.02	2.01	4.23	3.03	3.64
Tm	0.40	0.32	0.24	0.13	0.29	0.62	0.43	0.54
Yb	2.70	2.06	1.50	0.86	1.82	4.00	2.77	3.60
Lu	0.40	0.28	0.19	0.12	0.26	0.53	0.38	0.49
Eu/Eu*	0.55	0.54	0.56	0.70	0.62	0.47	0.52	0.51

Grp/Fm	Old Fort Point Formation (OFP)							
Unit	TLM	TLM	TLM	TLM	TLM	TLM	TLM	TLM
Type	siltstone	carbonate	siltstone	siltstone	siltstone	siltstone	siltstone	carbonate
Sxn	LL5	LL5	MR1	MR1	MR1	MR1	MR1	MR1
ID#	MDS04-152	MDS04-157	MDS04-176	MDS04-183	MDS04-186	MDS04-188B	MDS04-202	MDS04-204
SiO ₂	61.79	19.37	58.30	56.93	58.17	59.21	43.79	25.63
TiO ₂	0.68	0.13	0.74	0.63	0.65	0.79	0.72	0.23
Al ₂ O ₃	18.12	3.44	25.19	27.03	24.13	19.46	12.80	3.93
Fe ₂ O ₃	5.97	3.06	6.90	6.74	7.98	8.74	6.52	1.52
MnO	0.110	0.603	0.076	0.157	0.076	0.197	0.163	0.168
MgO	2.73	1.47	1.83	1.73	2.28	3.67	5.31	0.89
CaO	4.71	70.65	0.40	0.17	0.20	2.36	26.66	66.16
Na ₂ O	1.53	0.82	1.37	1.89	1.21	1.00	1.29	0.60
K ₂ O	3.97	0.24	4.67	4.36	4.93	4.16	2.21	0.61
P ₂ O ₅	0.15	0.10	0.30	0.13	0.14	0.16	0.24	0.11
LOI	6.9	34.8	4.7	4.7	6.1	9.7	23.1	33.5
Li	44.94	22.99	158.42	150.64	98.40	60.64	32.03	9.48
Sc	20.86	11.30	24.19	22.65	22.68	20.38	14.45	14.94
V	73.91	9.28	83.87	80.71	79.96	82.72	59.47	16.37
Rb	171.01	6.88	201.76	192.05	233.78	190.40	73.90	16.56
Sr	52.93	290.34	203.90	265.18	167.94	153.48	233.09	297.77
Y	24.63	15.31	40.31	24.95	32.34	36.64	18.69	17.61
Zr	216.21	30.44	99.05	68.03	109.61	201.52	354.95	133.74
Nb	17.09	2.89	16.43	15.03	17.64	18.65	14.82	4.17
Mo	0.44	0.09	0.36	0.19	0.30			1.65
Cs	4.81	0.15	6.43	7.00	8.75	7.03	2.49	0.56
Ba	1407.16	85.30	823.33	1092.85	1156.98	980.24	1051.65	293.34
Hf	6.01	0.79	2.99	2.16	3.28	5.74	9.32	3.51
Ta	1.25	0.13	1.24	1.15	1.32	1.32	1.02	0.29
Tl	0.90		1.07	1.03	1.19	1.00	0.37	0.08
Pb	3.39	10.67	16.53	11.04	9.06	7.56	12.81	24.76
Bi	0.04	0.14	0.31	0.06	0.12	0.05	0.08	0.26
Th	21.86	2.23	21.61	23.35	21.31	21.82	21.10	5.35
U	2.86	1.85	3.96	4.01	2.04	2.86	2.67	1.19
Cr	82.61	10.96	109.62	100.53	129.94	118.46	58.40	14.46
Co	12.90	6.22	15.34	23.09	14.41	13.97	14.25	2.71
Ni	41.43	12.40	46.40	45.02	69.89	71.32	30.16	8.41
Cu	25.22	3.34	37.96	14.62	4.03	3.52	4.76	34.64
Zn	87.52	36.64	108.82	99.03	96.51	87.43	75.29	35.28
As	1.15	0.49	17.33	56.18	27.94	18.94	8.47	6.66
Ge	1.68	0.39	1.98	2.28	2.05	1.49	0.78	0.25
Ag								
Cd		0.22					1.30	2.17
Sn	4.27	0.46	3.86	2.96	3.75	3.97	2.25	0.89
Sb	0.35		0.45	0.51	0.42	0.72	0.24	13.86
Re								
Ga	25.77	3.29	32.37	32.84	31.69	26.33	16.42	4.84
La	66.89	12.09	81.92	105.87	80.99	74.47	48.86	15.95
Ce	131.71	30.67	157.18	184.35	148.99	152.33	104.28	32.66
Pr	14.13	3.54	19.56	24.31	18.91	17.57	11.37	3.84
Nd	46.59	14.07	65.03	81.44	63.86	57.85	38.18	13.62
Sm	6.98	3.50	11.78	12.94	10.64	9.15	6.16	2.94
Eu	1.12	0.84	2.34	2.11	1.89	1.46	0.89	0.52
Gd	5.62	3.42	11.71	8.13	8.76	8.25	4.66	2.99
Tb	0.76	0.48	1.57	1.00	1.17	1.22	0.59	0.42
Dy	4.92	2.62	8.82	5.45	6.79	7.44	3.36	2.78
Ho	1.00	0.49	1.68	1.03	1.26	1.44	0.67	0.57
Er	3.02	1.37	4.45	2.81	3.61	4.07	1.93	1.67
Tm	0.45	0.19	0.62	0.40	0.50	0.59	0.27	0.23
Yb	2.98	1.18	3.75	2.57	3.08	3.60	1.83	1.52
Lu	0.41	0.15	0.52	0.35	0.44	0.50	0.27	0.20
Eu/Eu*	0.55	0.75	0.61	0.63	0.60	0.52	0.51	0.54

Grp/Fm	Old Fort Point Formation (OFP)							
Unit	TLM	TLM	TLM	TLM	TLM	TLM	TLM	GSM
Type	siltstone	carbonate	siltstone	siltstone	siltstone	siltstone	siltstone	mudstone
Sxn	CM1	CM1	JP1	JP1	JP1	JP1	JP1	CM1
ID#	MDS04-219	MDS04-227	RAR-01-22	RAR-01-23	RAR-01-24	RAR-01-27	RAR-01-28	MDS03-016
SiO ₂	60.87	11.52	60.52	62.35	62.17	51.50	55.26	65.18
TiO ₂	0.71	0.10	0.76	0.79	0.80	0.76	0.72	0.75
Al ₂ O ₃	18.82	3.21	21.18	18.47	17.83	17.11	13.70	20.99
Fe ₂ O ₃	8.62	3.01	8.19	7.17	6.90	7.36	5.10	6.50
MnO	0.115	0.843	0.147	0.275	0.181	0.256	0.093	0.051
MgO	4.47	1.13	3.28	2.98	3.28	5.25	3.16	3.34
CaO	1.66	78.71	0.88	2.61	3.34	11.91	17.44	2.36
Na ₂ O	0.88	0.24	0.51	0.51	1.03	0.90	1.51	0.89
K ₂ O	3.54	0.93	4.22	4.47	4.09	4.57	2.35	5.08
P ₂ O ₅	0.14	0.08	0.14	0.15	0.15	0.16	0.24	0.12
LOI	5.6	37.4	4.8	5.9	6.4	14.6	14.3	5.2
Li	124.12	11.77	162.43	75.18	66.18	14.84	63.67	62.61
Sc	21.15	10.67	20.83	16.97	16.55	14.27	10.30	21.01
V	168.84	30.94	88.36	85.56	92.25	86.77	53.47	111.01
Rb	129.16	27.65	186.77	205.61	191.75	176.22	91.15	165.37
Sr	79.78	1162.47	71.31	83.99	97.44	136.09	186.08	114.80
Y	26.87	42.16	27.96	31.28	31.64	26.53	20.97	23.02
Zr	160.40	8.92	152.96	218.87	268.74	213.47	322.32	148.71
Nb	15.48	1.09	18.57	18.94	17.83	16.00	15.43	14.62
Mo		0.30	0.23	0.20	0.19	0.20	0.34	18.98
Cs	4.06	0.72	6.12	7.00	6.91	7.36	3.18	5.03
Ba	780.99	136.56	876.92	863.79	851.37	1126.86	2324.65	748.63
Hf	4.47	0.23	5.73	8.13	8.70	6.13	11.92	4.37
Ta	1.08	0.07	1.55	1.68	1.46	1.24	1.41	1.07
Tl	0.71	0.15	1.08	1.32	0.90	1.05	0.51	0.97
Pb	12.27	20.03	8.63	16.30	10.86	27.30	8.08	19.27
Bi	0.11	0.20	0.84	0.39	0.32	0.32	0.04	0.31
Th	18.27	1.26	23.49	27.02	17.55	18.93	21.73	18.22
U	1.44	4.99	3.22	3.60	2.34	2.27	2.93	6.61
Cr	154.72	16.17	109.35	111.52	95.29	64.25	77.23	104.08
Co	20.78	12.21	26.52	25.36	20.69	22.41	13.89	14.93
Ni	72.27	13.57	66.94	119.08	42.75	40.96	37.84	61.14
Cu	13.95	17.02	31.77	2.09	13.43	1.84	2.40	44.95
Zn	139.38	28.44	98.82	78.41	61.71	74.35	59.39	98.76
As	22.89	7.79						6.01
Ge	1.94	0.19						1.26
Ag								0.04
Cd		0.70						
Sn	3.20	0.38	5.68	5.35	4.93	4.66	4.55	3.32
Sb	0.30	0.56	0.31	0.53	0.65	0.53	0.16	2.67
Re			0.0107			0.0011		
Ga	25.08	4.32						
La	55.55	14.64	75.27	67.00	63.69	63.91	46.61	57.18
Ce	114.30	29.45	142.28	134.35	133.38	126.14	95.15	110.32
Pr	13.09	3.76	16.69	15.39	14.82	13.39	10.40	13.69
Nd	44.00	15.30	63.45	58.59	57.31	52.66	38.34	48.30
Sm	7.66	5.26	10.57	10.13	10.07	8.20	6.09	8.20
Eu	1.39	1.23	1.57	1.54	1.49	1.28	0.89	1.51
Gd	6.16	7.06	7.25	7.52	8.25	6.43	4.89	6.62
Tb	0.85	1.21	0.93	1.01	1.03	0.82	0.64	0.90
Dy	5.21	7.35	5.59	5.99	6.05	4.81	3.83	5.46
Ho	1.01	1.36	1.08	1.16	1.17	0.93	0.77	1.08
Er	2.88	3.93	3.12	3.31	3.31	2.64	2.24	3.07
Tm	0.39	0.60	0.45	0.48	0.50	0.39	0.33	0.44
Yb	2.50	4.10	2.97	3.11	3.18	2.45	2.17	2.83
Lu	0.35	0.61	0.44	0.47	0.47	0.36	0.33	0.37
Eu/Eu*	0.62	0.62	0.55	0.54	0.50	0.54	0.50	0.63

Grp/Fm	Old Fort Point Formation (OFP)							
Unit	GSM	GSM	GSM	GSM	GSM	GSM	GSM	GSM
Type	carbonate	mudstone	carbonate	mudstone	mudstone	carbonate	mudstone	mudstone
Sxn	CM1	CM1	JP1	JP1	JP1	JP1	JP1	JP1
ID#	MDS03-018	MDS03-019	MDS04-006	MDS04-007	MDS04-008	MDS04-009	MDS04-010	MDS04-011
SiO ₂	6.71	60.41	14.40	64.41	62.78	8.30	61.33	64.56
TiO ₂	0.12	0.86	0.11	0.66	0.71	0.16	0.74	0.66
Al ₂ O ₃	3.47	25.00	6.59	20.00	22.23	4.53	23.01	18.47
Fe ₂ O ₃	2.60	6.80	3.93	5.32	6.00	3.59	6.23	6.19
MnO	0.392	0.050	0.382	0.054	0.013	0.366	0.010	0.043
MgO	1.45	4.10	2.21	2.80	2.41	2.69	2.59	3.01
CaO	83.44	3.83	70.81	1.55	0.16	79.22	0.17	2.31
Na ₂ O	0.39	0.96	0.32	1.12	1.26	0.29	1.19	1.15
K ₂ O	1.00	5.92	1.02	3.78	4.12	0.65	4.40	3.31
P ₂ O ₅	0.14	0.11	0.07	0.11	0.10	0.11	0.11	0.12
LOI	35.3	7.7	35.2	5.4	5.8	37.6	6.4	6.6
Li		81.36	63.15	98.90	109.29	40.76	104.47	110.27
Sc	7.46	18.25	18.72	21.12	21.05	8.70	21.80	16.58
V	27.17	198.51	44.66	109.85	122.22	14.76	161.12	84.58
Rb	25.20	100.48	53.00	165.38	166.97	19.56	190.13	138.72
Sr	1391.65	165.78	382.09	145.67	153.86	292.14	150.30	135.24
Y	71.87	33.27	16.66	27.77	30.13	13.37	33.06	23.30
Zr	15.50	161.14	22.73	195.98	169.25	24.34	194.07	184.18
Nb	1.33	14.84	2.19	16.56	17.15	2.67	18.38	15.33
Mo	0.63	5.48	1.79	1.21	4.54	0.29	4.83	2.90
Cs	0.75	4.09	1.08	4.67	6.45	0.39	7.26	3.85
Ba	117.22	751.70	233.20	708.37	697.31	93.84	769.57	570.52
Hf	0.39	4.33	0.57	5.25	4.98	0.64	5.49	5.31
Ta	0.09	1.02	0.15	1.22	1.31	0.19	1.46	1.25
Tl	0.12	0.95	0.42	0.90	1.00	0.11	1.15	0.82
Pb	47.33	2.23	6.26	7.11	30.20	4.52	23.98	18.15
Bi	0.27	0.03	0.12	0.19	0.43	0.07	0.51	0.69
Th	1.58	17.25	2.88	22.35	23.01	2.71	23.48	20.20
U	2.31	3.49	24.96	6.66	6.75	3.62	5.66	3.72
Cr	13.93	113.34	15.38	80.55	87.05	12.51	99.61	72.74
Co	3.98	4.49	9.65	9.87	16.48	3.66	14.81	18.35
Ni	10.61	25.02	18.43	30.28	40.79	10.34	40.38	32.37
Cu	9.99	7.44	8.22	58.39	37.36	9.90	44.04	59.89
Zn	29.74	98.89	56.59	89.01	100.43	41.26	102.00	94.25
As	9.55		11.86	17.36	25.26	14.27	31.67	19.48
Ge		1.57	0.53	1.52	1.50		1.58	1.36
Ag			0.06		0.24	0.08	0.44	0.03
Cd	1.22	0.31	0.32	0.59	0.32			
Sn	0.58	3.11	1.08	4.46	3.71	0.36	4.43	3.53
Sb	1.00	0.83	0.53	0.50	3.07	0.28	3.39	2.00
Re							0.0155	0.0232
Ga	3.71	25.87	9.76	27.56	28.31	4.47	30.65	24.40
La	29.85	64.39	13.53	69.94	74.87	14.00	78.01	65.72
Ce	57.91	118.63	28.86	131.43	136.93	28.67	143.21	126.24
Pr	8.23	15.29	3.42	15.75	16.48	3.44	17.51	14.28
Nd	33.77	53.14	13.31	54.67	57.21	13.87	58.98	47.22
Sm	10.58	8.95	3.83	9.39	8.96	3.73	9.30	6.29
Eu	2.72	1.74	0.70	1.26	1.11	0.62	1.12	1.04
Gd	14.02	7.36	4.10	7.01	7.01	3.70	7.29	4.72
Tb	2.26	0.99	0.52	0.89	1.00	0.46	1.04	0.65
Dy	13.27	5.98	2.98	5.46	6.11	2.65	6.22	4.52
Ho	2.32	1.20	0.55	1.07	1.23	0.48	1.22	0.95
Er	6.07	3.47	1.54	3.10	3.49	1.24	3.43	2.79
Tm	0.80	0.48	0.20	0.45	0.48	0.18	0.51	0.39
Yb	4.64	2.86	1.45	2.93	3.09	1.18	3.19	2.52
Lu	0.51	0.37	0.19	0.40	0.44	0.17	0.45	0.34
Eu/Eu*	0.69	0.66	0.55	0.48	0.43	0.52	0.42	0.58

Grp/Fm	Old Fort Point Formation (OFP)							
Unit	GSM	GSM	GSM	GSM	GSM	GSM	GSM	GSM
Type	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone
Sxn	LL1	LL1	MR1	MR1	CM1	CM1	LL5	CM2
ID#	MDS04-111	MDS04-112	MDS04-208	MDS04-209	MDS04-234B	MDS04-236	MDS05-007	MDS05-025
SiO ₂	65.84	65.15	61.65	58.13	61.01	59.22	63.90	62.11
TiO ₂	0.68	0.58	0.77	0.73	0.71	0.71	0.67	0.65
Al ₂ O ₃	21.43	23.05	25.59	25.56	19.11	18.94	20.73	19.84
Fe ₂ O ₃	3.36	2.55	4.16	7.81	4.63	4.93	5.41	6.91
MnO	0.032	0.006	0.012	0.050	0.062	0.100	0.093	0.050
MgO	1.61	1.34	0.65	0.90	3.01	2.80	2.49	3.99
CaO	0.17	0.05	0.44	0.57	5.50	7.54	0.47	1.34
Na ₂ O	1.47	0.97	1.86	1.71	0.97	0.43	1.60	0.68
K ₂ O	5.14	6.05	4.53	4.24	4.67	5.01	4.29	4.19
P ₂ O ₅	0.06	0.06	0.11	0.09	0.12	0.11	0.13	0.08
LOI	4.2	4.9	6.3	9.1	8.8	10.1	4.8	4.5
Li	57.26	27.28	62.16	119.61	58.52	60.56	60.14	94.74
Sc	23.14	20.70	24.86	26.85	20.48	20.20	20.55	17.32
V	149.33	90.08	147.01	104.70	169.88	97.12	76.13	71.41
Rb	191.94	208.33	210.84	190.72	155.66	168.07	143.90	143.08
Sr	60.29	64.05	233.14	250.75	275.44	262.73	70.89	103.89
Y	24.33	26.38	35.30	23.04	27.46	34.83	56.20	10.55
Zr	179.45	103.02	163.73	175.89	162.29	152.71	181.59	136.78
Nb	13.75	13.10	18.59	18.14	14.86	14.13	16.87	14.10
Mo	4.53	3.20	3.72	3.28	4.83	3.34	0.75	0.24
Cs	5.66	5.94	9.03	7.96	5.17	5.57	4.96	4.54
Ba	916.02	972.20	887.25	769.91	702.83	772.43	665.63	682.05
Hf	5.10	3.14	4.84	4.86	4.11	4.18	5.24	3.96
Ta	1.20	1.04	1.48	1.33	0.98	0.94	1.26	1.00
Tl	1.21	1.36	1.18	1.03	0.98	0.95	0.87	0.81
Pb	16.03	27.96	24.91	33.88	7.70	8.66	12.20	2.71
Bi	0.30	0.47	0.81	0.97	0.04	0.05	0.37	0.05
Th	20.90	17.26	24.56	19.81	15.95	15.79	22.84	16.66
U	4.64	3.43	3.95	12.60	4.41	3.20	6.05	1.74
Cr	89.01	66.93	105.31	110.32	108.98	98.54	63.79	83.15
Co	12.57	1.95	8.27	26.49	28.36	14.47	19.23	8.89
Ni	46.65	10.83	22.80	75.92	145.45	38.35	53.58	34.29
Cu	34.53	10.38	29.15	39.83	112.75	32.02	22.48	17.95
Zn	88.59	50.06	51.28	96.56	111.47	67.44	119.70	105.24
As	27.47	23.11	42.94	87.51	23.28	5.53	4.97	10.32
Ge	1.36	1.24	2.02	1.69	0.89	1.49	1.51	1.80
Ag	0.08						0.42	0.30
Cd					0.69		0.57	
Sn	4.18	3.41	4.61	3.77	2.86	2.78	3.47	2.91
Sb	0.61	0.94	8.83	7.92	1.21	1.05	0.29	0.46
Re								
Ga	31.19	30.63	36.98	33.15	22.82	21.91	25.44	24.80
La	69.50	76.68	90.19	69.15	43.82	57.73	75.68	60.72
Ce	127.32	132.95	164.39	127.42	75.34	108.57	146.97	110.17
Pr	14.94	16.79	20.19	15.87	9.07	13.79	19.29	14.22
Nd	49.20	58.09	66.64	53.58	29.54	47.62	68.75	47.24
Sm	7.49	9.43	11.23	9.57	5.27	8.43	15.72	7.99
Eu	1.32	1.64	1.65	1.57	1.04	1.53	3.35	1.54
Gd	5.72	6.99	8.26	6.76	4.99	7.28	16.77	5.61
Tb	0.81	0.94	1.16	0.78	0.79	1.00	2.19	0.57
Dy	4.95	5.44	7.00	4.57	4.73	6.28	11.87	2.76
Ho	0.95	1.04	1.38	0.89	0.96	1.25	2.17	0.45
Er	2.76	2.85	3.92	2.66	2.85	3.63	5.73	1.27
Tm	0.38	0.42	0.57	0.39	0.43	0.50	0.78	0.20
Yb	2.63	2.64	3.49	2.67	3.11	3.12	4.79	1.39
Lu	0.37	0.35	0.50	0.38	0.47	0.44	0.66	0.21
Eu/Eu*	0.62	0.62	0.53	0.60	0.63	0.60	0.63	0.71

Grp/Fm	Old Fort Point Formation (OFP)							
Unit	GSM	GSM	GSM	GSM	GSM	GSM	WMM	WMM
Type	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone	carbonate	siltstone
Sxn	PM1	PM1	PM1	MR2	JP1	CM1	CM1	CM1
ID#	MDS05-067	MDS05-072	MDS05-077	MDS05-128A	RAR-01-29	S87-31	MDS03-023	MDS03-026
SiO ₂	57.60	59.81	58.05	59.24	65.02	60.41	57.82	64.55
TiO ₂	0.67	0.76	0.69	0.67	0.65	0.71	0.55	0.67
Al ₂ O ₃	22.77	20.66	21.55	19.95	20.44	19.72	16.52	20.78
Fe ₂ O ₃	9.34	8.24	9.45	5.56	5.32	7.35	5.17	4.79
MnO	0.055	0.157	0.050	0.059	0.031	0.054	0.164	0.022
MgO	3.08	3.15	3.81	2.36	2.55	2.50	2.93	1.99
CaO	0.35	0.91	0.23	5.60	0.80	2.79	12.30	0.94
Na ₂ O	0.88	1.91	1.09	0.47	1.09	1.01	0.35	0.52
K ₂ O	4.96	4.04	4.74	5.73	3.81	5.20	3.93	5.47
P ₂ O ₅	0.11	0.15	0.11	0.11	0.08	0.10	0.09	0.11
LOI	4.6	4.5	4.5	10.2	4.4	5.6	12.0	4.1
Li	63.09	62.28	69.16	24.52	108.60	39.04	39.74	57.27
Sc	24.61	24.18	23.34	21.58	15.93	17.28	17.25	22.95
V	99.55	100.19	145.78	136.83	134.69	131.95	49.06	72.68
Rb	190.57	159.11	184.32	224.53	158.17	181.53	119.21	184.08
Sr	166.71	201.80	138.12	159.51	149.00	126.20	564.03	83.98
Y	21.53	26.59	24.96	33.63	25.05	20.67	25.72	16.42
Zr	74.78	155.29	91.27	167.92	156.12	148.83	99.29	102.32
Nb	14.34	16.70	14.19	15.63	15.81	14.79	8.78	15.36
Mo	0.31	0.43	0.47	4.13	6.39	6.12	0.32	0.35
Cs	6.73	5.67	5.88	6.61	4.83	5.63	3.75	5.36
Ba	793.40	691.35	1108.63	1121.31	687.63	845.63	581.93	861.52
Hf	2.37	4.52	2.88	5.03	5.24	5.11	2.86	2.87
Ta	1.06	1.16	1.02	1.18	1.34	1.19	0.59	1.15
Tl	1.04	0.83	1.02	1.24	1.06	1.16	0.74	1.08
Pb	18.23	24.54	21.98	5.16	20.18	78.64	4.47	2.75
Bi	0.11	0.36	0.37	0.59	0.62	0.75		
Th	17.36	18.99	17.33	21.94	20.11	18.25	10.05	22.44
U	2.05	2.67	1.85	2.50	7.67	4.81	1.61	2.19
Cr	127.46	103.38	124.52	75.94	76.24	87.90	67.68	86.81
Co	22.69	23.91	24.19	9.65	21.94	23.76	7.40	3.46
Ni	72.65	75.63	68.02	15.56	75.09	42.06	29.35	7.21
Cu	2.91	4.12	2.90	42.72	22.74	28.17	5.47	1.40
Zn	116.52	132.89	144.91	51.83	57.08	78.39	85.38	87.49
As				13.32			2.34	0.34
Ge	1.53	2.01	2.19	1.26			0.94	1.37
Ag	0.12	0.19	0.16	0.31				
Cd								
Sn	3.05	3.54	3.38	4.36	4.37	4.24	2.35	3.88
Sb	1.27	1.05	0.79	0.94	1.82	2.02	0.15	0.53
Re					0.0125			
Ga	25.80	24.17	20.07	17.25				
La	52.01	58.12	57.03	64.94	67.42	49.42	39.31	58.76
Ce	98.80	116.13	110.34	121.16	120.31	89.72	75.27	114.99
Pr	11.80	13.59	13.05	15.27	14.44	11.19	9.53	13.18
Nd	39.86	46.20	44.19	53.53	52.73	43.03	34.42	44.71
Sm	7.44	8.53	8.16	9.30	8.00	7.30	7.20	7.56
Eu	1.47	1.57	1.53	1.57	1.12	1.29	1.53	1.41
Gd	6.13	7.50	6.54	8.02	6.00	5.71	7.31	6.15
Tb	0.78	0.95	0.89	1.12	0.79	0.70	1.08	0.73
Dy	4.49	5.55	5.17	6.83	4.84	4.09	6.21	4.13
Ho	0.88	1.09	1.01	1.34	0.96	0.82	1.16	0.79
Er	2.41	3.02	2.87	3.74	2.74	2.45	3.23	2.32
Tm	0.36	0.43	0.40	0.54	0.41	0.36	0.45	0.33
Yb	2.38	2.78	2.57	3.40	2.70	2.43	3.18	2.27
Lu	0.29	0.38	0.33	0.50	0.39	0.35	0.45	0.31
Eu/Eu*	0.67	0.60	0.64	0.56	0.50	0.61	0.65	0.64

Grp/Fm	Old Fort Point Formation (OFP)							
Unit	WMM	WMM	WMM	WMM	WMM	WMM	WMM	WMM
Type	carbonate	siltstone	siltstone	siltstone	siltstone	siltstone	siltstone	carbonate
Sxn	JP1	JP3	JP3	LL4	LL4	LL4	LL4	CM1
ID#	MDS04-013	MDS04-014	MDS04-015	MDS04-029	MDS04-030	MDS04-041	MDS04-042	MDS04-243
SiO ₂	50.44	45.52	59.64	60.15	61.10	62.09	65.41	57.51
TiO ₂	0.13	0.62	0.71	0.73	0.66	0.64	0.62	0.72
Al ₂ O ₃	0.92	20.96	22.25	22.99	21.11	20.41	19.38	24.67
Fe ₂ O ₃	2.34	13.77	7.50	6.13	7.80	7.12	5.36	6.16
MnO	1.313	0.161	0.088	0.051	0.061	0.159	0.123	0.051
MgO	1.09	3.69	2.84	2.50	1.92	2.74	2.48	3.14
CaO	43.29	7.08	0.80	0.37	0.54	1.20	1.08	0.63
Na ₂ O	0.22	0.92	1.13	1.78	1.26	1.48	1.55	0.53
K ₂ O	0.11	2.03	4.68	4.92	5.17	3.86	3.68	6.24
P ₂ O ₅	0.07	5.05	0.15	0.15	0.13	0.14	0.14	0.10
LOI	26.1	5.3	4.9	3.8	3.5	5.0	4.3	4.5
Li	6.17	242.04	108.66	81.34	43.86	83.09	69.32	87.01
Sc	17.47	22.27	20.80	18.68	18.85	18.05	18.75	21.53
V	5.98	59.49	81.20	88.79	73.07	70.17	64.30	88.18
Rb	3.48	104.17	209.94	199.20	236.22	153.05	147.35	171.54
Sr	299.27	172.49	53.75	60.28	57.67	89.74	97.54	80.78
Y	4.79	189.42	26.49	30.61	29.03	27.08	35.67	23.63
Zr	97.09	119.98	113.32	152.22	126.21	136.85	147.46	101.52
Nb	1.63	14.41	18.09	19.86	16.77	16.60	15.80	13.16
Mo	0.44	0.32	1.64	0.28	0.33	0.32	0.52	0.42
Cs	0.09	2.26	3.61	5.32	6.98	3.15	3.38	4.52
Ba	46.41	380.16	957.10	1089.10	1266.25	601.15	586.04	984.98
Hf	2.53	3.18	3.21	4.47	3.91	4.07	4.40	2.96
Ta	0.09	1.35	1.29	1.41	1.30	1.23	1.16	0.90
Tl	0.04	0.44	1.02	1.12	1.33	0.89	0.88	1.21
Pb	8.76	45.05	18.00	6.00	22.29	4.11	4.75	2.84
Bi	0.06	0.53	0.52	0.92	0.56	0.41	0.23	0.09
Th	2.14	24.99	21.16	22.78	21.73	21.70	20.36	17.22
U	23.95	7.99	3.35	3.99	2.94	3.13	2.52	2.05
Cr		78.94	134.74	99.29	91.08	80.16	76.41	135.45
Co	5.74	28.87	19.88	17.64	16.01	12.72	6.34	15.53
Ni	5.41	84.81	78.47	48.42	40.74	38.35	32.03	36.96
Cu	3.65	57.96	44.33	130.97	3.31	17.90	32.11	7.95
Zn	24.96	182.73	128.24	102.85	87.67	94.92	80.41	93.27
As	5.80	11.00	14.51	1.54	4.53	1.70	1.43	30.20
Ge	0.32	2.10	1.77	1.97	1.88	2.08	1.93	2.03
Ag				0.11				
Cd								
Sn	0.21	2.68	4.41	3.77	3.58	3.44	3.32	3.50
Sb	0.35	0.33	0.39	0.19	0.53	0.13	0.08	0.44
Re								
Ga	0.83	30.69	31.85	31.40	28.88	27.59	25.32	32.21
La	6.11	73.82	77.91	76.83	73.30	71.40	72.27	87.76
Ce	14.75	158.14	152.86	154.44	146.46	143.90	145.62	170.38
Pr	1.33	22.53	18.49	18.37	16.92	16.21	16.84	19.22
Nd	4.63	98.56	62.82	62.98	57.68	55.45	57.55	60.97
Sm	0.75	51.91	10.35	10.83	9.03	8.86	9.68	8.85
Eu	0.12	12.93	1.41	1.76	1.63	1.63	1.63	1.61
Gd	0.71	89.41	7.00	8.33	7.67	7.24	8.65	6.91
Tb	0.10	10.21	0.89	1.05	1.06	0.94	1.17	0.87
Dy	0.69	47.65	5.36	6.18	6.26	5.54	6.80	4.85
Ho	0.14	7.35	1.03	1.16	1.19	1.08	1.28	0.93
Er	0.44	16.57	3.02	3.32	3.26	3.06	3.69	2.56
Tm	0.07	1.86	0.42	0.46	0.46	0.43	0.49	0.35
Yb	0.49	9.88	2.66	3.14	2.98	2.73	3.16	2.19
Lu	0.07	1.24	0.37	0.43	0.41	0.38	0.43	0.28
Eu/Eu*	0.49	0.58	0.51	0.57	0.60	0.63	0.55	0.63

Grp/Fm	Old Fort Point Formation (OFP)						MMGB	
Unit	WMM	WMM	WMM	WMM	WMM	WMM	Corral Ck.	Corral Ck.
Type	mudstone	mudstone	mudstone	mudstone	siltstone	siltstone	siltstone	mudstone
Sxn	PM1	PM1	PM1	MK1	JP1	JP1	JP1	LL8
ID#	MDS05-083	MDS05-087	MDS05-092	MDS05-134	RAR-01-25KK	RAR-01-30	RAR-01-31	MDS04-021
SiO ₂	61.81	67.68	65.07	62.29	68.56	60.90	59.74	56.09
TiO ₂	0.71	0.69	0.75	0.75	0.47	0.68	0.72	0.77
Al ₂ O ₃	19.62	18.36	19.10	23.87	17.03	22.54	23.04	26.99
Fe ₂ O ₃	7.51	4.10	4.30	5.26	5.46	7.38	7.32	7.28
MnO	0.053	0.033	0.038	0.016	0.188	0.115	0.136	0.055
MgO	3.53	2.56	3.46	0.63	1.71	2.46	2.35	2.38
CaO	1.09	0.84	1.56	0.07	2.86	1.00	1.50	0.26
Na ₂ O	0.90	1.63	1.51	1.22	1.26	1.28	1.27	1.63
K ₂ O	4.44	3.80	3.90	5.52	2.26	3.41	3.54	4.23
P ₂ O ₅	0.12	0.10	0.13	0.13	0.07	0.10	0.25	0.14
LOI	3.9	4.6	5.0	5.7	4.1	4.5	4.5	5.3
Li	52.84	49.57	58.58	67.36	115.23	141.84	140.21	146.25
Sc	21.06	18.59	19.74	27.70	12.26	16.61	16.09	26.69
V	177.96	149.04	124.89	151.71	55.10	72.42	69.36	89.26
Rb	164.08	132.81	134.38	229.78	86.91	137.51	143.99	165.67
Sr	82.56	83.95	111.23	169.83	209.79	206.55	198.27	126.28
Y	20.44	26.64	27.44	31.48	88.96	28.44	47.16	19.38
Zr	128.39	179.62	191.29	149.78	78.26	147.82	126.41	128.00
Nb	14.53	14.20	14.30	18.94	11.52	16.25	16.99	18.09
Mo	8.45	1.69	4.67	5.70	10.46	0.24	0.07	0.63
Cs	3.83	3.70	3.36	7.24	3.60	3.87	3.88	6.56
Ba	1036.19	798.94	614.55	881.90	384.01	555.73	565.66	610.26
Hf	3.87	5.20	5.53	4.75	2.67	4.81	4.56	4.02
Ta	1.06	1.04	1.02	1.59	0.98	1.38	1.66	1.48
Tl	1.14	1.14	1.19	1.32	1.53	0.84	0.88	0.74
Pb	6.48	8.35	13.83	9.94	417.08	37.37	25.66	5.39
Bi	0.16	0.03	0.08	0.11	0.47	0.50	0.85	0.15
Th	17.72	17.73	19.14	28.11	16.15	24.82	24.84	25.06
U	5.37	3.47	4.66	2.88	258.10	2.54	3.57	4.08
Cr	106.23	82.11	95.16	82.96	56.75	83.65	86.57	121.42
Co	17.22	11.19	7.39	14.61	230.64	14.59	13.94	15.11
Ni	63.74	39.09	40.60	36.24	60.85	29.53	32.90	56.87
Cu	18.50	7.61	8.59	20.58	79.49	20.38	30.77	47.32
Zn	98.20	88.02	92.02	122.22	46.32	74.55	73.09	114.10
As	10.65			34.33				6.24
Ge	1.89	1.56	1.76	1.63				1.94
Ag	0.27	0.34	0.34	0.29				
Cd			0.26					
Sn	3.26	3.71	2.55	5.10	4.69	4.61	4.34	4.04
Sb	0.64	0.52	0.54	0.86	6.01	0.10	0.12	0.05
Re					0.0065			
Ga	18.36	18.61	17.55	26.14				34.05
La	51.54	57.08	50.73	80.03	89.85	79.54	81.76	99.12
Ce	99.17	111.37	97.31	155.07	241.28	149.08	154.21	186.09
Pr	12.07	13.24	11.75	18.56	39.25	17.11	18.46	22.61
Nd	41.25	46.01	41.33	63.02	183.27	63.31	73.12	75.30
Sm	6.44	8.09	7.10	10.24	44.83	10.02	13.21	12.38
Eu	1.26	1.59	1.37	1.48	6.65	1.59	2.30	2.26
Gd	5.05	6.98	6.54	8.04	25.79	7.46	12.11	7.91
Tb	0.68	0.92	0.87	1.07	3.49	0.91	1.69	0.77
Dy	4.14	5.22	5.24	6.67	19.09	5.54	9.67	4.26
Ho	0.83	1.03	1.07	1.28	3.27	1.03	1.76	0.80
Er	2.43	2.96	3.08	3.87	7.87	2.97	4.62	2.32
Tm	0.35	0.42	0.44	0.54	0.96	0.42	0.62	0.32
Yb	2.32	2.70	2.78	3.57	5.41	2.71	3.83	2.30
Lu	0.31	0.36	0.40	0.49	0.69	0.40	0.54	0.30
Eu/Eu*	0.68	0.65	0.62	0.50	0.60	0.57	0.56	0.70

Grp/Fm	Middle Miette Group - below OFP (MMGB)							
Unit	Corral Ck.	Corral Ck.	Corral Ck.	Corral Ck.	Corral Ck.	Corral Ck.	MMG	MMG
Type	mudstone	mudstone	mudstone	mudstone	mudstone	clast	mudstone	mudstone
Sxn	LL4	LL5	LL2	LL4	LL2	LL5	MR1	MR1
ID#	MDS04-024	MDS04-116	MDS05-003	MDS05-163	RAR-R01-120E	MDS04-113B	MDS04-173	MDS04-174
SiO ₂	56.64	54.80	57.78	52.94	61.84	31.32	54.55	58.07
TiO ₂	0.59	0.67	0.73	0.87	0.92	0.39	0.88	0.78
Al ₂ O ₃	25.56	27.25	26.10	28.63	21.16	12.22	19.32	25.20
Fe ₂ O ₃	7.31	7.11	6.54	5.96	7.81	1.14	14.41	7.25
MnO	0.026	0.032	0.031	0.013	0.073	0.014	0.169	0.065
MgO	2.65	2.49	1.77	2.30	2.36	0.71	3.71	1.90
CaO	0.14	0.18	0.15	0.25	0.91	28.55	0.81	0.30
Na ₂ O	1.29	1.11	0.79	0.74	1.02	0.83	0.71	1.40
K ₂ O	5.48	5.99	5.81	7.83	3.73	3.85	5.08	4.66
P ₂ O ₅	0.10	0.15	0.09	0.21	0.07	20.58	0.19	0.15
LOI	4.7	5.3	6.0	5.2	4.5	3.3	11.6	4.9
Li	107.86	93.06	68.82	61.13	116.01	16.60	17.51	140.51
Sc	22.32	22.19	28.17	27.06	19.20	14.96	20.31	24.63
V	83.20	75.99	111.42	123.49	90.93	71.79	74.15	85.62
Rb	232.30	229.11	210.15	232.52	165.61	135.66	204.42	200.54
Sr	123.44	103.37	103.71	85.89	124.03	2087.40	73.13	176.22
Y	23.88	21.11	37.11	27.82	23.93	224.28	29.86	37.73
Zr	79.53	69.55	109.74	156.56	226.87	141.99	203.55	190.47
Nb	13.86	18.50	15.98	21.65	19.71	15.06	20.90	22.48
Mo	0.32	0.21	1.35	0.84	0.68	0.59	0.51	0.60
Cs	4.98	5.67	8.42	5.46	4.86	4.15	6.50	6.72
Ba	857.60	942.99	736.29	983.43	617.02	656.12	548.22	741.90
Hf	2.34	2.23	3.28	4.63	6.57	2.15	5.83	5.54
Ta	1.06	1.24	1.28	1.84	1.69	0.72	1.44	1.61
Tl	1.22	1.26	1.18	1.60	0.95	0.71	1.01	1.01
Pb	3.17	10.73	38.62	15.27	20.23	30.10	17.39	9.55
Bi	0.29	0.23	0.73	0.39	0.31	0.41	0.47	0.22
Th	20.10	20.76	16.81	31.63	22.50	13.20	22.28	30.22
U	4.10	4.12	3.85	5.15	3.61	46.96	5.69	4.12
Cr	105.09	105.33	79.79	104.61	113.40	52.37	126.96	104.23
Co	12.81	8.53	7.47	10.59	18.68	6.54	20.84	11.94
Ni	51.17	49.89	21.28	38.50	33.96	15.13	36.12	47.01
Cu	28.85	25.80	25.07	34.60	18.69	19.51	42.24	42.76
Zn	102.59	101.85	104.89	101.22	66.46	95.28	71.57	114.73
As	1.80	2.57	13.69	3.88		7.00	16.77	13.50
Ge	1.75	1.87	2.17	2.13		1.05	1.36	2.06
Ag			0.37	0.46				
Cd				0.13				
Sn	3.43	4.06	3.95	6.22	5.08	2.71	2.92	3.80
Sb	0.07		0.66	0.15	0.12		1.14	1.41
Re					0.0005			
Ga	33.40	34.48	31.64	35.05		22.88	25.14	30.26
La	93.38	92.15	82.76	99.46	63.06	65.66	52.40	64.43
Ce	161.35	167.36	164.12	194.18	122.20	223.40	109.70	132.36
Pr	21.15	20.49	21.24	23.53	13.71	37.31	13.04	16.70
Nd	71.54	69.57	76.37	78.79	51.14	191.98	44.74	59.11
Sm	11.40	10.69	14.78	12.68	8.51	55.44	8.60	11.73
Eu	1.97	1.74	2.63	2.29	1.56	21.55	1.44	2.13
Gd	7.98	6.65	10.97	8.94	6.22	62.15	6.95	9.95
Tb	0.91	0.78	1.40	1.07	0.80	7.92	0.97	1.33
Dy	5.18	4.51	8.20	6.07	4.58	41.29	5.90	7.64
Ho	0.94	0.88	1.58	1.14	0.87	7.16	1.17	1.47
Er	2.76	2.51	4.40	3.34	2.41	15.67	3.46	4.16
Tm	0.36	0.37	0.61	0.50	0.36	1.49	0.52	0.61
Yb	2.33	2.45	4.10	3.21	2.42	7.21	3.47	3.91
Lu	0.31	0.31	0.54	0.44	0.34	0.85	0.49	0.50
Eu/Eu*	0.63	0.63	0.63	0.66	0.66	1.13	0.57	0.61

Grp/Fm	MMGB		Middle Kaza Group (MKG)					
Unit	MMG	MKG	MKG	MKG	MKG	MKG	MKG	MKG
Type	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone
Sxn	MR1	CM1	CM1	CM2	CM2	CM2	CM2	CM2
ID#	MDS04-175	MDS03-001	MDS04-212	MDS05-027	MDS05-030	MDS05-035	MDS05-041	MDS05-043
SiO ₂	60.02	58.00	54.97	55.88	57.45	50.58	63.78	60.45
TiO ₂	0.79	0.69	0.87	0.67	0.69	0.70	0.75	0.63
Al ₂ O ₃	24.03	21.92	24.47	25.28	24.75	28.68	18.05	21.75
Fe ₂ O ₃	7.00	9.28	9.05	8.09	7.54	8.86	7.41	7.73
MnO	0.064	0.065	0.098	0.084	0.112	0.069	0.131	0.053
MgO	1.73	3.73	3.54	2.58	2.53	2.75	2.94	3.00
CaO	0.22	0.47	0.31	0.23	0.15	0.14	1.13	0.23
Na ₂ O	1.19	0.47	0.99	0.37	0.45	0.34	1.13	0.56
K ₂ O	4.61	5.07	5.32	6.41	6.00	7.49	4.24	5.29
P ₂ O ₅	0.17	0.11	0.15	0.17	0.10	0.10	0.21	0.08
LOI	4.5	4.6	4.3	5.1	4.7	5.0	4.8	4.3
Li	155.59	87.73	106.10	73.73	72.25	85.01	73.96	84.68
Sc	28.84	23.64	25.06	24.20	24.59	28.62	24.93	23.55
V	79.79	86.78	114.32	88.28	99.48	95.50	114.53	97.03
Rb	203.95	187.33	177.93	220.93	229.05	233.70	209.77	199.56
Sr	166.67	55.17	70.61	82.44	101.94	72.00	103.55	52.10
Y	20.43	29.01	30.79	28.93	23.82	27.83	24.21	29.82
Zr	119.63	112.23	158.14	78.80	92.43	92.85	163.76	169.37
Nb	18.87	11.54	15.00	14.57	15.90	12.82	14.57	14.92
Mo	0.33	0.20	0.43	0.62	0.27	0.25	0.94	0.25
Cs	6.82	7.06	5.43	8.04	7.42	7.41	8.72	6.21
Ba	798.38	932.23	855.80	1198.43	986.94	1333.59	1021.57	1116.34
Hf	3.67	3.20	4.59	2.48	2.83	2.96	4.70	4.93
Ta	1.44	0.82	1.10	1.09	1.10	0.96	1.02	1.02
Tl	1.16	1.02	0.89	1.22	1.31	1.39	1.05	1.05
Pb	9.72	3.20	41.10	3.37	4.33	3.29	26.22	3.24
Bi	0.09		0.13	0.03	0.04	0.05	0.44	0.02
Th	23.86	15.61	17.81	17.92	21.99	19.40	17.03	20.45
U	3.95	2.37	2.36	2.47	3.22	2.07	3.50	2.63
Cr	114.87	128.23	183.34	88.64	102.52	97.58	144.08	120.16
Co	14.45	24.72	23.82	13.75	13.39	16.50	12.36	20.74
Ni	47.35	90.96	77.15	31.89	40.58	42.41	68.37	59.63
Cu	37.31	7.34	54.20	3.46	34.04	14.62	31.64	43.05
Zn	111.40	129.12	112.35	114.69	111.19	120.17	127.14	113.51
As	19.72	0.23			4.36			
Ge	1.93	2.39	1.80	2.30	2.37	2.34	2.32	2.00
Ag				0.18	0.19	0.19	0.32	0.29
Cd								
Sn	3.69	3.43	3.04	3.35	3.23	2.87	2.98	3.21
Sb	0.38	0.96	0.52	0.34	0.39	0.55	0.38	0.34
Re								
Ga	31.02		31.45	24.16	25.37	23.69	20.77	20.05
La	73.76	37.78	64.16	78.55	85.95	73.12	55.50	73.72
Ce	142.78	72.36	127.24	138.18	149.45	131.85	110.74	134.56
Pr	16.96	8.61	14.64	17.70	19.90	17.05	12.84	17.11
Nd	56.07	30.07	50.56	58.82	65.70	56.76	43.69	58.12
Sm	8.81	6.26	8.68	9.47	11.34	9.70	8.11	10.40
Eu	1.45	1.69	1.65	1.66	2.05	1.90	1.56	2.16
Gd	6.14	7.32	7.31	8.13	8.55	8.22	6.51	8.59
Tb	0.69	1.08	1.03	1.06	1.01	1.09	0.86	1.14
Dy	4.25	6.82	6.17	6.56	5.31	6.23	5.04	6.51
Ho	0.84	1.30	1.19	1.20	0.94	1.13	0.99	1.26
Er	2.56	3.58	3.42	3.16	2.84	3.08	2.97	3.62
Tm	0.38	0.48	0.51	0.50	0.39	0.45	0.46	0.54
Yb	2.59	2.97	3.26	3.03	2.71	2.91	2.97	3.56
Lu	0.36	0.41	0.45	0.39	0.37	0.42	0.41	0.49
Eu/Eu*	0.60	0.77	0.64	0.58	0.64	0.65	0.66	0.70

Grp/Fm	Middle Miette Group - above OFP (MMGA)							
Unit	Hector	Hector	Hector	Wynd	Wynd	Wynd	Wynd	Wynd
Type	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone
Sxn	LL4	LL4	LL4	JP6	JP6	JP6	JP8	JP8
ID#	MDS05-164	MDS05-166	MDS05-167	RAR-01-07	RAR-01-08	RAR-01-09	RAR-01-11	RAR-01-12
SiO ₂	59.33	57.98	59.03	54.87	54.63	54.28	57.56	54.42
TiO ₂	0.55	0.87	0.63	1.09	1.04	0.90	0.83	0.88
Al ₂ O ₃	25.79	25.23	24.54	24.53	26.08	26.61	23.74	25.74
Fe ₂ O ₃	5.39	6.20	5.63	9.27	7.80	7.83	7.64	8.08
MnO	0.049	0.013	0.014	0.042	0.031	0.032	0.042	0.042
MgO	1.76	2.21	2.49	3.01	2.63	2.47	2.44	2.55
CaO	0.10	0.26	0.41	0.24	0.15	0.08	0.10	0.08
Na ₂ O	0.41	0.80	0.43	0.84	0.78	0.57	0.53	0.45
K ₂ O	6.32	6.03	6.35	5.72	6.48	6.94	6.80	7.41
P ₂ O ₅	0.09	0.16	0.25	0.10	0.10	0.08	0.11	0.09
LOI	4.1	5.0	5.7	4.3	4.4	4.5	3.9	4.1
Li	70.76	80.31	78.08	93.77	85.57	78.25	99.16	103.39
Sc	20.34	27.55	18.60	22.85	22.54	21.41	22.70	20.83
V	70.99	100.81	79.41	121.92	108.47	106.14	114.33	116.33
Rb	206.85	193.28	209.28	229.45	257.95	266.74	274.79	303.55
Sr	84.27	124.55	111.28	66.26	71.84	68.51	28.71	28.76
Y	27.19	23.66	27.32	26.60	29.02	18.12	23.56	24.15
Zr	78.29	157.03	111.58	259.27	171.57	72.40	142.31	122.38
Nb	12.37	18.00	14.66	25.24	25.97	22.25	20.58	22.14
Mo	0.28	0.41	0.45	0.20	0.19	0.06	0.23	0.26
Cs	4.96	5.25	6.01	5.53	5.37	6.37	6.82	6.97
Ba	1035.40	1079.07	935.17	962.67	1051.70	1103.20	1474.31	1607.13
Hf	2.52	4.82	3.49	5.55	6.34	2.67	5.52	4.61
Ta	0.92	1.53	1.12	2.09	2.43	1.78	2.00	1.80
Tl	1.14	1.12	1.10	1.13	1.31	1.44	1.53	1.71
Pb	13.68	10.87	30.36	5.90	16.45		39.68	6.87
Bi	0.32	0.40	0.47	0.16	0.38	0.11	0.15	0.18
Th	18.02	25.14	22.39	29.80	32.11	26.97	29.06	37.01
U	3.82	5.39	5.22	5.97	6.46	5.70	3.69	3.84
Cr	62.66	87.20	72.78	121.93	111.82	97.93	91.10	113.21
Co	21.33	10.49	10.63	15.31	17.90	9.68	5.67	2.73
Ni	34.50	41.50	30.46	39.38	35.75	25.11	23.93	20.10
Cu	45.71	28.84	29.90	18.35	21.18	27.71	18.31	12.15
Zn	83.93	86.89	98.11	80.87	73.34	72.97	92.78	58.97
As	2.22	5.48	16.19					
Ge	1.60	1.66	1.98					
Ag	0.23	0.31	0.33					
Cd		0.18						
Sn	3.17	4.29	3.39	6.37	7.24	7.02	6.19	6.14
Sb	0.08	0.12	0.29	0.18	0.14	0.11	0.12	0.08
Re				0.0017	0.0111		0.0003	0.0074
Ga	30.38	33.02	27.85					
La	80.81	87.57	90.25	87.86	80.92	78.80	106.24	183.23
Ce	154.08	176.18	169.74	166.43	156.88	130.36	195.44	311.98
Pr	18.73	20.66	20.61	18.84	17.67	15.17	21.36	35.37
Nd	61.92	68.71	68.97	69.68	62.94	50.02	78.20	126.44
Sm	10.47	10.38	11.49	10.84	9.14	5.69	12.10	18.95
Eu	1.91	1.74	2.09	1.54	1.49	1.01	2.09	3.10
Gd	8.08	7.36	9.04	6.96	7.09	3.98	8.33	11.52
Tb	1.01	0.85	1.14	0.89	0.95	0.50	0.90	1.14
Dy	5.96	5.21	6.16	5.39	5.82	3.31	4.85	5.35
Ho	1.10	1.02	1.17	1.06	1.12	0.68	0.89	0.98
Er	3.20	2.99	3.09	3.07	3.21	2.03	2.51	2.71
Tm	0.44	0.46	0.46	0.45	0.47	0.31	0.38	0.40
Yb	2.75	2.99	2.70	3.00	3.07	2.16	2.52	2.69
Lu	0.38	0.39	0.38	0.46	0.45	0.30	0.38	0.39
Eu/Eu*	0.64	0.61	0.63	0.55	0.57	0.65	0.64	0.64

Grp/Fm	Middle Miette Group - above OFP (MMGA)							
Unit	Wynd	Wynd	Wynd	Wynd	Wynd	Wynd	MMG	MMG
Type	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone
Sxn	JP8	JP8	JP8	JP7	JP7	JP7	MR1	MR1
ID#	RAR-01-13	RAR-01-14	RAR-01-17	RAR-01-32	RAR-01-33	RAR-01-34	MDS04-210	MDS04-211
SiO ₂	54.41	55.11	56.76	55.58	55.64	55.39	62.23	58.06
TiO ₂	0.77	0.82	0.72	0.93	0.86	0.94	0.63	0.69
Al ₂ O ₃	28.88	25.88	26.81	25.00	25.05	25.71	20.97	24.28
Fe ₂ O ₃	3.98	7.64	6.07	8.97	8.70	7.72	6.31	7.40
MnO	0.010	0.031	0.021	0.063	0.052	0.043	0.077	0.058
MgO	1.74	2.54	1.99	2.73	2.69	2.47	2.05	2.25
CaO	0.01	0.15	0.07	0.50	0.06	0.27	2.49	1.50
Na ₂ O	0.22	0.54	0.55	0.24	0.29	0.55	1.42	1.52
K ₂ O	9.65	6.97	6.73	5.74	6.41	6.53	3.56	3.93
P ₂ O ₅	0.03	0.11	0.07	0.07	0.06	0.13	0.07	0.10
LOI	4.6	4.2	4.2	4.8	4.4	6.4	10.7	5.9
Li	57.89	116.47	103.57	76.37	86.92	72.40	109.54	161.81
Sc	20.97	22.20	17.44	24.12	20.98	21.57	23.83	21.31
V	118.35	120.48	98.60	126.11	112.19	114.18	76.07	66.27
Rb	385.05	281.06	289.83	218.25	243.75	262.05	152.46	178.94
Sr	23.55	36.35	45.30	47.40	42.37	67.91	179.50	198.44
Y	21.31	18.29	16.14	27.40	16.62	23.73	38.47	30.01
Zr	75.38	104.87	75.48	147.88	132.47	181.08	127.46	138.31
Nb	18.23	21.44	15.86	22.35	21.21	22.91	14.66	16.27
Mo	1.00	0.17	0.24	0.36	0.40	0.31	0.66	
Cs	9.14	6.78	6.44	2.77	4.53	4.56	4.98	5.47
Ba	2056.84	1380.37	1577.70	1115.94	1346.98	1366.39	631.48	735.44
Hf	3.53	4.03	3.03	5.11	5.59	6.09	3.65	4.07
Ta	1.47	1.85	1.38	1.85	2.07	1.97	1.06	1.26
Tl	2.12	1.56	1.70	1.27	1.37	1.41	0.83	0.91
Pb	10.44	1.16	1.91	14.95	10.68	12.78	10.42	17.19
Bi	0.17	0.09	0.07	0.44	0.06	0.50	0.45	0.17
Th	15.02	24.94	19.45	28.08	27.27	22.13	16.45	21.33
U	3.03	3.54	3.84	4.31	4.53	5.25	2.88	2.23
Cr	96.87	104.02	85.43	102.90	98.90	112.25	84.66	86.48
Co	0.24	2.84	6.01	12.41	10.05	13.23	14.13	24.91
Ni	10.11	23.46	49.14	32.01	30.46	28.67	30.34	36.59
Cu	2.50	18.34	16.18	31.88	19.32	18.05	33.09	48.64
Zn	49.80	68.60	76.41	80.02	86.10	76.66	94.86	113.45
As							24.75	34.98
Ge							1.65	1.92
Ag								
Cd								
Sn	6.19	5.82	5.95	6.33	6.24	6.43	3.47	3.90
Sb	0.90	0.08	0.03	0.16	0.05	0.19	2.49	0.63
Re	0.0071		0.0062		0.0100			
Ga							28.08	31.21
La	65.73	69.10	47.66	77.47	64.99	81.90	55.31	74.59
Ce	113.63	133.43	71.84	148.39	117.11	152.70	105.89	144.64
Pr	14.26	15.52	8.77	16.72	13.00	17.08	12.48	16.93
Nd	52.43	58.15	30.12	61.96	47.35	62.67	41.76	55.58
Sm	8.25	9.58	4.50	10.16	6.97	9.41	6.91	9.40
Eu	1.28	1.56	0.76	1.58	1.08	1.52	1.28	1.71
Gd	4.76	6.57	3.83	7.71	4.77	6.64	7.80	8.04
Tb	0.61	0.70	0.55	0.98	0.59	0.81	1.29	1.05
Dy	3.97	3.87	3.39	5.79	3.61	4.70	7.91	6.21
Ho	0.80	0.73	0.68	1.13	0.71	0.91	1.46	1.18
Er	2.39	2.12	1.95	3.28	2.11	2.64	4.00	3.34
Tm	0.35	0.32	0.30	0.48	0.32	0.41	0.52	0.48
Yb	2.24	2.17	1.95	3.19	2.31	2.79	3.41	3.10
Lu	0.32	0.32	0.29	0.46	0.34	0.40	0.44	0.43
Eu/Eu*	0.63	0.60	0.56	0.55	0.58	0.59	0.53	0.61

Grp/Fm	Upper Kaza Group (UKG)							
Unit	MMGA	UKG	UKG	UKG	UKG	UKG	UKG	UKG
Type	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone
Sxn	MK1	CM1	CM1	CM3	CM3	CM3	CM3	CM3
ID#	MDS05-132	MDS03-030	MDS04-250	RAR-R01-17	RAR-R01-21	RAR-R01-42	RAR-R01-43	RAR-R01-54
SiO ₂	63.15	52.28	47.11	59.05	54.96	63.90	55.68	59.14
TiO ₂	0.83	0.78	1.09	0.72	0.91	0.54	0.92	0.68
Al ₂ O ₃	23.48	29.32	33.48	22.45	24.70	20.57	23.86	22.76
Fe ₂ O ₃	3.27	5.31	4.84	7.21	8.28	6.20	9.69	6.95
MnO	0.016	0.012	0.018	0.052	0.073	0.041	0.063	0.042
MgO	1.55	2.06	1.92	3.23	3.40	2.91	3.49	2.80
CaO	0.19	0.54	0.26	0.22	0.10	0.03	0.13	0.26
Na ₂ O	0.95	0.51	0.37	0.82	0.59	0.19	0.50	0.23
K ₂ O	6.23	8.70	10.31	5.94	6.65	5.42	5.36	6.68
P ₂ O ₅	0.11	0.18	0.21	0.10	0.09	0.04	0.10	0.20
LOI	4.4	4.9	5.0	4.3	4.4	3.7	4.4	4.9
Li	56.27	62.55	58.84	83.32	85.90	80.60	97.83	84.32
Sc	24.51	30.99	29.75	19.90	22.35	16.49	22.97	18.80
V	98.17	109.24	136.30	94.50	112.43	82.06	134.68	91.07
Rb	267.98	311.10	368.54	213.15	227.10	193.21	189.28	226.69
Sr	103.63	68.87	94.02	58.60	41.56	41.35	78.39	56.54
Y	32.14	45.37	64.27	25.81	18.41	20.07	20.03	22.78
Zr	134.29	91.80	131.78	168.53	125.72	86.88	127.83	91.20
Nb	22.58	17.69	22.53	13.80	16.06	10.64	16.04	12.39
Mo	0.88	0.27		0.50	0.64	0.18	0.39	0.70
Cs	6.78	8.43	9.92	6.12	6.96	6.18	5.06	6.81
Ba	1066.66	1532.10	2039.71	1165.99	1277.32	1028.68	1088.69	1264.64
Hf	4.15	2.90	4.07	5.78	5.10	2.36	4.72	3.62
Ta	1.72	1.36	1.70	1.15	1.45	0.77	1.20	1.05
Tl	1.42	1.79	2.18	1.20	1.30	1.08	1.05	1.33
Pb	12.26	8.21	7.59	18.79	8.35	1.04	1.52	30.12
Bi	0.34	0.19	0.10	0.26	0.10	0.05	0.17	0.39
Th	24.24	30.51	32.05	17.05	19.58	15.04	17.13	15.26
U	2.97	2.61	3.16	4.17	3.22	2.71	3.12	3.73
Cr	87.06	107.33	135.70	116.45	160.99	83.27	175.50	145.07
Co	2.95	7.96	6.83	37.70	11.52	7.00	16.83	23.82
Ni	3.90	13.85	29.66	122.86	31.42	44.91	60.08	48.28
Cu	8.68	3.00	11.48	60.00	12.06	10.50	26.09	27.59
Zn	71.80	93.08	72.98	67.18	67.15	60.65	82.84	67.79
As	10.86	2.82	14.34					
Ge	1.86	1.51	2.05					
Ag	0.32							
Cd								
Sn	5.47	5.56	7.60	3.84	5.41	4.27	4.24	4.44
Sb	0.80	0.88	0.91	0.90	0.29	0.34	0.44	0.61
Re				0.0029		0.0023		0.0025
Ga	26.63		50.72					
La	90.06	141.46	155.89	53.11	54.92	65.30	29.91	58.38
Ce	167.32	279.59	325.70	100.84	104.91	111.25	51.20	102.28
Pr	20.93	31.31	34.58	11.73	12.01	13.83	5.69	12.31
Nd	71.76	108.58	116.96	43.77	44.92	51.57	21.64	46.18
Sm	11.83	18.60	20.10	7.59	7.52	8.44	4.08	7.89
Eu	1.98	3.49	3.81	1.34	1.57	1.66	0.81	1.50
Gd	9.27	15.70	16.35	5.98	5.74	5.78	4.10	6.44
Tb	1.16	1.91	2.24	0.83	0.71	0.68	0.66	0.82
Dy	6.64	11.32	13.16	4.85	4.19	3.69	4.06	4.86
Ho	1.27	2.23	2.59	0.98	0.83	0.72	0.81	0.96
Er	3.60	6.00	7.21	2.89	2.42	2.06	2.40	2.67
Tm	0.51	0.81	0.99	0.43	0.37	0.32	0.37	0.39
Yb	3.32	4.79	5.90	2.95	2.49	2.13	2.41	2.54
Lu	0.45	0.63	0.78	0.44	0.38	0.32	0.36	0.37
Eu/Eu*	0.58	0.63	0.65	0.61	0.73	0.73	0.61	0.65

Grp/Fm	Upper Miette Group (UMG)							CG-IF
Unit	UMG	UMG	UMG	UMG	UMG	UMG	UMG	IF
Type	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone	mudstone
Sxn	MR3	MR3	MR3	MR3	MR3	MR3	MR3	CM3
ID#	RAR-01-06	RAR-01-38	RAR-01-39	RAR-R01-12	PRAR-R01-12	SRAR-R01-12	XRAR-R01-12	Y RAR-R01-62
SiO ₂	64.98	67.21	64.91	56.56	58.23	59.02	61.11	52.49
TiO ₂	0.74	0.60	0.60	0.72	0.95	0.88	1.01	0.96
Al ₂ O ₃	22.23	20.13	19.98	20.56	24.06	25.37	25.10	26.71
Fe ₂ O ₃	3.46	4.32	6.30	5.91	7.17	5.29	4.11	7.75
MnO	0.011	0.010	0.041	0.011	0.011	0.010	0.011	0.063
MgO	1.28	1.71	2.13	1.45	1.64	1.95	1.13	3.31
CaO	0.05	0.10	0.62	8.52	0.49	0.23	0.03	0.14
Na ₂ O	2.86	2.14	2.10	2.30	2.92	2.43	2.61	0.85
K ₂ O	4.17	3.51	3.08	3.56	3.91	4.37	4.62	7.38
P ₂ O ₅	0.03	0.06	0.08	0.19	0.37	0.21	0.03	0.10
LOI	5.9	3.6	3.9	7.5	5.6	4.1	5.4	4.4
Li	70.44	94.00	129.15	79.01	121.97	121.11	78.54	83.41
Sc	16.32	14.23	15.42	14.56	19.80	19.54	19.20	24.02
V	168.62	92.54	113.17	90.03	130.68	114.74	157.26	127.51
Rb	186.14	142.62	124.52	155.86	185.72	208.01	212.37	247.51
Sr	342.39	210.66	253.84	562.46	648.63	558.09	603.94	47.84
Y	48.41	17.45	28.90	42.11	23.69	26.73	34.93	16.79
Zr	86.21	79.87	84.97	104.24	135.29	144.15	121.55	183.38
Nb	19.93	15.29	14.68	17.00	26.24	24.30	26.24	16.23
Mo	4.05	0.50	0.68	0.76	0.86	0.40	0.92	0.24
Cs	7.38	5.16	4.99	4.67	5.66	2.20	7.36	7.05
Ba	878.42	799.14	574.86	814.72	769.55	808.62	869.67	1732.15
Hf	2.74	2.95	2.07	3.60	5.11	4.47	4.62	6.06
Ta	1.60	1.22	1.12	1.28	2.29	1.89	2.18	1.43
Tl	1.14	0.78	0.70	0.88	1.01	1.23	1.25	1.41
Pb	28.82	8.33	15.01	47.59	52.07	20.08	35.74	1.64
Bi	0.53	0.12	0.65	0.65	1.14	0.73	0.71	0.12
Th	10.11	16.22	20.43	18.79	24.73	24.91	13.92	21.07
U	2.77	4.02	4.32	2.18	3.64	2.37	2.27	2.71
Cr	168.34	69.10	86.12	85.54	108.15	112.02	163.46	175.70
Co	0.98	3.47	21.56	10.11	12.08	2.26	2.91	13.98
Ni	12.10	43.17	32.16	25.07	23.24	18.42	13.11	48.31
Cu	12.27	23.22	25.47	13.67	20.94	4.42	8.35	18.36
Zn	41.67	62.48	57.61	49.06	47.06	69.70	51.70	55.28
As								
Ge								
Ag								
Cd								
Sn	6.22	5.57	4.30	4.71	6.04	5.87	6.46	5.24
Sb	0.70	0.15	0.14	1.29	0.74	0.09	0.62	0.56
Re	0.0273		0.0083	0.0052	0.0042	0.0034		
Ga								
La	104.82	55.83	82.01	101.68	81.73	59.80	73.56	63.75
Ce	207.81	100.28	145.18	182.86	154.71	108.42	133.92	119.01
Pr	26.98	12.26	17.37	22.29	17.71	13.33	16.03	13.53
Nd	103.39	45.16	62.14	82.99	64.79	48.69	59.10	52.34
Sm	16.10	7.41	10.03	13.00	9.95	7.71	9.40	8.80
Eu	1.95	1.10	1.47	1.81	1.49	1.11	1.32	1.70
Gd	11.55	4.80	7.78	10.94	6.31	5.76	7.49	6.04
Tb	1.50	0.59	0.97	1.42	0.78	0.76	1.06	0.68
Dy	9.07	3.51	5.68	8.50	4.60	4.78	6.64	3.85
Ho	1.79	0.68	1.05	1.62	0.89	0.98	1.34	0.73
Er	4.85	1.92	2.97	4.33	2.47	2.91	3.87	2.27
Tm	0.66	0.29	0.41	0.61	0.37	0.41	0.56	0.37
Yb	3.73	1.88	2.70	3.62	2.38	2.51	3.46	2.63
Lu	0.47	0.26	0.37	0.48	0.32	0.33	0.49	0.41
Eu/Eu*	0.44	0.57	0.51	0.47	0.58	0.51	0.48	0.72

Grp/Fm	Cariboo Group - Isaac Formation (IF)							
Unit	IF	IF	IF	IF	IF	IF	IF	IF
Type	mudstone	mudstone	mudstone	clast	mudstone	mudstone	mudstone	mudstone
Sxn	CM3	CM3	CM3	CM3	CM3	CM3	CM3	CM3
ID#	IRAR-R01-14D	IRAR-R01-14K	IRAR-R01-14Q	IRAR-R01-14Z	HT04019	HT04024	HT04028	HT04030
SiO ₂	53.88	50.25	53.47	51.85	51.89	60.94	68.14	49.39
TiO ₂	0.93	1.21	1.09	1.18	0.88	0.94	0.78	0.54
Al ₂ O ₃	26.15	29.53	25.27	28.41	26.41	18.44	13.96	12.64
Fe ₂ O ₃	9.90	8.38	8.43	4.23	11.48	7.75	9.11	7.30
MnO	0.063	0.021	0.021	0.010	0.060	0.098	0.120	0.100
MgO	3.15	2.66	2.50	1.61	3.52	3.78	2.92	4.37
CaO	0.26	0.17	1.95	2.84	0.30	2.57	0.93	20.66
Na ₂ O	1.43	0.91	0.92	0.94	1.23	0.65	1.33	1.80
K ₂ O	3.83	6.46	4.68	6.56	3.81	4.41	2.48	2.94
P ₂ O ₅	0.20	0.13	1.43	2.10	0.21	0.23	0.07	0.06
LOI	4.9	4.7	4.4	4.1	5.6	5.6	3.7	17.7
Li	135.68	95.84	104.64	67.05	165.66	66.07	85.80	21.57
Sc	21.79	25.45	23.66	21.02	28.71	21.45	21.01	14.76
V	142.50	163.88	139.16	174.85	150.48	92.24	74.11	52.11
Rb	135.48	215.67	159.93	175.27	127.18	132.82	86.83	92.46
Sr	242.48	142.92	202.70	138.07	194.14	247.51	78.02	509.81
Y	28.92	25.12	24.52	37.07	38.64	30.99	28.76	20.48
Zr	94.09	242.18	254.10	367.13	109.62	236.25	390.79	187.20
Nb	17.31	19.82	18.03	17.89	15.80	24.60	21.63	11.39
Mo	0.63	0.33	0.35	0.65	0.84	0.70	0.94	0.62
Cs	5.88	6.09	5.71	4.92	5.21	4.54	3.54	3.36
Ba	753.03	1123.40	718.64	1380.39	720.93	530.29	377.54	417.77
Hf	3.11	7.14	7.73	8.78	3.49	6.94	11.37	5.47
Ta	1.14	1.47	1.51	1.54	1.15	1.74	1.56	0.76
Tl	0.76	1.21	0.89	1.18	0.72	0.69	0.40	0.41
Pb	22.29	21.65	22.10	23.52	30.84	21.87	27.17	26.72
Bi	0.31	0.16	0.19	0.15	0.79	0.51	0.38	0.32
Th	17.58	17.02	18.90	20.87	19.99	16.46	19.29	9.77
U	4.09	3.41	5.31	15.05	4.72	3.63	2.76	2.12
Cr	189.93	228.12	208.05	256.47	166.62	115.00	84.21	47.93
Co	18.23	35.76	27.83	10.65	27.35	21.70	20.99	9.52
Ni	70.51	53.37	59.34	30.72	77.93	46.94	60.24	26.68
Cu	29.36	23.75	28.22	9.17	64.86	39.53	45.27	26.08
Zn	103.37	55.98	83.61	38.51	164.15	89.84	116.15	76.21
As					8.89	4.65		
Ge					1.99	1.87	1.62	0.92
Ag					0.36	0.44	0.33	0.30
Cd						0.14		
Sn	5.49	6.08	5.50	2.12	2.61	3.96	1.93	1.51
Sb	0.47	0.15	0.31	0.25	0.52	0.84	0.42	0.42
Re				0.0049				
Ga					32.57	19.56	17.51	12.15
La	43.85	59.81	57.78	34.50	69.77	56.11	50.85	31.57
Ce	76.86	116.22	103.55	59.26	137.74	116.65	104.61	67.77
Pr	8.24	12.70	11.41	6.52	15.87	13.95	12.20	7.69
Nd	28.59	48.03	43.95	26.52	53.41	49.13	41.09	27.21
Sm	4.73	8.31	8.96	8.00	9.64	10.30	7.04	5.56
Eu	1.06	1.51	2.30	2.07	2.09	1.88	1.36	1.22
Gd	5.19	6.75	8.85	11.60	9.27	8.56	5.94	5.41
Tb	0.84	0.86	1.04	1.52	1.33	1.12	0.86	0.69
Dy	5.37	5.08	5.47	8.32	8.42	6.34	5.52	4.10
Ho	1.09	0.99	0.98	1.56	1.63	1.27	1.18	0.77
Er	3.05	2.94	2.77	4.48	4.70	3.62	3.44	2.22
Tm	0.44	0.45	0.42	0.66	0.63	0.53	0.51	0.32
Yb	2.81	2.84	3.05	4.54	4.08	3.43	3.51	2.15
Lu	0.42	0.44	0.46	0.68	0.52	0.48	0.48	0.29
Eu/Eu*	0.66	0.62	0.79	0.66	0.68	0.61	0.65	0.68

APPENDIX I: Total %C analyses for carbonate CO₂.

Sample #	total %C	%CO ₂ tot.	%CO ₂ carb.	Sample #	total %C	%CO ₂ total	%CO ₂ carb.
HT04019	0.109	0.40	0.02	MDS04-250	0.098	0.36	0.02
HT04024	1.021	3.74	3.08	MDS05-003	0.649	2.38	0.02
HT04028	0.479	1.76	1.43	MDS05-007	0.160	0.59	0.02
HT04030	5.098	18.68	16.60	MDS05-025	0.306	1.12	0.82
MDS03-01	0.038	0.14	0.07	MDS05-027	0.029	0.11	0.02
MDS03-03	0.604	2.21	2.14	MDS05-030	0.052	0.19	0.00
MDS03-05	0.835	3.06	2.99	MDS05-035	0.022	0.08	0.02
MDS03-07	0.870	3.19	3.11	MDS05-041	0.352	1.29	1.13
MDS03-13	0.761	2.79	2.72	MDS05-043	0.045	0.16	0.02
MDS03-16	0.898	3.29	1.93	MDS05-067	0.070	0.26	0.02
MDS03-19	2.235	8.19	2.66	MDS05-072	0.264	0.97	0.72
MDS03-23	3.842	14.08	11.89	MDS05-077	0.024	0.09	0.02
MDS03-26	0.167	0.61	0.54	MDS05-083	0.401	1.47	0.91
MDS03-30	0.099	0.36	0.29	MDS05-087	0.755	2.77	0.23
MDS04-001	1.417	5.19	4.80	MDS05-092	0.800	2.93	0.64
MDS04-002	3.472	12.72	12.30	MDS05-128A	2.742	10.05	6.35
MDS04-003	4.005	14.68	14.25	MDS05-132	1.206	4.42	0.02
MDS04-007	0.600	2.20	0.73	MDS05-134	1.001	3.67	0.02
MDS04-008	0.654	2.40	0.93	MDS05-157	0.424	1.55	0.02
MDS04-010	0.962	3.52	2.06	MDS05-163	0.177	0.65	0.02
MDS04-011	0.795	2.91	0.82	MDS05-164	0.067	0.25	0.02
MDS04-014	0.080	0.29	0.02	MDS05-166	0.106	0.39	0.02
MDS04-015	0.119	0.44	0.02	MDS05-167	0.138	0.51	0.02
MDS04-021	0.061	0.22	0.02	RAR-01-06	2.221	8.14	2.30
MDS04-024	0.028	0.10	0.02	RAR-01-07	0.104	0.38	0.38
MDS04-029	0.062	0.23	0.02	RAR-01-08	0.073	0.27	0.23
MDS04-030	0.038	0.14	0.02	RAR-01-09	0.057	0.21	0.17
MDS04-041	0.246	0.90	0.30	RAR-01-11	0.066	0.24	0.21
MDS04-042	0.226	0.83	0.15	RAR-01-12	0.048	0.18	0.14
MDS04-043	0.170	0.62	0.02	RAR-01-13	0.240	0.88	0.26
MDS04-044	0.391	1.43	0.02	RAR-01-14	0.085	0.31	0.31
MDS04-045	0.525	1.92	1.49	RAR-01-17	0.044	0.16	4.15
MDS04-048	0.296	1.08	0.49	RAR-01-22	0.265	0.97	0.97
MDS04-065	1.114	4.08	3.56	RAR-01-23	0.830	3.04	5.85
MDS04-089	0.516	1.89	1.43	RAR-01-24	1.151	4.22	6.43
MDS04-105	3.577	13.11	12.36	RAR-01-25KK	0.679	2.49	2.41
MDS04-111	0.344	1.26	0.02	RAR-01-27	3.458	12.67	12.63
MDS04-112	0.580	2.13	0.02	RAR-01-28	3.265	11.96	11.96
MDS04-116	0.074	0.27	0.02	RAR-01-29	0.470	1.72	1.39
MDS04-118	0.238	0.87	0.41	RAR-01-30	0.204	0.75	0.75
MDS04-133	1.093	4.01	3.65	RAR-01-31	0.261	0.96	0.92
MDS04-152	0.711	2.60	1.98	RAR-01-32	0.237	0.87	0.83
MDS04-166	0.475	1.74	0.02	RAR-01-33	0.089	0.33	0.25
MDS04-167	0.381	1.40	0.02	RAR-01-34	0.085	0.31	0.24
MDS04-168	0.072	0.26	0.02	RAR-01-38	0.300	1.10	1.03
MDS04-169	0.063	0.23	0.02	RAR-01-39	0.534	1.96	0.02
MDS04-174	0.549	2.01	1.55	RAR-R01-120E	0.546	2.00	1.78
MDS04-175	0.043	0.16	0.02	RAR-R01-12P	0.411	1.50	0.95
MDS04-176	0.198	0.73	0.45	RAR-R01-12S	0.907	3.32	2.66
MDS04-183	0.132	0.49	0.20	RAR-R01-12X	0.367	1.34	1.05
MDS04-186	0.646	2.37	2.07	RAR-R01-12Y	1.251	4.59	3.01
MDS04-188B	2.083	7.63	6.99	RAR-R01-17	0.110	0.40	0.37
MDS04-202	5.835	21.38	20.95	RAR-R01-21	0.064	0.23	0.23
MDS04-208	1.667	6.11	0.02	RAR-R01-42	0.024	0.09	0.09
MDS04-209	0.955	3.50	0.02	RAR-R01-43	0.020	0.07	0.07
MDS04-210	1.171	4.29	2.44	RAR-R014-DD	0.149	0.55	0.55
MDS04-211	0.616	2.26	1.47	RAR-R014-K	0.037	0.14	0.14
MDS04-212	0.037	0.13	0.02	RAR-R014-Q	0.093	0.34	0.30
MDS04-219	0.316	1.16	0.82	RAR-R014-Z	0.084	0.31	0.27
MDS04-234B	2.268	8.31	4.31	RAR-R01-54	0.135	0.50	0.46
MDS04-236	2.399	8.79	3.75	RAR-R01-62	0.056	0.21	0.21

APPENDIX J: Electron microprobe analyses of carbonate phases from the Old Fort Point Formation.

Sample Number	Old Fort Point Fm.			Oxide analyses (wt%)							Total (wt%)	Total (mol)	Normalized carbonate (wt%)					(ppm)	
	Lct.	Facies	Phase	CaO	MgO	FeO	MnO	SrO	SiO ₂	CaCO ₃			MgCO ₃	FeCO ₃	MnCO ₃	Sr			
MDS03-008-L1-1	CM1	TLM-2	CC3	55.18	0.77	1.66	1.27	0.14	0.00	59.02	1.0457	94.10	1.83	2.21	1.71	1184			
MDS03-008-L1-2	CM1	TLM-2	CC3	55.37	0.70	1.64	1.29	0.23	0.03	59.26	1.0483	94.18	1.66	2.18	1.73	1945			
MDS03-008-L1-3	CM1	TLM-2	CC3	55.26	0.78	1.70	1.23	0.22	0.02	59.21	1.0482	94.00	1.85	2.26	1.65	1860			
MDS03-008-L1-4	CM1	TLM-2	CC3	55.61	0.72	1.81	1.45	0.19	0.00	59.78	1.0573	93.79	1.69	2.38	1.93	1607			
MDS03-014-L1-1	CM1	TLM-3	CC2	59.06	0.71	1.26	0.43	0.17	0.05	61.68	1.0963	96.06	1.61	1.60	0.55	1438			
MDS03-014-L1-2	CM1	TLM-3	CC2	57.51	0.76	1.14	0.34	0.13	0.01	59.89	1.0665	96.16	1.77	1.49	0.45	1099			
MDS03-014-L1-3	CM1	TLM-3	CC2	57.84	0.70	1.03	0.37	0.14	0.02	60.10	1.0699	96.40	1.62	1.34	0.49	1184			
MDS03-014-L1-4	CM1	TLM-3	CC1	57.43	0.93	0.22	0.31	0.02	0.03	58.94	1.0548	97.09	2.19	0.29	0.41	169			
MDS03-014-L2-1	CM1	TLM-3	CC2	57.65	0.82	0.62	0.34	0.09	0.05	59.57	1.0628	96.73	1.91	0.81	0.45	761			
MDS03-014-L2-2	CM1	TLM-3	CC2	57.83	0.82	0.88	0.37	0.12	0.00	60.02	1.0704	96.34	1.90	1.14	0.49	1015			
MDS03-014-L2-3	CM1	TLM-3	CC2	57.14	0.77	0.67	0.33	0.07	0.42	59.40	1.0528	96.78	1.81	0.89	0.44	592			
MDS03-014-L2-4	CM1	TLM-3	CC2	56.95	0.68	0.75	0.39	0.14	0.00	58.91	1.0499	96.72	1.61	0.99	0.52	1184			
MDS03-014-L2-5	CM1	TLM-3	CC1	56.22	0.97	0.31	0.37	0.04	0.41	58.32	1.0365	96.72	2.32	0.42	0.50	338			
MDS03-014-L3-1	CM1	TLM-3	CC2	57.52	0.76	0.30	0.33	0.03	0.00	58.94	1.0537	97.34	1.79	0.40	0.44	254			
MDS03-014-L3-2	CM1	TLM-3	CC2	56.77	0.71	0.30	0.33	0.04	0.00	58.15	1.0392	97.41	1.69	0.40	0.45	338			
MDS03-014-L3-3	CM1	TLM-3	CC2	57.71	0.74	0.26	0.35	0.09	0.19	59.34	1.0570	97.36	1.74	0.34	0.47	761			
MDS03-014-L3-4	CM1	TLM-3	CC2	57.10	0.72	0.28	0.31	0.02	0.00	58.43	1.0445	97.48	1.71	0.37	0.42	169			
MDS03-015-L1-1	CM1	GSM-1	CC2	57.36	0.71	0.87	0.35	0.10	0.27	59.66	1.0586	96.62	1.66	1.14	0.47	846			
MDS03-015-L1-2	CM1	GSM-1	CC2	55.63	0.75	1.10	0.40	0.16	0.00	58.04	1.0334	96.00	1.80	1.48	0.55	1353			
MDS03-015-L1-3	CM1	GSM-1	CC2	57.12	0.64	0.98	0.34	0.19	0.04	59.31	1.0550	96.54	1.50	1.29	0.45	1607			
MDS03-015-L1-4	CM1	GSM-1	CC2	56.58	0.73	0.87	0.27	0.13	0.31	58.89	1.0444	96.60	1.73	1.16	0.36	1099			
MDS03-015-L1-5	CM1	GSM-1	CC2	56.64	0.99	0.64	0.32	0.09	0.17	58.85	1.0490	96.28	2.34	0.85	0.43	761			
MDS03-015-L1-6	CM1	GSM-1	CC2	55.30	0.68	0.99	0.34	0.12	1.47	58.90	1.0229	96.40	1.65	1.35	0.47	1015			
MDS03-015-L2-1	CM1	GSM-1	CC4	57.30	0.34	0.83	0.29	0.34	0.00	59.10	1.0497	97.34	0.80	1.10	0.39	2875			
MDS03-015-L2-2	CM1	GSM-1	CC4	57.55	0.36	0.81	0.29	0.41	0.01	59.43	1.0552	97.25	0.85	1.07	0.39	3467			
MDS03-015-L2-3	CM1	GSM-1	CC4	56.27	0.39	0.89	0.34	0.41	0.00	58.30	1.0349	96.95	0.93	1.20	0.46	3467			
MDS03-015-L2-4	CM1	GSM-1	CC4	58.19	0.40	1.03	0.32	0.52	0.00	60.46	1.0723	96.76	0.93	1.34	0.42	4397			
MDS03-019-L1-1	CM1	GSM-1	DOL2	30.11	14.68	10.36	0.57	0.04	0.00	55.76	1.0538	50.95	34.56	13.68	0.76	338			
MDS03-019-L1-2	CM1	GSM-1	DOL2	29.86	14.37	10.85	0.58	0.13	0.07	55.86	1.0496	50.73	33.96	14.39	0.78	1099			
MDS03-019-L1-3	CM1	GSM-1	CC3	57.36	0.73	1.28	0.32	0.14	0.00	59.83	1.0649	96.05	1.70	1.67	0.42	1184			
MDS03-019-L1-4	CM1	GSM-1	CC3	57.36	0.60	1.33	0.34	0.20	0.00	59.83	1.0633	96.19	1.40	1.74	0.45	1691			
MDS03-019-L2-1	CM1	GSM-1	CC3	57.52	0.74	1.23	0.26	0.16	0.00	59.91	1.0666	96.16	1.72	1.60	0.34	1353			
MDS03-019-L2-2	CM1	GSM-1	CC3	56.27	0.75	1.24	0.27	0.20	0.01	58.74	1.0453	95.99	1.78	1.65	0.36	1691			
MDS03-019-L2-3	CM1	GSM-1	CC3	57.59	0.88	1.40	0.23	0.16	0.00	60.26	1.0733	95.68	2.03	1.82	0.30	1353			
MDS03-019-L2-4	CM1	GSM-1	CC3	57.00	0.88	1.43	0.24	0.18	0.02	59.75	1.0636	95.56	2.05	1.87	0.32	1522			
MDS03-214-L1-1	CM1	TLM-1	DOL2	28.68	13.96	10.97	1.91	0.05	0.00	55.57	1.0379	49.27	33.37	14.71	2.59	423			
MDS03-214-L1-2	CM1	TLM-1	DOL2	29.36	13.63	11.27	1.92	0.07	0.00	56.25	1.0464	50.03	32.31	14.99	2.59	592			
MDS03-214-L1-3	CM1	TLM-1	DOL2	29.83	15.72	6.99	2.13	0.13	0.00	54.80	1.0507	50.63	37.12	9.26	2.86	1099			
MDS03-214-L1-4	CM1	TLM-1	DOL2	29.90	15.97	7.16	1.85	0.10	0.04	55.02	1.0562	50.48	37.51	9.43	2.47	846			
MDS04-001-A1-1	JP1	TLM-1	DOL2	29.51	14.70	8.66	1.37	0.04	0.00	54.28	1.0312	51.03	35.36	11.69	1.87	338			
MDS04-001-A1-2	JP1	TLM-1	DOL2	29.27	12.32	12.44	0.94	0.04	0.00	55.01	1.0144	51.45	30.13	17.07	1.31	338			
MDS04-001-A1-3	JP1	TLM-1	DOL2	29.38	14.71	9.37	1.32	0.04	0.02	54.84	1.0383	50.46	35.15	12.56	1.79	338			

Sample Number	Old Fort Point Fm.			Oxide analyses (wt%)							Total		Normalized carbonate (wt%)					(ppm)	
	Lct.	Facies	Phase	CaO	MgO	FeO	MnO	SrO	SiO ₂	Total (wt%)	Total (mol)		CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	Sr		
MDS04-001-A1-4	JP1	TLM-1	DOL1	34.43	19.22	0.60	0.32	0.00	0.00	54.57	1.1036		55.63	43.20	0.76	0.41		0	
MDS04-001-A1-5	JP1	TLM-1	DOL1	31.19	22.28	0.10	0.00	0.00	0.02	53.59	1.1103		50.09	49.78	0.13	0.00		0	
MDS04-001-A1-6	JP1	TLM-1	DOL1	34.20	20.66	0.34	0.07	0.00	0.65	55.92	1.1281		54.06	45.43	0.42	0.09		0	
MDS04-001-A1-7	JP1	TLM-1	DOL2	29.91	15.33	6.99	1.40	0.00	0.04	53.06	1.0307		51.75	36.90	9.44	1.91		85	
MDS04-001-A2-1	JP1	TLM-1	DOL1	30.19	21.57	0.36	0.47	0.01	0.46	53.67	1.0852		49.61	49.31	0.46	0.61		85	
MDS04-001-A2-2	JP1	TLM-1	DOL2	30.79	15.17	6.78	1.33	0.01	0.02	54.10	1.0386		52.86	36.23	9.09	1.81		85	
MDS04-001-A2-3	JP1	TLM-1	DOL1	34.56	19.71	0.49	0.08	0.00	0.65	55.49	1.1132		55.36	43.93	0.61	0.10		0	
MDS04-001-A2-4	JP1	TLM-1	DOL2	28.79	12.51	12.27	0.96	0.02	0.15	54.70	1.0083		50.92	30.78	16.94	1.34		169	
MDS04-001-A2-5	JP1	TLM-1	DOL2	28.46	14.50	9.60	1.06	0.02	0.38	54.02	1.0160		49.95	35.41	13.15	1.47		169	
MDS04-002-L1-1	JP1	TLM-2	DOL2	28.49	12.16	13.18	0.79	0.06	0.03	54.71	1.0049		50.55	30.02	18.25	1.11		507	
MDS04-002-L1-2	JP1	TLM-2	DOL2	28.63	12.08	13.31	0.87	0.03	0.00	54.92	1.0081		50.64	29.73	18.38	1.22		254	
MDS04-002-L1-3	JP1	TLM-2	DOL2	28.97	14.74	9.32	1.16	0.03	0.06	54.28	1.0287		50.22	35.55	12.61	1.59		254	
MDS04-002-L1-4	JP1	TLM-2	DOL2	29.05	14.98	8.65	1.35	0.04	0.00	54.07	1.0295		50.32	36.10	11.69	1.85		338	
MDS04-004-A1-1	JP1	TLM-3	CC2	55.44	0.37	0.50	0.11	0.03	0.13	56.58	1.0066		98.21	0.91	0.69	0.15		254	
MDS04-004-A1-2	JP1	TLM-3	CC2	55.44	0.44	0.24	0.12	0.00	0.17	56.41	1.0045		98.41	1.09	0.33	0.17		0	
MDS04-004-A1-3	JP1	TLM-3	CC2	55.53	0.41	0.61	0.14	0.03	0.26	56.98	1.0112		97.93	1.01	0.84	0.20		254	
MDS04-004-A1-4	JP1	TLM-3	CC2	55.15	0.47	0.24	0.15	0.00	1.17	57.18	1.0005		98.29	1.17	0.33	0.21		0	
MDS04-004-A1-5	JP1	TLM-3	CC2	55.35	0.55	0.06	0.06	0.00	0.15	56.17	1.0023		98.47	1.36	0.08	0.08		0	
MDS04-004-A1-6	JP1	TLM-3	CC1	54.68	0.43	0.50	0.07	0.01	0.26	55.95	0.9938		98.12	1.07	0.70	0.10		85	
MDS04-004-A1-7	JP1	TLM-3	CC1	53.16	0.48	0.32	0.06	0.00	1.75	55.77	0.9651		98.22	1.23	0.46	0.09		0	
MDS04-004-A2-1	JP1	TLM-3	CC2	55.39	0.46	0.79	0.13	0.03	0.10	56.90	1.0123		97.57	1.13	1.09	0.18		254	
MDS04-004-A2-2	JP1	TLM-3	CC2	56.12	0.41	0.76	0.16	0.00	0.07	57.52	1.0237		97.75	0.99	1.03	0.22		0	
MDS04-004-A2-3	JP1	TLM-3	CC2	56.72	0.44	0.85	0.16	0.02	0.06	58.25	1.0366		97.57	1.05	1.14	0.22		169	
MDS04-004-A2-4	JP1	TLM-3	CC2	55.71	0.41	0.60	0.10	0.02	0.20	57.04	1.0136		98.01	1.00	0.82	0.14		169	
MDS04-004-A2-5	JP1	TLM-3	CC1	54.70	0.73	0.22	0.04	0.00	0.98	56.67	0.9971		97.82	1.82	0.31	0.06		0	
MDS04-004-A2-6	JP1	TLM-3	CC1	56.13	0.54	0.00	0.11	0.00	0.04	56.82	1.0158		98.53	1.32	0.00	0.15		0	
MDS04-004-A2-7	JP1	TLM-3	CC1	55.46	0.57	0.13	0.03	0.01	0.73	56.93	1.0054		98.36	1.41	0.18	0.04		85	
MDS04-004-A2-8	JP1	TLM-3	CC1	55.55	0.55	0.12	0.13	0.00	0.49	56.84	1.0077		98.30	1.35	0.17	0.18		0	
MDS04-009-L1-1	JP1	GSM-1	CC2	54.80	0.33	0.73	0.87	0.02	0.71	57.46	1.0080		96.94	0.81	1.01	1.22		169	
MDS04-009-L1-2	JP1	GSM-1	CC1	54.61	1.22	0.02	0.17	0.00	0.54	56.56	1.0067		96.73	3.01	0.03	0.24		0	
MDS04-009-L1-3	JP1	GSM-1	CC1	54.53	1.37	0.05	0.12	0.00	0.78	56.85	1.0087		96.39	3.37	0.07	0.17		0	
MDS04-009-L1-4	JP1	GSM-1	CC1	54.66	1.35	0.09	0.06	0.00	0.65	56.81	1.0103		96.48	3.32	0.12	0.08		0	
MDS04-009-L2-1	JP1	GSM-1	CC2	55.94	0.47	0.58	0.57	0.02	0.41	57.99	1.0255		97.27	1.14	0.79	0.78		169	
MDS04-009-L2-2	JP1	GSM-1	CC1	56.78	0.76	0.16	0.19	0.01	0.28	58.18	1.0364		97.70	1.82	0.21	0.26		85	
MDS04-009-L3-1	JP1	GSM-1	CC2	55.44	0.37	0.90	0.59	0.01	0.79	58.10	1.0187		97.04	0.90	1.23	0.82		85	
MDS04-009-L3-2	JP1	GSM-1	CC1	55.95	0.93	0.12	0.19	0.00	0.53	57.72	1.0251		97.33	2.25	0.16	0.26		0	
MDS04-009-L4-1	JP1	GSM-1	CC2	55.50	0.38	0.84	0.79	0.03	0.60	58.14	1.0223		96.81	0.92	1.14	1.09		254	
MDS04-009-L4-2	JP1	GSM-1	CC1	56.47	1.47	0.09	0.19	0.00	0.23	58.45	1.0474		96.14	3.48	0.12	0.26		0	
MDS04-009-L5-1	JP1	GSM-1	CC2	54.99	0.69	1.21	0.58	0.02	1.50	58.99	1.0229		95.86	1.67	1.65	0.80		169	
MDS04-009-L5-2	JP1	GSM-1	CC1	57.42	0.92	0.04	0.12	0.00	0.09	58.59	1.0490		97.61	2.18	0.05	0.16		0	
MDS04-028B-A1-P1-1	LL4	WMM-8	CC3	55.29	0.52	0.75	1.34	0.25	0.00	58.15	1.0310		95.63	1.25	1.01	1.83		2114	
MDS04-028B-A1-P1-2	LL4	WMM-8	CC3	56.03	0.32	0.50	1.41	0.10	0.00	58.39	1.0350		96.53	0.77	0.67	1.92		846	

Sample Number	Lct.	Old Fort Point Frn.			Oxide analyses (wt%)							Total		Normalized carbonate (wt%)					(ppm)	
		Facies	Phase	CaO	MgO	FeO	MnO	SrO	SiO ₂	Total	(wt%)	Total	(mol)	CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	Sr		
MDS04-028B-A1-P1-3	LL4	WMM-8	CC3	55.79	0.34	0.45	1.40	0.12	0.00	58.10	1.0306	1.0306	96.53	0.82	0.61	1.91	1015			
MDS04-028B-A1-P1-4	LL4	WMM-8	CC3	55.85	0.40	0.54	1.67	0.12	0.00	58.61	1.0382	1.0382	95.92	0.96	0.72	2.27	1015			
MDS04-028B-A2-P1-1	LL4	WMM-8	CC3	55.97	0.61	0.62	1.24	0.27	0.04	58.80	1.0424	1.0424	95.75	1.45	0.83	1.68	2283			
MDS04-028B-A2-P1-2	LL4	WMM-8	CC3	56.05	0.35	0.41	1.14	0.18	0.00	58.13	1.0320	1.0320	96.85	0.84	0.55	1.56	1522			
MDS04-028B-A2-P1-3	LL4	WMM-8	CC3	55.76	0.57	0.57	1.48	0.14	0.00	58.60	1.0388	1.0388	95.71	1.36	0.76	2.01	1184			
MDS04-028B-A2-P1-4	LL4	WMM-8	CC3	56.19	0.68	0.67	1.54	0.21	0.03	59.32	1.0523	1.0523	95.22	1.60	0.89	2.06	1776			
MDS04-028B-A2-P1-5	LL4	WMM-8	CC3	54.77	0.48	0.55	1.79	0.14	0.00	57.73	1.0230	1.0230	95.47	1.16	0.75	2.47	1184			
MDS04-028B-A3-P1-1	LL4	WMM-8	DOL2	32.63	13.89	5.94	2.98	0.05	0.02	55.51	1.0517	1.0517	55.33	32.76	7.86	3.99	423			
MDS04-028B-A3-P1-2	LL4	WMM-8	CC3	57.00	0.36	0.60	1.22	0.15	0.00	59.33	1.0526	1.0526	96.56	0.85	0.79	1.63	1268			
MDS04-028B-A3-P1-3	LL4	WMM-8	DOL2	30.73	14.11	6.34	3.16	0.07	1.04	55.53	1.0316	1.0316	53.12	33.93	8.55	4.32	592			
MDS04-028B-A3-P1-4	LL4	WMM-8	CC3	53.27	0.44	0.54	1.01	0.14	0.00	55.43	0.9842	0.9842	96.52	1.11	0.76	1.45	1184			
MDS04-028B-A3-P1-5	LL4	WMM-8	CC1	56.74	1.17	0.22	0.32	0.00	0.25	58.71	1.0484	1.0484	96.51	2.77	0.29	0.43	0			
MDS04-028B-A3-P1-6	LL4	WMM-8	CC1	56.87	1.26	0.06	0.16	0.01	0.18	58.54	1.0485	1.0485	96.71	2.98	0.08	0.22	85			
MDS04-028E-A1-L1-1	LL4	WMM-8	CC-BLD	58.54	1.03	0.02	0.06	0.04	0.00	59.70	1.0710	1.0710	97.47	2.39	0.03	0.08	338			
MDS04-028E-A1-L1-2	LL4	WMM-8	CC-BLD	57.71	0.74	0.02	0.14	0.00	0.00	58.61	1.0497	1.0497	98.04	1.75	0.03	0.19	0			
MDS04-028E-A1-L1-3	LL4	WMM-8	CC-BLD	56.17	1.14	0.34	0.17	0.06	0.00	57.88	1.0377	1.0377	96.52	2.73	0.46	0.23	507			
MDS04-028E-A1-L1-4	LL4	WMM-8	CC-BLD	56.98	1.14	0.24	0.09	0.03	0.00	58.52	1.0493	1.0493	96.83	2.70	0.32	0.12	254			
MDS04-028E-A1-L1-5	LL4	WMM-8	CC-BLD	57.77	1.11	0.07	0.03	0.03	0.01	59.02	1.0594	1.0594	97.24	2.60	0.09	0.04	254			
MDS04-028E-A1-L2-1	LL4	WMM-8	CC-BLD	55.68	0.34	0.44	0.88	0.00	0.00	57.34	1.0198	1.0198	97.36	0.83	0.60	1.22	0			
MDS04-028E-A1-L2-2	LL4	WMM-8	CC-BLD	54.66	0.53	0.74	1.49	0.00	0.00	57.42	1.0191	1.0191	95.64	1.29	1.01	2.06	0			
MDS04-028E-A1-L2-3	LL4	WMM-8	CC-BLD	54.91	0.60	0.30	1.43	0.01	0.00	57.25	1.0185	1.0185	96.14	1.46	0.41	1.98	85			
MDS04-028E-A1-L2-4	LL4	WMM-8	CC-BLD	55.59	0.52	0.42	1.26	0.01	0.00	57.90	1.0279	1.0279	96.44	1.26	0.57	1.73	85			
MDS04-028E-A1-L2-5	LL4	WMM-8	CC-BLD	54.17	0.70	1.13	1.33	0.03	0.36	57.78	1.0181	1.0181	94.87	1.71	1.54	1.84	254			
MDS04-028E-A1-L2-6	LL4	WMM-8	CC-BLD	54.57	0.87	0.50	1.72	0.00	0.00	57.70	1.0259	1.0259	94.85	2.10	0.68	2.36	0			
MDS04-028E-A1-P1-1	LL4	WMM-8	CC2	56.24	0.40	1.27	0.40	0.14	0.00	58.48	1.0377	1.0377	96.64	0.96	1.70	0.54	1184			
MDS04-028E-A1-P1-2	LL4	WMM-8	CC2	56.67	0.28	0.95	0.39	0.08	0.00	58.48	1.0371	1.0371	97.44	0.67	1.27	0.53	676			
MDS04-028E-A1-P1-3	LL4	WMM-8	CC1	57.81	1.17	0.19	0.05	0.06	0.19	59.47	1.0639	1.0639	96.89	2.73	0.25	0.07	507			
MDS04-028E-A1-P1-4	LL4	WMM-8	CC1	56.64	1.02	0.34	0.15	0.06	0.23	58.44	1.0428	1.0428	96.85	2.43	0.45	0.20	507			
MDS04-028E-A2-L1-1	LL4	WMM-8	CC-BLD	56.15	0.70	0.30	1.24	0.00	0.00	58.39	1.0403	1.0403	96.25	1.67	0.40	1.68	0			
MDS04-028E-A2-L1-2	LL4	WMM-8	CC-BLD	54.48	0.79	0.46	1.89	0.00	0.00	57.65	1.0241	1.0241	94.86	1.91	0.63	2.60	0			
MDS04-028E-A2-L1-3	LL4	WMM-8	CC-BLD	55.69	0.75	0.41	1.58	0.01	0.00	58.44	1.0397	1.0397	95.51	1.79	0.55	2.14	85			
MDS04-028E-A2-L1-4	LL4	WMM-8	CC-BLD	54.97	0.83	0.39	1.23	0.01	0.00	57.43	1.0237	1.0237	95.75	2.01	0.53	1.69	85			
MDS04-028E-A2-P1-1	LL4	WMM-8	CC-BLD	56.84	0.92	0.00	0.07	0.01	0.01	57.86	1.0375	1.0375	97.69	2.20	0.00	0.10	85			
MDS04-028E-A2-P1-3	LL4	WMM-8	CC-BLD	56.37	1.14	0.00	0.04	0.07	0.00	57.62	1.0348	1.0348	97.14	2.73	0.00	0.05	592			
MDS04-028E-A2-P1-4	LL4	WMM-8	CC-BLD	56.29	1.37	0.05	0.00	0.00	0.00	57.71	1.0384	1.0384	96.66	3.27	0.07	0.00	0			
MDS04-049B-A1-1	LL1	TLM-2	DOL2	28.80	16.84	5.24	2.58	0.01	0.03	53.50	1.0407	1.0407	49.35	40.14	7.01	3.49	85			
MDS04-049B-A1-2	LL1	TLM-2	DOL2	29.08	17.17	4.91	2.68	0.07	0.16	54.07	1.0514	1.0514	49.32	40.51	6.50	3.59	592			
MDS04-049B-A1-3	LL1	TLM-2	DOL2	29.19	17.02	4.87	2.36	0.04	0.09	53.57	1.0442	1.0442	49.85	40.43	6.49	3.19	338			
MDS04-049B-A1-4	LL1	TLM-2	DOL2	29.25	18.12	4.67	2.58	0.00	0.00	54.62	1.0725	1.0725	48.63	41.91	6.06	3.39	0			
MDS04-049B-A1-5	LL1	TLM-2	DOL2	29.96	16.81	4.76	2.74	0.00	0.00	54.27	1.0561	1.0561	50.58	39.49	6.27	3.66	0			
MDS04-049B-A1-6	LL1	TLM-2	DOL2	29.20	17.36	4.51	2.35	0.00	0.05	53.47	1.0472	1.0472	49.72	41.12	5.99	3.16	0			
MDS04-077-A1-1	LL1	TLM-3	CC2	54.16	1.63	1.18	1.01	0.07	1.26	59.31	1.0377	1.0377	93.07	3.90	1.58	1.37	592			

Sample Number	Old Fort Point Fm.			Oxide analyses (wt%)							Total (wt%)	Total (mol)	Normalized carbonate (wt%)					(ppm)	
	Lct.	Facies	Phase	CaO	MgO	FeO	MnO	SrO	SiO ₂	CaCO ₃			MgCO ₃	FeCO ₃	MnCO ₃	Sr			
MDS04-077-A1-2	LL1	TLM-3	CC1	55.15	0.66	0.10	0.21	0.00	0.64	56.76	1.0041	97.94	1.63	0.14	0.29	0			
MDS04-077-A1-3	LL1	TLM-3	CC1	54.46	0.75	0.09	0.17	0.00	0.57	56.04	0.9934	97.76	1.87	0.13	0.24	0			
MDS04-077-A1-4	LL1	TLM-3	CC2	56.49	0.44	0.42	0.94	0.08	0.01	58.38	1.0382	97.02	1.05	0.56	1.28	676			
MDS04-077-A1-5	LL1	TLM-3	CC2	54.62	0.37	0.27	0.96	0.03	0.04	56.29	1.0008	97.32	0.92	0.38	1.35	254			
MDS04-077-A1-6	LL1	TLM-3	CC1	54.94	0.69	0.00	0.58	0.00	0.00	56.21	1.0050	97.48	1.70	0.00	0.81	0			
MDS04-077-A1-7	LL1	TLM-3	CC1	57.20	0.56	0.11	0.28	0.00	0.34	58.49	1.0393	98.14	1.34	0.15	0.38	0			
MDS04-077-A2-1	LL1	TLM-3	CC2	54.28	0.25	0.41	1.13	0.05	0.34	56.46	0.9963	97.15	0.62	0.57	1.60	423			
MDS04-077-A2-2	LL1	TLM-3	CC1	55.15	0.59	0.28	0.01	0.00	0.54	56.57	1.0021	98.14	1.46	0.39	0.01	0			
MDS04-077-A2-3	LL1	TLM-3	CC1	54.55	0.61	0.09	0.20	0.00	0.84	56.29	0.9919	98.06	1.53	0.13	0.28	0			
MDS04-077-A3-1	LL1	TLM-3	CC3	56.41	0.08	0.22	0.41	0.00	0.00	57.12	1.0167	98.94	0.20	0.30	0.57	0			
MDS04-077-A3-2	LL1	TLM-3	CC3	54.00	0.25	0.70	1.27	0.00	0.05	56.27	0.9968	96.60	0.62	0.98	1.80	0			
MDS04-077-A3-3	LL1	TLM-3	CC3	54.66	0.19	0.66	1.28	0.00	0.00	56.79	1.0066	96.83	0.47	0.91	1.79	0			
MDS04-077-A3-4	LL1	TLM-3	CC3	56.04	0.17	0.22	0.11	0.00	0.00	56.54	1.0081	99.12	0.42	0.30	0.15	0			
MDS04-088-L1-1	LL1	TLM-4	CC1	55.23	0.57	0.17	0.16	0.00	1.47	57.60	1.0036	98.13	1.41	0.24	0.22	0			
MDS04-088-L1-3	LL1	TLM-4	CC4	56.42	0.49	0.59	0.48	0.09	0.00	58.07	1.0342	97.28	1.18	0.79	0.65	761			
MDS04-088-L1-4	LL1	TLM-4	CC4	56.81	0.49	0.45	0.42	0.06	0.00	58.23	1.0380	97.59	1.17	0.60	0.57	507			
MDS04-088-L1-5	LL1	TLM-4	CC4	57.46	0.60	0.63	0.54	0.03	0.00	59.26	1.0562	97.01	1.41	0.83	0.72	254			
MDS04-088-L2-1	LL1	TLM-4	DOL2	29.39	17.26	5.44	1.79	0.00	0.08	53.96	1.0532	49.76	40.66	7.19	2.40	0			
MDS04-088-L2-2	LL1	TLM-4	CC2	55.67	0.59	0.60	0.63	0.09	0.02	57.60	1.0256	96.79	1.43	0.81	0.87	761			
MDS04-088-L2-3	LL1	TLM-4	CC1	57.47	0.74	0.01	0.00	0.00	0.12	58.34	1.0433	98.23	1.76	0.01	0.00	0			
MDS04-088-L3-1	LL1	TLM-4	DOL2	30.22	16.94	5.96	1.71	0.05	0.00	54.88	1.0667	50.52	39.39	7.78	2.26	423			
MDS04-088-L3-2	LL1	TLM-4	DOL2	30.15	16.59	6.35	2.05	0.00	0.00	55.14	1.0665	50.41	38.59	8.29	2.71	0			
MDS04-088-L3-3	LL1	TLM-4	DOL2	29.15	17.48	5.82	1.45	0.03	0.01	53.94	1.0552	49.26	41.09	7.68	1.94	254			
MDS04-088-L3-4	LL1	TLM-4	DOL2	29.44	17.55	5.98	1.59	0.00	0.00	54.56	1.0660	49.25	40.84	7.81	2.10	0			
MDS04-088-L3-5	LL1	TLM-4	CC3	57.68	0.43	0.51	0.60	0.02	0.03	59.27	1.0550	97.49	1.01	0.67	0.80	169			
MDS04-088-L3-6	LL1	TLM-4	CC4	57.50	0.52	0.12	0.28	0.02	0.34	58.78	1.0441	98.20	1.24	0.16	0.38	169			
MDS04-088-L3-7	LL1	TLM-4	CC3	56.54	0.44	0.44	0.47	0.04	0.00	57.93	1.0323	97.66	1.06	0.59	0.64	338			
MDS04-088-L4-1	LL1	TLM-4	DOL2	29.39	17.00	6.20	1.46	0.05	0.00	54.10	1.0532	49.76	40.04	8.19	1.95	423			
MDS04-088-L4-2	LL1	TLM-4	DOL2	29.54	17.57	6.03	1.71	0.03	0.00	54.88	1.0710	49.18	40.70	7.84	2.25	254			
MDS04-088-L4-3	LL1	TLM-4	DOL2	29.17	17.83	5.84	1.14	0.00	0.11	54.09	1.0598	49.08	41.74	7.67	1.52	0			
MDS04-088-L4-4	LL1	TLM-4	CC3	57.15	0.76	0.09	0.26	0.00	0.67	58.93	1.0429	97.72	1.81	0.12	0.35	0			
MDS04-088-L4-5	LL1	TLM-4	CC3	57.24	0.37	0.03	1.25	0.00	0.00	58.89	1.0479	97.40	0.88	0.04	1.68	0			
MDS04-103-A1-1	LL1	TLM-3	CC1	56.15	0.50	0.03	0.15	0.00	0.06	56.89	1.0162	98.53	1.22	0.04	0.21	0			
MDS04-103-A1-2	LL1	TLM-3	CC2	57.10	0.32	0.27	0.35	0.01	0.54	58.59	1.0349	98.38	0.77	0.36	0.48	85			
MDS04-103-A1-3	LL1	TLM-3	CC1	57.22	0.58	0.10	0.31	0.00	0.46	58.67	1.0405	98.06	1.38	0.13	0.42	0			
MDS04-103-A1-4	LL1	TLM-3	CC1	56.36	0.57	0.06	0.16	0.00	0.44	57.59	1.0222	98.31	1.38	0.08	0.22	0			
MDS04-103-A1-5	LL1	TLM-3	CC2	56.46	0.61	0.10	0.19	0.01	0.36	57.73	1.0261	98.12	1.47	0.14	0.26	85			
MDS04-103-A1-6	LL1	TLM-3	CC2	56.97	0.49	0.05	0.51	0.00	0.25	58.27	1.0359	98.07	1.17	0.07	0.69	0			
MDS04-103-A1-7	LL1	TLM-3	CC1	57.82	0.41	0.13	0.30	0.00	0.17	58.83	1.0472	98.45	0.97	0.17	0.40	0			
MDS04-103-A1-8	LL1	TLM-3	CC2	56.87	0.48	0.05	0.63	0.00	0.15	58.18	1.0356	97.93	1.15	0.07	0.86	0			
MDS04-103-A2-1	LL1	TLM-3	CC4	55.42	0.57	0.89	0.35	0.04	0.00	57.27	1.0201	96.87	1.39	1.21	0.48	338			
MDS04-103-A2-2	LL1	TLM-3	CC4	55.86	0.19	0.83	0.17	0.02	0.00	57.07	1.0150	98.14	0.46	1.14	0.24	169			

Sample Number	Old Fort Point Fm.			Oxide analyses (wt%)							Total (wt%)	Total (mol)	Normalized carbonate (wt%)					(ppm)
	Lct.	Facies	Phase	CaO	MgO	FeO	MnO	SrO	SiO ₂	CaCO ₃			MgCO ₃	FeCO ₃	MnCO ₃	Sr		
MDS04-103-A2-3	LL1	TLM-3	CC1	56.13	0.47	0.03	0.39	0.00	0.51	57.53	1.0185	98.27	1.14	0.04	0.54	0		
MDS04-103-A2-L1-1	LL1	TLM-3	CC4	56.35	0.54	1.02	0.35	0.01	0.00	58.27	1.0375	96.85	1.29	1.37	0.48	85		
MDS04-103-A2-L1-2	LL1	TLM-3	CC4	56.96	0.30	0.75	0.21	0.08	0.00	58.30	1.0374	97.90	0.72	1.01	0.29	676		
MDS04-103-A2-L1-3	LL1	TLM-3	CC4	57.33	0.46	0.90	0.33	0.05	0.01	59.08	1.0514	97.23	1.09	1.19	0.44	423		
MDS04-103-A2-L1-4	LL1	TLM-3	CC4	56.96	0.52	1.02	0.43	0.00	0.00	58.93	1.0488	96.84	1.23	1.35	0.58	0		
MDS04-103-A3-1	LL1	TLM-3	CC4	57.71	0.39	1.19	0.33	0.05	0.00	59.67	1.0605	97.03	0.91	1.56	0.44	423		
MDS04-103-A3-2	LL1	TLM-3	CC4	59.49	0.14	0.70	0.32	0.14	0.00	60.79	1.0801	98.21	0.32	0.90	0.42	1184		
MDS04-103-A3-3	LL1	TLM-3	CC1	55.61	0.64	0.03	0.26	0.00	0.69	57.23	1.0116	98.03	1.57	0.04	0.36	0		
MDS04-103-A3-4	LL1	TLM-3	CC2	55.41	0.36	0.04	0.38	0.00	0.73	56.92	1.0029	98.52	0.89	0.06	0.53	0		
MDS04-103-A3-L3-1	LL1	TLM-3	CC4	56.44	0.52	1.23	0.31	0.05	0.01	58.56	1.0414	96.64	1.24	1.64	0.42	423		
MDS04-103-A3-L3-2	LL1	TLM-3	CC4	57.21	0.35	0.81	0.25	0.10	0.04	58.76	1.0448	97.64	0.83	1.08	0.34	846		
MDS04-103-A3-L3-3	LL1	TLM-3	CC4	57.42	0.29	0.72	0.20	0.10	0.00	58.73	1.0451	97.97	0.69	0.96	0.27	846		
MDS04-103-A3-L3-4	LL1	TLM-3	CC4	57.59	0.22	0.72	0.18	0.12	0.01	58.84	1.0463	98.15	0.52	0.96	0.24	1015		
MDS04-108-A1-1	LL1	TLM-3	DOL2	29.45	12.51	12.18	0.53	0.06	0.07	54.80	1.0132	51.83	30.63	16.73	0.74	507		
MDS04-108-A1-2	LL1	TLM-3	DOL2	29.87	12.76	11.82	0.72	0.04	0.22	55.43	1.0243	52.00	30.90	16.06	0.99	338		
MDS04-108-A1-3	LL1	TLM-3	CC2	55.68	0.41	0.30	0.11	0.00	0.00	56.50	1.0088	98.42	1.01	0.41	0.15	0		
MDS04-108-A1-4	LL1	GSM-1	CC1	57.97	0.27	0.13	0.08	0.00	0.00	58.45	1.0433	99.08	0.64	0.17	0.11	0		
MDS04-108-A1-5	LL1	GSM-1	CC1	55.99	0.32	0.30	0.13	0.03	0.08	56.85	1.0127	98.59	0.78	0.41	0.18	254		
MDS04-108-A1-6	LL1	TLM-3	CC2	55.77	0.42	0.88	0.20	0.12	0.10	57.49	1.0213	97.37	1.02	1.20	0.28	1015		
MDS04-108-A1-7	LL1	TLM-3	DOL2	29.60	12.56	11.71	0.50	0.00	0.77	55.14	1.0094	52.29	30.87	16.15	0.70	0		
MDS04-108-A1-8	LL1	TLM-3	CC4	56.63	0.12	0.26	0.12	0.00	0.00	57.13	1.0181	99.19	0.29	0.36	0.17	0		
MDS04-108-A1-9	LL1	TLM-3	CC4	54.88	0.45	0.52	0.22	0.00	0.00	56.07	1.0001	97.85	1.12	0.72	0.31	0		
MDS04-108-A1-L1-1	LL1	TLM-3	CC4	56.75	0.19	0.30	0.21	0.00	0.01	57.46	1.0238	98.84	0.46	0.41	0.29	0		
MDS04-108-A1-L1-2	LL1	TLM-3	CC4	57.24	0.25	0.35	0.18	0.00	0.00	58.02	1.0343	98.68	0.60	0.47	0.25	0		
MDS04-108-A1-L1-3	LL1	TLM-3	CC4	57.06	0.37	0.42	0.22	0.01	0.00	58.08	1.0357	98.24	0.89	0.56	0.30	85		
MDS04-108-A1-L1-4	LL1	TLM-3	CC4	56.66	0.40	0.47	0.13	0.00	0.00	57.66	1.0286	98.22	0.96	0.64	0.18	0		
MDS04-108-A1-L1-5	LL1	TLM-3	CC4	58.04	0.13	0.21	0.13	0.00	0.01	58.52	1.0429	99.23	0.31	0.28	0.18	0		
MDS04-108-A1-L1-6	LL1	TLM-3	CC4	56.28	0.48	0.45	0.16	0.00	0.00	57.37	1.0240	98.01	1.16	0.61	0.22	0		
MDS04-108-A2-1	LL1	TLM-3	CC4	57.61	0.42	0.60	0.24	0.02	0.00	58.89	1.0497	97.87	0.99	0.80	0.32	169		
MDS04-108-A2-10	LL1	GSM-1	CC1	54.19	0.38	0.24	0.12	0.02	0.45	55.40	0.9810	98.50	0.96	0.34	0.17	169		
MDS04-108-A2-2	LL1	TLM-3	CC4	56.14	0.34	0.35	0.14	0.01	0.01	56.99	1.0165	98.49	0.83	0.48	0.19	85		
MDS04-108-A2-4	LL1	TLM-3	DOL2	29.10	11.14	10.40	0.82	0.00	5.48	56.94	0.9516	54.53	29.04	15.21	1.21	0		
MDS04-108-A2-5	LL1	GSM-1	CC1	56.48	0.47	0.08	0.13	0.00	0.16	57.32	1.0217	98.57	1.14	0.11	0.18	0		
MDS04-108-A2-6	LL1	TLM-3	CC2	54.66	0.25	0.44	0.18	0.00	1.28	56.81	0.9895	98.50	0.63	0.62	0.26	0		
MDS04-108-A2-7	LL1	TLM-3	CC2	55.22	0.37	0.91	0.23	0.18	0.06	56.97	1.0118	97.32	0.91	1.25	0.32	1522		
MDS04-108-A2-8	LL1	GSM-1	CC1	55.46	0.37	0.30	0.17	0.00	0.29	56.59	1.0047	98.43	0.91	0.42	0.24	0		
MDS04-108-A2-9	LL1	TLM-3	CC2	56.42	0.37	0.89	0.31	0.15	0.12	58.26	1.0337	97.33	0.89	1.20	0.42	1268		
MDS04-108-A2-L1-1	LL1	TLM-3	CC4	56.30	0.22	0.10	0.16	0.00	0.00	56.78	1.0130	99.10	0.54	0.14	0.22	0		
MDS04-108-A2-L1-2	LL1	TLM-3	CC4	55.66	0.49	0.52	0.21	0.00	0.00	56.88	1.0149	97.80	1.20	0.71	0.29	0		
MDS04-108-A2-L1-3	LL1	TLM-3	CC4	55.57	0.79	0.78	0.23	0.00	0.00	57.37	1.0246	96.71	1.91	1.06	0.32	0		
MDS04-108-A2-L1-4	LL1	TLM-3	CC4	56.04	0.22	0.23	0.11	0.00	0.05	56.65	1.0095	98.99	0.54	0.32	0.15	0		
MDS04-108-A2-L1-5	LL1	TLM-3	CC4	55.26	0.62	0.64	0.19	0.00	0.00	56.71	1.0123	97.34	1.52	0.88	0.26	0		

Sample Number	Old Fort Point Fm.			Oxide analyses (wt%)							Total (wt%)	Total (mol)	Normalized carbonate (wt%)					(ppm)
	Lct.	Facies	Phase	CaO	MgO	FeO	MnO	SrO	SiO ₂	CaCO ₃ MgCO ₃ FeCO ₃ MnCO ₃ Sr								
MDS04-108-A2-L1-6	LL1	TLM-3	CC4	57.19	0.57	0.55	0.22	0.00	0.03	58.56	1.0447	97.62	1.35	0.73	0.30	0		
MDS04-108-A2-L1-7	LL1	TLM-3	CC4	57.08	0.35	0.33	0.18	0.00	0.00	57.94	1.0336	98.47	0.84	0.44	0.25	0		
MDS04-108-A2-L1-8	LL1	TLM-3	CC4	55.65	0.38	0.49	0.32	0.00	0.00	56.84	1.0131	97.95	0.93	0.67	0.45	0		
MDS04-108-A3-1	LL1	TLM-3	DOL2	26.60	13.25	9.07	0.57	0.01	3.89	53.39	0.9374	50.60	35.07	13.47	0.86	85		
MDS04-108-A3-2	LL1	TLM-3	DOL2	28.92	13.22	12.28	0.38	0.05	0.00	54.85	1.0205	50.53	32.14	16.75	0.52	423		
MDS04-108-A3-3	LL1	TLM-3	DOL2	29.00	14.52	9.86	0.39	0.09	0.01	53.87	1.0211	50.64	35.28	13.44	0.54	761		
MDS04-108-A3-4	LL1	TLM-3	CC2	56.96	0.18	0.86	0.12	0.13	0.06	58.31	1.0353	98.11	0.43	1.16	0.16	1099		
MDS04-108-A3-5	LL1	GSM-1	CC1	55.10	0.48	0.30	0.12	0.01	0.00	56.01	1.0004	98.21	1.19	0.42	0.17	85		
MDS04-124-L1-1	LL5	TLM-1	CC3	56.23	0.39	0.53	1.50	0.12	0.10	58.87	1.0422	96.20	0.93	0.71	2.03	1015		
MDS04-124-L1-2	LL5	TLM-1	CC3	56.80	0.49	0.67	1.57	0.03	0.09	59.65	1.0568	95.84	1.15	0.88	2.09	254		
MDS04-124-L1-3	LL5	TLM-1	CC3	56.26	0.40	0.52	1.54	0.05	0.14	58.91	1.0426	96.22	0.95	0.69	2.08	423		
MDS04-124-L1-4	LL5	TLM-1	CC3	54.98	0.45	0.93	1.56	0.08	0.10	58.10	1.0274	95.42	1.09	1.26	2.14	676		
MDS04-155-A1-1	LL5	TLM-3	CC1	55.62	0.52	0.18	0.47	0.00	0.58	57.37	1.0138	97.83	1.27	0.25	0.65	0		
MDS04-155-A1-10	LL5	TLM-3	CC2	56.74	0.20	0.71	0.89	0.00	0.04	58.58	1.0392	97.36	0.48	0.95	1.21	0		
MDS04-155-A1-11	LL5	TLM-3	CC2	55.38	0.58	1.07	1.06	0.05	0.19	58.33	1.0323	95.66	1.39	1.44	1.45	423		
MDS04-155-A1-2	LL5	TLM-3	CC2	56.78	0.65	0.25	0.78	0.00	0.75	59.21	1.0431	97.07	1.55	0.33	1.05	0		
MDS04-155-A1-3	LL5	TLM-3	CC2	54.63	0.25	0.85	1.02	0.13	0.04	56.92	1.0080	96.64	0.62	1.17	1.43	1099		
MDS04-155-A1-4	LL5	TLM-3	CC1	55.28	0.63	0.24	0.52	0.00	0.91	57.58	1.0120	97.40	1.54	0.33	0.72	0		
MDS04-155-A1-6	LL5	TLM-3	CC1	56.36	0.60	0.14	0.23	0.06	0.19	57.58	1.0258	97.98	1.45	0.19	0.32	507		
MDS04-155-A1-7	LL5	TLM-3	CC1	55.70	0.68	0.24	0.58	0.03	0.65	57.88	1.0220	97.19	1.65	0.33	0.80	254		
MDS04-155-A1-8	LL5	TLM-3	CC2	55.03	0.48	0.36	0.88	0.03	0.86	57.64	1.0109	97.07	1.18	0.50	1.23	254		
MDS04-155-A1-9	LL5	TLM-3	CC2	57.15	0.42	0.36	0.72	0.04	0.36	59.05	1.0451	97.51	1.00	0.48	0.97	338		
MDS04-155-A2-1	LL5	TLM-3	CC2	56.92	0.58	0.78	0.78	0.18	0.24	59.48	1.0533	96.36	1.37	1.03	1.04	1522		
MDS04-155-A2-2	LL5	TLM-3	CC2	55.91	0.45	0.56	0.90	0.07	0.47	58.36	1.0294	96.85	1.08	0.76	1.23	592		
MDS04-155-A2-3	LL5	TLM-3	CC2	56.99	0.25	0.61	0.67	0.08	0.04	58.64	1.0413	97.59	0.60	0.82	0.91	676		
MDS04-155-A3-1	LL5	TLM-3	CC3	55.76	0.34	0.88	0.82	0.05	0.53	58.38	1.0271	96.81	0.82	1.19	1.13	423		
MDS04-155-A3-2	LL5	TLM-3	CC3	56.51	0.40	1.06	0.98	0.04	0.00	58.99	1.0466	96.28	0.95	1.41	1.32	338		
MDS04-155-A3-3	LL5	TLM-3	CC3	56.65	0.82	0.26	0.64	0.00	0.58	58.95	1.0431	96.84	1.95	0.35	0.86	0		
MDS04-155-A3-4	LL5	TLM-3	CC3	55.79	0.53	0.24	0.55	0.00	0.04	57.15	1.0191	97.62	1.29	0.33	0.76	0		
MDS04-155-A3-5	LL5	TLM-3	CC3	55.35	0.71	0.13	0.84	0.00	0.01	57.04	1.0182	96.93	1.73	0.18	1.16	0		
MDS04-155-A3-6	LL5	TLM-3	CC3	56.31	0.40	0.92	0.85	0.04	0.03	58.55	1.0393	96.62	0.95	1.23	1.15	338		
MDS04-155-A3-7	LL5	TLM-3	CC3	56.72	0.95	0.30	0.55	0.00	0.25	58.77	1.0469	96.61	2.25	0.40	0.74	0		
MDS04-155-A3-8	LL5	TLM-3	CC3	55.61	0.37	0.86	0.94	0.03	0.00	57.81	1.0264	96.62	0.89	1.17	1.29	254		
MDS04-155-A3-9	LL5	TLM-3	CC3	55.45	0.86	0.22	0.58	0.00	0.08	57.19	1.0213	96.81	2.09	0.30	0.80	0		
MDS04-155-L1-1	LL5	TLM-3	CC3	55.31	0.28	0.79	0.80	0.07	0.04	57.29	1.0163	97.05	0.68	1.08	1.11	592		
MDS04-155-L1-2	LL5	TLM-3	CC3	56.03	0.41	0.93	0.93	0.07	0.06	58.43	1.0361	96.43	0.98	1.25	1.27	592		
MDS04-155-L1-3	LL5	TLM-3	CC3	56.27	0.74	0.14	0.63	0.00	0.08	57.86	1.0326	97.17	1.78	0.19	0.86	0		
MDS04-155-L1-4	LL5	TLM-3	CC3	56.01	0.83	0.14	0.61	0.00	0.02	57.61	1.0299	96.98	2.00	0.19	0.83	0		
MDS04-155-L2-1	LL5	TLM-3	CC3	55.25	0.30	0.79	0.83	0.08	0.08	57.33	1.0163	96.94	0.73	1.08	1.15	676		
MDS04-155-L2-2	LL5	TLM-3	CC3	55.83	0.24	0.98	0.88	0.13	0.03	58.09	1.0290	96.75	0.58	1.33	1.21	1099		
MDS04-155-L2-3	LL5	TLM-3	CC3	56.76	0.80	0.09	0.50	0.00	0.00	58.15	1.0403	97.29	1.91	0.12	0.68	0		
MDS04-155-L2-4	LL5	TLM-3	CC3	56.28	0.83	0.15	0.60	0.00	0.04	57.90	1.0347	96.99	1.99	0.20	0.82	0		

Sample Number	Old Fort Point Fm.			Oxide analyses (wt%)							Total		Normalized carbonate (wt%)					(ppm)	
	Lct.	Facies	Phase	CaO	MgO	FeO	MnO	SrO	SiO ₂	Total (wt%)	Total (mol)		CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	Sr		
MDS04-155-L3-1	LL5	TLM-3	CC3	56.01	0.20	0.63	0.79	0.02	0.02	57.67	1.0238		97.55	0.48	0.86	1.09		169	
MDS04-155-L3-2	LL5	TLM-3	CC3	57.38	0.06	0.05	0.16	0.04	0.00	57.69	1.0281		99.52	0.14	0.07	0.22		338	
MDS04-155-L3-3	LL5	TLM-3	CC3	57.65	0.21	0.09	0.42	0.01	0.03	58.41	1.0405		98.80	0.50	0.12	0.57		85	
MDS04-161-L1-1	LL5	GSM-1	CC2	55.86	0.38	0.74	0.55	0.07	0.17	57.77	1.0244		97.24	0.92	1.01	0.76		592	
MDS04-161-L1-2	LL5	GSM-1	CC2	55.61	0.37	0.68	0.71	0.13	0.03	57.53	1.0218		97.05	0.90	0.93	0.98		1099	
MDS04-161-L1-3	LL5	GSM-1	CC1	57.06	0.75	0.38	0.29	0.01	0.00	58.49	1.0456		97.31	1.78	0.51	0.39		85	
MDS04-161-L1-4	LL5	GSM-1	CC1	57.14	0.60	0.13	0.12	0.00	0.00	57.99	1.0373		98.23	1.43	0.17	0.16		0	
MDS04-161-L2-1	LL5	GSM-1	CC2	56.41	0.37	0.73	0.57	0.09	0.02	58.19	1.0343		97.25	0.89	0.98	0.78		761	
MDS04-161-L2-2	LL5	GSM-1	CC1	55.66	1.18	0.19	0.16	0.02	0.08	57.29	1.0269		96.65	2.85	0.26	0.22		169	
MDS04-161-L3-1	LL5	GSM-1	CC2	55.72	0.57	0.41	0.36	0.00	0.90	57.96	1.0185		97.55	1.39	0.56	0.50		0	
MDS04-161-L3-2	LL5	GSM-1	CC1	56.52	0.85	0.09	0.18	0.01	0.52	58.17	1.0328		97.58	2.04	0.12	0.25		85	
MDS04-161-L3-3	LL5	GSM-1	CC2	56.44	0.35	0.67	0.45	0.12	0.12	58.15	1.0321		97.51	0.84	0.90	0.61		1015	
MDS04-161-L3-4	LL5	GSM-1	CC2	57.42	0.36	0.58	0.38	0.01	0.08	58.83	1.0464		97.85	0.85	0.77	0.51		85	
MDS04-188A-A1-1	MR1	TLM-1	ANK	28.39	8.17	20.01	0.68	0.00	0.12	57.42	1.0970		50.78	20.33	27.93	0.96		0	
MDS04-188A-A1-10	MR1	TLM-2	DOL1	33.96	19.05	1.30	0.25	0.00	0.08	54.64	1.0998		55.06	42.97	1.65	0.32		0	
MDS04-188A-A1-2	MR1	TLM-1	ANK	27.03	3.71	25.60	0.59	0.00	3.55	60.53	0.9386		51.35	9.81	37.96	0.89		0	
MDS04-188A-A1-3	MR1	TLM-2	DOL2	31.01	16.61	4.00	1.23	0.00	0.70	53.55	1.0380		53.27	39.70	5.36	1.67		0	
MDS04-188A-A1-4	MR1	TLM-2	DOL2	30.31	16.13	6.73	0.77	0.04	0.05	54.10	1.0456		51.69	38.27	8.96	1.04		338	
MDS04-188A-A1-5	MR1	TLM-2	DOL2	30.53	13.20	9.98	0.69	0.00	0.63	55.03	1.0205		53.35	32.09	13.61	0.95		0	
MDS04-188A-A1-6	MR1	TLM-1	ANK	27.78	3.72	26.40	0.38	0.00	0.22	58.52	0.9604		51.58	9.61	38.26	0.56		0	
MDS04-188A-A1-7	MR1	TLM-1	ANK	28.84	8.73	19.10	0.68	0.00	0.04	57.46	1.0063		51.11	21.52	26.42	0.95		0	
MDS04-188A-A1-8	MR1	TLM-1	ANK	27.80	3.64	27.02	0.50	0.00	0.58	59.54	0.9691		51.15	9.32	38.80	0.73		0	
MDS04-188A-A1-9	MR1	TLM-2	DOL1	32.17	20.35	1.71	0.21	0.01	0.08	54.53	1.1054		51.90	45.67	2.15	0.27		85	
MDS04-202-A1-1	MR1	TLM-3	CC2	56.76	0.47	1.22	0.25	0.00	0.04	58.74	1.0443		96.92	1.12	1.63	0.34		0	
MDS04-202-A1-10	MR1	TLM-3	CC3	57.35	0.55	1.62	0.14	0.00	0.02	59.68	1.0608		96.40	1.29	2.13	0.19		0	
MDS04-202-A1-11	MR1	TLM-3	CC3	55.28	0.57	1.79	0.21	0.00	1.27	59.12	1.0277		95.91	1.38	2.42	0.29		0	
MDS04-202-A1-12	MR1	TLM-3	DOL2	29.22	12.40	13.65	0.34	0.00	0.04	55.65	1.0234		50.91	30.06	18.56	0.47		0	
MDS04-202-A1-13	MR1	TLM-3	CC3	55.34	0.68	1.88	0.17	0.00	0.00	58.07	1.0322		95.60	1.63	2.53	0.23		0	
MDS04-202-A1-14	MR1	TLM-3	DOL2	28.93	12.71	13.31	0.24	0.01	0.09	55.29	1.0199		50.58	30.91	18.16	0.33		85	
MDS04-202-A1-15	MR1	TLM-3	CC3	56.05	0.64	1.65	0.21	0.00	0.00	58.55	1.0413		95.99	1.52	2.21	0.28		0	
MDS04-202-A1-2	MR1	TLM-3	CC2	55.25	0.60	1.58	0.20	0.00	0.00	57.63	1.0249		96.13	1.45	2.15	0.28		0	
MDS04-202-A1-3	MR1	TLM-3	CC2	56.14	0.49	0.68	0.04	0.00	0.19	57.54	1.0233		97.83	1.19	0.92	0.06		0	
MDS04-202-A1-4	MR1	TLM-3	CC2	57.02	0.62	1.70	0.13	0.00	0.06	59.53	1.0576		96.14	1.45	2.24	0.17		0	
MDS04-202-A1-5	MR1	TLM-3	CC2	56.58	0.63	1.80	0.12	0.00	0.00	59.13	1.0513		95.97	1.49	2.38	0.16		0	
MDS04-202-A1-6	MR1	TLM-3	CC2	55.28	0.53	1.44	0.16	0.00	1.42	58.85	1.0217		96.48	1.34	1.96	0.22		0	
MDS04-202-A1-7	MR1	TLM-3	CC2	55.52	0.53	1.04	0.18	0.00	0.28	57.55	1.0202		97.04	1.29	1.42	0.25		0	
MDS04-202-A1-8	MR1	TLM-3	CC3	55.93	0.57	1.59	0.05	0.01	0.00	58.15	1.0344		96.41	1.37	2.14	0.07		85	
MDS04-202-A1-9	MR1	TLM-3	CC3	55.85	0.64	1.72	0.21	0.00	0.01	58.43	1.0387		95.88	1.53	2.30	0.29		0	
MDS04-202-A2-1	MR1	TLM-3	DOL2	30.81	14.29	9.52	0.19	0.00	0.04	54.85	1.0391		52.87	34.12	12.75	0.26		0	
MDS04-202-A2-10	MR1	TLM-3	DOL2	29.29	12.33	13.89	0.45	0.00	0.00	55.96	1.0278		50.81	29.76	18.81	0.62		0	
MDS04-202-A2-11	MR1	TLM-3	CC3	56.16	0.63	1.61	0.13	0.00	0.09	58.62	1.0413		96.17	1.50	2.15	0.18		0	
MDS04-202-A2-12	MR1	TLM-3	DOL2	27.91	13.05	10.42	0.66	0.00	4.00	56.04	0.9758		51.01	33.18	14.86	0.95		0	

Sample Number	Old Fort Point Fm.			Oxide analyses (wt%)							Total		Normalized carbonate (wt%)					(ppm)	
	Lct.	Facies	Phase	CaO	MgO	FeO	MnO	SrO	SiO ₂	Total (wt%)	Total (mol)		CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	Sr		
MDS04-202-A2-13	MR1	TLM-3	DOL2	28.29	12.19	12.82	0.32	0.00	1.89	55.51	0.9898		50.97	30.55	18.03	0.46	0		
MDS04-202-A2-2	MR1	TLM-3	CC3	57.94	0.56	0.67	0.07	0.05	0.14	59.43	1.0579		97.66	1.31	0.88	0.09	423		
MDS04-202-A2-3	MR1	TLM-3	CC3	56.15	0.43	1.39	0.16	0.01	0.04	58.18	1.0336		96.87	1.03	1.87	0.22	85		
MDS04-202-A2-5	MR1	TLM-3	CC3	56.97	0.41	0.94	0.33	0.08	0.11	58.84	1.0447		97.24	0.97	1.25	0.45	676		
MDS04-202-A2-6	MR1	TLM-3	DOL2	29.37	12.01	13.81	0.32	0.00	0.02	55.53	1.0184		51.43	29.26	18.87	0.44	0		
MDS04-202-A2-7	MR1	TLM-3	CC3	55.96	0.42	1.37	0.20	0.02	0.05	58.02	1.0304		96.84	1.01	1.85	0.27	169		
MDS04-202-A2-8	MR1	TLM-3	DOL2	29.01	12.34	13.33	0.26	0.00	0.02	54.96	1.0126		51.09	30.23	18.32	0.36	0		
MDS04-202-A2-9	MR1	TLM-3	CC3	53.07	0.49	1.15	0.33	0.00	3.72	58.76	0.9791		96.65	1.24	1.63	0.48	0		
MDS04-202-A3-1	MR1	TLM-3	CC3	55.67	0.49	1.53	0.15	0.00	0.04	57.88	1.0283		96.54	1.18	2.07	0.21	0		
MDS04-202-A3-2	MR1	TLM-3	CC3	57.19	0.71	1.82	0.16	0.00	0.03	59.91	1.0650		95.76	1.65	2.38	0.21	0		
MDS04-202-A3-3	MR1	TLM-3	CC3	54.44	0.60	1.74	0.18	0.00	0.07	57.03	1.0124		95.89	1.47	2.39	0.25	0		
MDS04-202-A4-1	MR1	TLM-3	CC2	54.55	0.53	0.72	0.07	0.00	1.25	57.12	0.9969		97.58	1.32	1.01	0.10	0		
MDS04-202-A4-2	MR1	TLM-3	CC2	55.67	0.29	0.70	0.47	0.05	0.00	57.18	1.0168		97.63	0.71	0.96	0.65	423		
MDS04-202-A4-3	MR1	TLM-3	CC1	56.51	0.41	0.31	0.02	0.03	0.02	57.30	1.0228		98.52	0.99	0.42	0.03	254		
MDS04-202-A4-4	MR1	TLM-3	CC2	54.98	0.49	1.22	0.17	0.00	0.08	56.94	1.0119		96.88	1.20	1.68	0.24	0		
MDS04-249B-L1-1	CM1	WMM-6	CC2	55.20	0.68	2.40	0.32	0.37	0.00	58.97	1.0433		94.34	1.62	3.20	0.43	3129		
MDS04-249B-L1-2	CM1	WMM-6	CC2	54.37	0.65	2.21	0.34	0.31	0.00	57.88	1.0247		94.61	1.57	3.00	0.47	2621		
MDS04-249B-L1-3	CM1	WMM-6	CC2	53.98	0.59	2.13	0.32	0.33	0.00	57.35	1.0151		94.82	1.44	2.92	0.44	2790		
MDS04-249B-L1-4	CM1	WMM-6	CC2	55.51	0.61	2.28	0.28	0.40	0.00	59.08	1.0452		94.70	1.45	3.04	0.38	3382		
MDS04-249B-L1-5	CM1	WMM-6	CC2	54.12	0.63	2.27	0.37	0.31	0.05	57.75	1.0210		94.52	1.53	3.09	0.51	2621		
MDS05-120-A1-1	JP1	TLM-3	CC2	58.20	0.38	0.52	0.34	0.08	0.11	59.63	1.0602		97.89	0.89	0.68	0.45	676		
MDS05-120-A1-10	JP1	TLM-3	CC2	57.47	0.37	0.60	0.26	0.02	0.03	58.82	1.0462		97.95	0.88	0.80	0.35	169		
MDS05-120-A1-11	JP1	TLM-3	CC1	58.19	0.38	0.02	0.00	0.00	0.06	58.72	1.0473		99.07	0.90	0.03	0.00	0		
MDS05-120-A1-12	JP1	TLM-3	CC1	57.76	0.34	0.00	0.03	0.00	0.09	58.22	1.0388		99.15	0.81	0.00	0.04	0		
MDS05-120-A1-2	JP1	TLM-3	CC1	57.74	0.38	0.00	0.08	0.00	0.48	58.72	1.0402		98.99	0.91	0.00	0.11	0		
MDS05-120-A1-3	JP1	TLM-3	CC1	56.28	0.42	0.27	0.26	0.00	0.75	58.04	1.0214		98.25	1.02	0.37	0.36	0		
MDS05-120-A1-4	JP1	TLM-3	CC1	57.57	0.40	0.19	0.37	0.01	0.26	58.81	1.0445		98.29	0.95	0.25	0.50	85		
MDS05-120-A1-5	JP1	TLM-3	CC2	59.41	0.47	0.66	0.41	0.08	0.20	61.31	1.0869		97.47	1.07	0.85	0.53	676		
MDS05-120-A1-6	JP1	TLM-3	CC2	58.64	0.39	0.31	0.35	0.02	0.09	59.80	1.0648		98.20	0.91	0.41	0.46	169		
MDS05-120-A1-7	JP1	TLM-3	CC1	57.45	0.43	0.01	0.04	0.00	0.80	58.74	1.0358		98.90	1.03	0.01	0.05	0		
MDS05-120-A1-8	JP1	TLM-3	CC1	57.44	0.44	0.13	0.19	0.01	0.68	58.89	1.0398		98.51	1.05	0.17	0.26	85		
MDS05-120-A1-9	JP1	TLM-3	CC2	58.32	0.37	0.63	0.29	0.06	0.21	60.00	1.0627		97.86	0.86	0.83	0.38	507		
MDS05-120-A2-1	JP1	TLM-3	DOL2	30.03	15.59	8.12	0.86	0.00	0.10	54.73	1.0474		51.13	36.93	10.79	1.16	0		
MDS05-120-A2-2	JP1	TLM-3	CC3	56.98	0.41	0.77	0.36	0.06	0.01	58.59	1.0427		97.44	0.98	1.03	0.49	507		
MDS05-120-A2-3	JP1	TLM-3	DOL2	29.73	11.80	14.21	0.40	0.05	0.00	56.28	1.0268		51.63	28.51	19.26	0.55	423		
MDS05-120-A2-4	JP1	TLM-3	DOL2	29.77	15.15	8.86	0.77	0.01	0.03	54.62	1.0410		51.00	36.10	11.85	1.04	85		
MDS05-120-A2-5	JP1	TLM-3	DOL2	29.95	15.27	8.01	0.84	0.02	0.34	54.43	1.0364		51.53	36.55	10.76	1.14	169		
MDS05-120-A2-6	JP1	TLM-3	CC3	58.20	0.44	0.72	0.40	0.05	0.01	59.82	1.0649		97.45	1.02	0.94	0.53	423		
MDS05-120-A2-7	JP1	TLM-3	DOL2	30.34	14.87	8.35	0.58	0.00	0.34	54.49	1.0343		52.31	35.67	11.24	0.79	0		
MDS05-120-A2-8	JP1	TLM-3	CC3	58.01	0.55	0.15	0.54	0.00	0.22	59.47	1.0578		97.79	1.29	0.20	0.72	0		
MDS05-120-A2-9	JP1	TLM-3	CC3	58.08	0.33	0.81	0.30	0.03	0.01	59.56	1.0597		97.73	0.77	1.06	0.40	254		
MDS05-120-A3-1	JP1	TLM-3	CC3	55.03	0.38	0.64	0.77	0.00	2.22	59.04	1.0105		97.11	0.93	0.88	1.07	0		

Sample Number	Lct.	Old Fort Point Fm.		Oxide analyses (wt%)							Total (wt%)	Total (mol)	Normalized carbonate (wt%)					(ppm)	
		Facies	Phase	CaO	MgO	FeO	MnO	SrO	SiO ₂	CaCO ₃			MgCO ₃	FeCO ₃	MnCO ₃	Sr			
MDS05-120-A3-2	JP1	TLM-3	CC3	57.24	0.40	0.70	0.34	0.04	0.08	58.80	1.0456	97.62	0.95	0.93	0.46	338			
MDS05-120-A3-3	JP1	TLM-3	DOL2	29.95	14.82	9.17	0.78	0.00	0.00	54.72	1.0403	51.34	35.34	12.27	1.06	0			
MDS05-120-A3-4	JP1	TLM-3	CC2	58.31	0.30	0.75	0.24	0.04	0.14	59.78	1.0615	97.95	0.70	0.98	0.32	338			
MDS05-120-A3-5	JP1	TLM-3	DOL2	30.76	15.16	7.38	0.63	0.02	0.03	54.00	1.0364	52.92	36.29	9.91	0.86	169			
MDS05-120-A3-6	JP1	TLM-3	DOL2	30.88	15.50	7.03	0.66	0.07	0.05	54.21	1.0431	52.79	36.86	9.38	0.89	592			
MDS05-133A-A1-L1-1	MK1	WMM-8	CC3	55.67	0.69	1.01	0.23	0.15	0.00	57.76	1.0288	96.49	1.66	1.37	0.32	1268			
MDS05-133A-A1-L1-2	MK1	WMM-8	CC3	55.88	0.77	1.15	0.25	0.17	0.00	58.22	1.0370	96.09	1.84	1.54	0.34	1438			
MDS05-133A-A1-L1-3	MK1	WMM-8	CC3	55.86	0.84	1.02	0.20	0.20	0.00	58.14	1.0362	96.13	2.01	1.37	0.27	1691			
MDS05-133A-A1-L1-4	MK1	WMM-8	CC3	55.76	0.75	1.23	0.20	0.16	0.03	58.14	1.0347	96.10	1.80	1.65	0.27	1353			
MDS05-133A-A1-L1-5	MK1	WMM-8	CC3	55.72	0.79	1.01	0.28	0.14	0.00	57.94	1.0328	96.20	1.90	1.36	0.38	1184			
MDS05-133A-A2-L1-1	MK1	WMM-8	CC3	56.72	0.29	0.64	0.04	0.15	0.00	57.84	1.0298	98.22	0.70	0.86	0.05	1268			
MDS05-133A-A2-L1-2	MK1	WMM-8	CC3	57.27	0.23	0.62	0.12	0.10	0.00	58.38	1.0384	98.35	0.55	0.83	0.16	846			
MDS05-133A-A2-L1-3	MK1	WMM-8	CC3	56.17	0.25	0.78	0.12	0.14	0.00	57.51	1.0220	98.01	0.61	1.06	0.17	1184			
MDS05-133A-A2-L1-4	MK1	WMM-8	CC3	56.87	0.21	0.70	0.10	0.14	0.00	58.08	1.0320	98.26	0.50	0.94	0.14	1184			
MDS05-133A-A2-L1-5	MK1	WMM-8	CC3	56.60	0.26	0.72	0.15	0.16	0.00	57.89	1.0297	98.02	0.63	0.97	0.21	1353			
MDS05-133A-A2-L1-6	MK1	WMM-8	CC3	56.38	0.30	0.85	0.14	0.11	0.01	57.79	1.0279	97.81	0.72	1.15	0.19	930			
MDS05-140-A1-P1-1	MK1	WMM-6	CC2	55.09	0.74	1.05	0.00	0.42	0.00	57.31	1.0201	96.30	1.80	1.43	0.00	3551			
MDS05-140-A1-P1-2	MK1	WMM-6	CC2	55.89	0.78	1.30	0.00	0.51	0.01	58.49	1.0399	95.84	1.86	1.74	0.00	4313			
MDS05-140-A1-P1-3	MK1	WMM-6	CC2	56.19	0.77	1.11	0.00	0.48	0.01	58.65	1.0420	96.16	1.83	1.48	0.00	4059			
MDS05-140-A1-P1-4	MK1	WMM-6	CC2	57.81	0.80	1.19	0.09	0.51	0.00	60.53	1.0743	95.95	1.85	1.54	0.12	4313			

APPENDIX K: TOC (total organic carbon) and $\delta^{13}\text{C}_{\text{org}}$ analyses.

Sample Name	Lct.	Unit	%C-EA	%C-EA ^d	%C-MS	$\delta^{13}\text{C}_{\text{org}}$	$\delta^{13}\text{C}_{\text{org}}^{\text{d}}$
MDS03-16	CM1	GSM	0.383	0.362		-23.44	
MDS03-18	CM1	GSM	4.927		3.81	-21.22	
MDS03-19	CM1	GSM	1.380	1.358		-21.83	
MDS04-001	JP1	TLM	0.134		0.08	-26.72	
MDS04-003	JP1	TLM	0.151		0.08	-26.95	
MDS04-006	JP1	GSM	0.314		0.17	-28.80	
MDS04-009	JP1	GSM	0.397		0.25	-27.43	
MDS04-011	JP1	GSM	0.701	0.570	0.44	-31.08	
MDS04-013	JP1	WMM	0.102				
MDS04-014	JP3	WMM	0.464		0.28	-28.56	
MDS04-015	JP3	WMM	0.261		0.15	-27.32	
MDS04-021	LL8	MMGB	0.265		0.20	-26.99	
MDS04-023	LL4	MMGB	0.305		0.19	-27.90	
MDS04-024	LL4	MMGB	0.227		0.17	-28.05	
MDS04-028	LL4	MMGB	0.128		0.08	-26.42	
MDS04-029	LL4	WMM	0.187		0.14	-27.08	
MDS04-030	LL4	WMM	0.171		0.14	-27.74	
MDS04-031	LL4	WMM	0.154		0.15	-27.59	
MDS04-037	LL4	WMM	0.217		0.15	-27.62	
MDS04-039	LL4	WMM	0.162		0.19	-27.76	
MDS04-041	LL4	WMM	0.187		0.14	-28.16	
MDS04-042	LL4	WMM	0.209		0.16	-29.35	
MDS04-043	LL4	MMGA	0.561		0.36	-31.06	
MDS04-044	LL4	MMGA	0.787	0.507	0.56	-29.99	
MDS04-045	LL4	MMGA	0.118		0.69	-29.57	
MDS04-048	LL1	TLM	0.177		0.15	-27.39	
MDS04-051	LL1	TLM	0.151		0.11	-27.34	
MDS04-065	LL1	TLM	1.075	0.155	0.13	-27.23	
MDS04-089	LL1	TLM	0.142		0.11	-27.80	
MDS04-103	LL1	TLM	0.275		0.19	-26.45	
MDS04-105	LL1	TLM	0.229		0.18	-28.44	
MDS04-109	LL1	GSM	0.256		0.17	-27.66	
MDS04-111	LL1	GSM	0.767	0.466	0.51	-31.70	
MDS04-112	LL1	GSM	1.088	0.687	0.75	-31.21	
MDS04-113A	LL5	MMGB	0.084				
MDS04-113B	LL5	MMGB	0.394		0.27	-27.95	

Sample Name	Lct.	Unit	%C-EA	%C-EA ^d	%C-MS	$\delta^{13}\text{C}_{\text{org}}$	$\delta^{13}\text{C}_{\text{org}}^{\text{d}}$
MDS04-114B	LL5	MMGB	0.232		0.19	-28.00	
MDS04-114C	LL5	MMGB	6.790		6.60	-26.37	
MDS04-115	LL5	MMGB	0.304		0.24	-27.42	
MDS04-116	LL5	TLM	0.281		0.18	-27.66	
MDS04-117	LL5	TLM	0.306		0.15	-27.71	
MDS04-118	LL5	TLM	0.133		0.12	-27.24	
MDS04-119	LL5	TLM	0.266		0.15	-27.34	
MDS04-133	LL5	TLM	0.096				
MDS04-152	LL5	TLM	0.194		0.15	-28.38	
MDS04-157	LL5	TLM	0.265		0.20	-26.88	
MDS04-166	LL5	MMGA	0.945	0.583	0.65	-35.40	
MDS04-167	LL5	MMGA	0.821	0.522	0.58	-31.90	
MDS04-168	LL5	MMGA	0.283		0.22	-28.47	
MDS04-169	LL5	MMGA	0.524	0.193	0.18	-29.50	
MDS04-172	MR1	MMGB	0.112				
MDS04-173	MR1	MMGB	0.130		0.12	-25.91	
MDS04-174	MR1	MMGB	0.133		0.12	-26.39	
MDS04-175	MR1	TLM	0.088				
MDS04-176	MR1	TLM	0.076				
MDS04-183	MR1	TLM	0.078				
MDS04-186	MR1	TLM	0.080				
MDS04-188B	MR1	TLM	0.249		0.10	-26.94	
MDS04-202	MR1	TLM	0.119				
MDS04-204	MR1	TLM	0.089				
MDS04-208	MR1	GSM	2.249	1.818	1.91	-24.72	
MDS04-209	MR1	GSM	1.573	1.208	1.01	-24.67	
MDS04-210	MR1	MMGA	0.543	0.469	0.36	-24.77	
MDS04-211	MR1	MMGA	0.219	0.214	0.15	-26.14	
MDS04-212	CM1	MKG	0.072	0.061	0.07	-27.26	
MDS04-219	CM1	TLM	0.102	0.083			
MDS04-227	CM1	TLM	0.112				
MDS04-234B	CM1	GSM	0.852		0.95	-22.41	
MDS04-236	CM1	GSM	1.662		1.09	-22.03	
MDS04-250	CM1	UKG	0.164		0.17	-24.64	
MDS05-003	LL2	MMGB	0.749		0.77	-22.98	
MDS05-007	LL5	GSM	0.176		0.18	-30.22	
MDS05-008	LL5	GSM	0.255		0.26	-33.25	
MDS05-009	LL5	GSM	0.146		0.16	-31.36	
MDS05-010	LL5	GSM	0.134		0.16	-30.42	
MDS05-011	LL5	GSM	0.548		0.59	-34.78	
MDS05-012	LL6	GSM	0.267		0.27	-31.58	
MDS05-013	LL6	GSM	0.360		0.38	-31.89	
MDS05-014	LL6	GSM	0.524		0.55	-32.26	
MDS05-015	LL6	GSM	0.488		0.51	-30.45	
MDS05-023	CM2	TLM	0.072				
MDS05-024	CM2	GSM	0.132				

Sample Name	Lct.	Unit	%C-EA	%C-EA ^d	%C-MS	$\delta^{13}\text{C}_{\text{org}}$	$\delta^{13}\text{C}_{\text{org}}^{\text{d}}$
MDS05-025	CM2	GSM	0.082				
MDS05-026	CM2	MKG	0.076				
MDS05-027	CM2	MKG	0.048				
MDS05-028	CM2	MKG	0.049				
MDS05-029	CM2	MKG	0.046				
MDS05-030	CM2	MKG	0.054				
MDS05-031	CM2	MKG	0.047				
MDS05-032	CM2	MKG	0.053				
MDS05-033	CM2	MKG	0.053				
MDS05-034	CM2	MKG	0.067				
MDS05-035	CM2	MKG	0.053				
MDS05-036	CM2	MKG	0.052				
MDS05-037	CM2	MKG	0.052				
MDS05-038	CM2	MKG	0.053				
MDS05-039	CM2	MKG	0.082				
MDS05-040	CM2	MKG	0.058				
MDS05-041	CM2	MKG	0.043				
MDS05-042	CM2	MKG	0.075	0.075			
MDS05-043	CM2	MKG	0.060				
MDS05-044	PM1	HTC	0.106				
MDS05-045	PM1	HTC	0.107				
MDS05-048	PM1	HTC	0.096				
MDS05-052	PM1	TLM	0.111				
MDS05-066	PM1	TLM	0.079				
MDS05-067	PM1	GSM	0.085				
MDS05-068	PM1	GSM	0.085	0.076			
MDS05-069	PM1	GSM	0.076				
MDS05-070	PM1	GSM	0.061				
MDS05-071	PM1	GSM	0.054				
MDS05-072	PM1	GSM	0.067				
MDS05-073	PM1	GSM	0.070				
MDS05-074	PM1	GSM	0.053				
MDS05-076	PM1	GSM	0.072				
MDS05-077	PM1	GSM	0.069				
MDS05-078	PM1	GSM	0.072				
MDS05-079	PM1	GSM	0.094				
MDS05-083	PM1	WMM	0.151	0.149	0.16	-26.16	
MDS05-084	PM1	WMM	0.408		0.46	-26.26	
MDS05-087	PM1	WMM	0.659	0.710	0.71	-26.40	-26.25
MDS05-090	PM1	WMM	0.605		0.61	-26.27	
MDS05-092	PM1	WMM	0.619		0.63	-25.89	
MDS05-096B	PM1	WMM	0.481		0.51	-19.25	
MDS05-099	PM1	WMM	0.854		0.93	-19.73	
MDS05-104	PM1	WMM	0.940		1.04	-17.86	
MDS05-111B	PM1	WMM	4.140		4.55	-18.34	
MDS05-112	PM1	WMM	0.948		0.97	-14.94	

Sample Name	Lct.	Unit	%C-EA	%C-EA ^d	%C-MS	$\delta^{13}\text{C}_{\text{org}}$	$\delta^{13}\text{C}_{\text{org}}^{\text{d}}$
MDS05-114	PM1	HTC	0.107				
MDS05-115	PM1	HTC	0.099				
MDS05-116	PM1	HTC	0.096				
MDS05-128A	MR2	GSM	0.998		1.02	-20.71	
MDS05-128B	MR2	GSM	0.480		0.51	-21.14	
MDS05-129	MR2	WMM	0.100				
MDS05-131	MK1	MM	0.124		0.13	-25.62	
MDS05-132	MK1	MM	1.237		1.30	-20.50	
MDS05-134	MK1	WMM	1.046		1.10	-20.18	
MDS05-135	MK1	WMM	0.694	0.694	0.75	-20.27	
MDS05-136	MK1	WMM	2.569		2.51	-19.11	
MDS05-142	MK1	WMM	0.319		0.36	-20.06	
MDS05-143	MK1	WMM	7.059		7.13	-18.60	
MDS05-147	MK1	WMM	4.896		4.99	-17.39	
MDS05-150A	MK1	WMM	0.137		0.18	-17.56	
MDS05-150B	MK1	WMM	0.119		0.13	-24.68	
MDS05-152	MK1	MMGA	0.121		0.13	-24.04	-32.49
MDS05-153	MK1	MMGA	0.069				
MDS05-154	LL1	GSM	0.566	0.600	0.62	-32.42	
MDS05-155	LL1	MMGA	0.630		0.63	-31.82	
MDS05-156	LL1	MMGA	0.469		0.50	-30.91	
MDS05-157	LL1	MMGA	0.466		0.51	-30.60	
MDS05-158	LL1	MMGA	0.138		0.16	-26.32	
MDS05-159	LL1	MMGA	0.135		0.14	-28.15	
MDS05-160	LL1	MMGA	0.119		0.12	-27.54	
MDS05-161	LL1	MMGA	0.135		0.14	-27.06	
MDS05-162	LL1	MMGA	0.132		0.14	-27.35	
MDS05-163	LL1	MMGB	0.217		0.23	-26.99	
MDS05-164	LL4	MMGA	0.112		0.12	-27.96	
MDS05-165	LL4	MMGA	0.103		0.11	-27.97	
MDS05-166	LL4	MMGA	0.171		0.18	-28.08	
MDS05-167	LL4	MMGA	0.196		0.22	-29.75	
AKA05-001	CM3	IF	1.371		1.51	-24.68	
AKA05-002	CM3	IF	0.293		0.32	-24.53	
AKA05-003	CM3	IF	0.396		0.45	-24.76	
AKA05-010	CM3	IF	0.366		0.39	-24.52	
AKA05-012	CM3	IF	1.109	1.137	1.24	-23.86	
C5-A2	CM3	IF	0.322				
C5-A7	CM3	IF	0.166				
C5-B3	CM3	IF	0.256				
C5-C0b	CM3	IF	0.293				
C5-C1	CM3	IF	0.283				
C5-C2b	CM3	IF	0.183				
C5-C5	CM3	IF	0.190				
C5-Z4	CM3	IF	0.230				
CM-1	CM3	IF	3.103		1.92	-23.86	

Sample Name	Lct.	Unit	%C-EA	%C-EA ^d	%C-MS	$\delta^{13}\text{C}_{\text{org}}$	$\delta^{13}\text{C}_{\text{org}}^{\text{d}}$
EE-0CL	CM3	IF	3.946		4.25	-25.99	
EE-3	CM3	IF	0.144				
EE-4	CM3	IF	0.130				
HT04-019	CM3	IF	0.174				
HT04-024	CM3	IF	0.181				
HT04-028	CM3	IF	0.090				
HT04-030	CM3	IF	0.306				
RAR-01-06*	MR3	UMG	0.98			-15.10	
RAR-01-11*	JP7	MMGA	0.01			-26.58	
RAR-01-12*	JP7	MMGA	0.01			-25.10	
RAR-01-13*	JP7	MMGA	0.17			-27.68	
RAR-01-14*	JP7	MMGA	0.00				
RAR-01-17*	JP7	MMGA	0.01			-25.59	
RAR-01-22*	JP1	TLM	0.00			-25.48	
RAR-01-23*	JP1	TLM	0.01				
RAR-01-24*	JP1	TLM	0.00			-26.21	
RAR-01-25KK*	JP1	WMM	0.02			-27.90	
RAR-01-27*	JP1	TLM	0.01			-25.74	
RAR-01-28*	JP1	TLM	0.00			-26.12	
RAR-01-29*	JP1	GSM	0.09			-31.22	
RAR-01-30*	JP1	WMM	0.00			-25.71	
RAR-01-31*	JP1	WMM	0.01				
RAR-01-32*	JP6	MMGA	0.01			-27.53	
RAR-01-33*	JP6	MMGA	0.02			-27.34	
RAR-01-34*	JP6	MMGA	0.02			-27.67	
RAR-01-38*	MR3	UMG	0.02				
RAR-01-39*	MR3	UMG	1.78			-25.63	
RAR-01-07*	JP5	MMGA	0.00				
RAR-01-08*	JP5	MMGA	0.01				
RAR-01-09*	JP5	MMGA	0.01				
RAR-R01-120E*	LL9	MMGB	0.06			-24.42	
RAR-R01-12P*	MR3	UMG	0.15			-13.70	
RAR-R01-12S*	MR3	UMG	0.18			-15.63	
RAR-R01-12X*	MR3	UMG	0.08			-17.97	
RAR-R01-12Y*	MR3	UMG	0.43			-14.04	
RAR-R01-17*	CM3	UKG	0.01			-28.11	
RAR-R01-21*	CM3	UKG	0.00				
RAR-R01-42*	CM3	UKG	0.00			-24.80	
RAR-R01-43*	CM3	UKG	0.00			-24.80	
RAR-R01-54*	CM3	UKG	0.01			-29.42	
RAR-R01-62*	CM3	UKG	0.00			-26.32	
RAR-R014-DD*	CM3	IF	0.00				
RAR-R014-K*	CM3	IF	0.00			-24.71	
RAR-R014-Q*	CM3	IF	0.01			-23.30	
RAR-R014-Z*	CM3	IF	0.01			-22.14	
S87-31*	CM1	GSM	0.50				

APPENDIX L: Duplicate carbonate $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analyses.

Sample name	Lct.	Unit	Phase	$\delta^{13}\text{C}_{\text{PDB}}$	$\delta^{13}\text{C}_{\text{PDB}}^{\text{d}}$	$\delta^{18}\text{O}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{PDB}}^{\text{d}}$
MDS04-059	LL1	TLM	CC1+CC2	-10.60	-10.60	-15.95	-15.93
MDS04-072	LL1	TLM	CC1+CC2	-9.06	-9.11	-15.80	-15.74
MDS04-082	LL1	TLM	CC1+CC2	-8.74	-8.72	-15.71	-15.76
MDS04-091-1	LL1	TLM	CC1+CC2	-8.22	-8.19	-15.63	-15.68
MDS04-102	LL1	TLM	CC1+CC2	-7.80	-7.79	-15.27	-15.25
MDS04-136B	LL5	TLM	CC1+CC2	-8.61	-8.56	-14.50	-14.50
MDS04-146	LL5	TLM	CC1+CC2	-8.62	-8.62	-14.71	-14.66
MDS04-157	LL5	TLM	CC1+CC2	-7.90	-7.90	-14.52	-14.48
MDS04-195	MR1	TLM	CC1+CC2	-10.70	-10.69	-16.34	-16.21
MDS04-206	MR1	TLM	CC1+CC2	-9.00	-9.02	-16.82	-16.82
MDS05-057	PM1	TLM	CC1+CC2	-2.80	-2.74	-16.94	-16.83
MDS04-123	LL5	TLM	CC3	-11.86	-11.84	-15.25	-15.24
MDS04-202	MR1	TLM	DOL2	-10.36	-10.37	-17.20	-17.15
MDS03-014	CM1	GSM	CC1+CC2	-8.33	-8.42	-17.88	-17.92
MDS04-233	CM1	GSM	CC1+CC2	-9.05	-9.43	-18.02	-18.00
MDS05-098	PM1	WMM	CC2-WMM	-5.21	-5.03	-14.17	-14.03
MDS05-110	PM1	WMM	CC2-WMM	-1.63	-1.19	-13.63	-13.40
MDS05-136	MK1	WMM	CC2-WMM	-3.89	-4.04	-16.94	-16.98
MDS05-148	MK1	WMM	CC2-WMM	-3.74	-3.60	-17.94	-18.07
MDS03-024	CM1	WMM	CC3	-6.36	-6.39	-18.02	-18.00
MDS04-244	CM1	WMM	CC3	-6.59	-6.67	-18.24	-18.24
MDS05-081	PM1	WMM	CC3	-11.28	-11.00	-16.85	-16.66
MDS04-027	LL4	WMM-cl	CC1+CC2	-8.88	-8.79	-16.96	-17.08
MDS04-028E-2	LL4	WMM-cl	CC1+CC2	-10.17	-10.05	-15.33	-15.33
MDS04-046D	LL4	WMM-cl	CC2-WMM	-8.95	-9.06	-14.92	-14.93
MDS04-028A	LL4	WMM-cl	DOL-SMC	-0.96	-1.28	-5.07	-5.08
RAR03-01H	CM1	UKG	CC	-0.62	-0.64	-17.88	-17.90
RAR-90-W17B	MP1	FF-cl	DOL-SMC	-5.89	-5.71	-12.56	-12.54

APPENDIX M: Pyrite $\delta^{34}\text{S}$ analyses and description.

Sample name	Lct.	Unit	%S	$\delta^{34}\text{S}_{\text{CDT}}$	$\delta^{34}\text{S}_{\text{CDT}}^{\text{d}}$	Pyrite description
MDS04-004	JP1	TLM	66.05	28.38		nice flat cubes
MDS04-005	JP1	TLM	66.09	17.29		nice small cubes
MDS04-008	JP1	GSM	63.09	0.31	-0.76	grainy looking cubes
MDS04-020	JP4	TLM	63.44	14.48		grainy looking cubes
MDS04-139A	LL5	TLM	65.32	-13.83	-14.32	medium cubes
MDS04-142	LL5	TLM	58.89	-13.91		tiny cubes
MDS04-145	LL5	TLM	53.88	-6.42		tiny cubes
MDS04-163	LL5	TLM	62.63	7.49		tiny cubes
MDS05-001	LL2	MMGB	64.52	25.17		tiny cubes
MDS05-002	LL2	MMGB	50.45	24.41		tiny cubes
MDS04-178	MR1	TLM	64.38	23.70		large poor cubes
MDS04-179	MR1	TLM	58.24	20.82		large poor cubes
MDS04-180	MR1	TLM	57.90	15.92		medium poor cubes
MDS04-181	MR1	TLM	53.24	17.72		grainy large cubes
MDS04-184	MR1	TLM	57.75	13.58		poor large cubes
MDS04-185	MR1	TLM	61.36	13.75		large cubes
MDS04-189	MR1	TLM	51.21	11.08	9.30	very grainy, not cubes
MDS04-190	MR1	TLM	57.23	12.00		very grainy, not cubes
MDS04-191A	MR1	TLM	64.22	11.26		poor medium cubes
MDS04-191B-1	MR1	TLM	56.74	14.60		medium multi-cubes
MDS04-191B-2	MR1	TLM	54.26	14.30		single cube
MDS04-191B-3	MR1	TLM	54.61	14.30		single cube
MDS04-191B-4	MR1	TLM	55.21	14.34		half cube
MDS04-191B-5	MR1	TLM	52.88	14.25		half cube
MDS04-192	MR1	TLM	57.13	11.26		rusty poor cubes
MDS04-193	MR1	TLM	53.47	12.93		grainy large cubes
MDS04-194-1	MR1	TLM	55.40	14.81		half cube
MDS04-194-2	MR1	TLM	58.75	15.15		half cube
MDS04-205	MR1	TLM	51.87	22.78		medium cubes
MDS05-123	MR2	TLM	49.26	15.00		nice cubes
MDS05-124	MR2	TLM	44.60	14.00	14.05	large cubes
MDS05-125	MR2	TLM	43.76	13.70		tiny two cubes
MDS05-129-1	MR2	WMM	51.64	-1.60		multi large cubes
MDS05-129-2	MR2	WMM	54.05	-1.67		half cube
MDS05-129-3	MR2	WMM	50.10	-1.60		half cube
MDS05-129-4	MR2	WMM	44.31	-1.28		single cube
MDS04-224	CM1	TLM	41.79	-31.28		large cubes
MDS04-228	CM1	TLM	37.92	-30.36		large cubes
MDS04-247	CM1	WMM	35.12	-4.02		large cubes
MDS05-021	CM2	GSM	34.47	-26.95		large cubes
MDS05-023	CM2	GSM	33.74	-26.97		large cubes

Sample name	Lct.	Unit	%S	$\delta^{34}\text{S}_{\text{CDT}}$	$\delta^{34}\text{S}_{\text{CDT}}^{\text{d}}$	Pyrite description
MDS05-046	PM1	HTC	42.15	18.34		medium poor cubes
MDS05-047	PM1	HTC	41.00	9.15		medium poor cubes
MDS05-049	PM1	HTC	41.60	13.36		large broken cubes
MDS05-051	PM1	TLM	38.35	-11.41		small poor cubes
MDS05-053	PM1	TLM	40.53	-16.49		tiny good cubes
MDS05-065	PM1	TLM	29.28	-8.25		small, rusty cubes
MDS05-066-1	PM1	TLM	34.29	-7.91		large broken cube
MDS05-066-2	PM1	TLM	29.11	-9.93		large broken cube
MDS05-082	PM1	WMM	33.52	-14.59		small good cubes
MDS05-083-1	PM1	WMM	33.09	-15.55		nice large cube
MDS05-083-2	PM1	WMM	40.70	-15.78		silver grainy, not cube
MDS05-084	PM1	WMM	59.05	-29.09		large good cubes
MDS05-087	PM1	WMM	51.73	-29.56	-29.54	medium good cubes
MDS05-090-1	PM1	WMM	59.49	-27.76		two large black cubes
MDS05-090-2	PM1	WMM	59.49	-27.68		large broken cube
MDS05-090-3	PM1	WMM	57.53	-27.86		medium good cube
MDS05-090-4	PM1	WMM	59.02	-27.82		large cube outer
MDS05-090-5	PM1	WMM	57.44	-27.81		large cube inner
MDS05-092-1	PM1	WMM	59.07	-27.12		multi medium cubes
MDS05-092-2	PM1	WMM	59.92	-27.28		single medium cube
MDS05-093	PM1	WMM	59.52	-27.41		good small cubes
MDS05-114-1	PM1	HTC	45.10	-3.95		large poor cube
MDS05-114-2	PM1	HTC	30.81	-3.81		large grainy, not cube
JS06-019	PM2	GSM	45.89	-29.16	-29.09	tiny good cubes

APPENDIX N: Assignment #4: The Old Fort Point Formation

MAY 3RD

ASSIGNMENT #4:

OLD FORT POINT
FORMATION

16-5/20-0

GEOLOGY 219 FIELD SCHOOL

JASON FRENCH
SHAHIN DASTIGARD
MARK SMITH

3) GEOLOGICAL HISTORY

The geological history of the Old Fort Point Formation is a very complex sequence of events. It begins with the deposition of a shale unit that has suspended out in a deep marine setting. This was then overlain by a second shale unit of a differing composition interbedded with a conglomerate/breccia unit. This formed by a turbidite current flow deposit of the conglomerate, breccia, and diamictites. It appears to have its clasts originated from a storm current action closer to the shore. The turbidite (density controlled) flowed down the shelf onto the deep marine plain settling out in a fan shape. The sequence completed with another period of deposition of shale (differing composition from previous two).

^{and carbonate units} The evidence supporting the origin of a marine environment range from the shape of the beds to sedimentary structures. It has fine grained slate, that form along with the other units exhibiting a vertical & horizontal continuity possessing persistent thick beds. The presence of carbonate clasts lends to the marine origin theory. The conglomerate unit is comprised of a combination of the conglomerate/breccia/diamictites. These units together help to rule out fluvial activity & create support for the marine origin with deposition by mass movement/gravity flow (density controlled turbidite). Other sedimentary structures found throughout the area help support a marine origin. The trough cross-beds in the argillite (some traction deposits), and the parallel laminae running throughout the area. The minor presence of syneresis cracks suggests a salinity change. The angular carbonate rip-up clasts indicate with the imbrication a unidirectional current flow in the deposition of the conglomerate. Graded bedding is also present in the conglomerate unit.

The previous four units then underwent regional metamorphism altering, into the blue slate, argillite, conglomerate and green slate visible at the localities at the present.

The area experienced substantial tectonic activity influencing its final appearance. The major fold in the area is a secondary fold in the (anticline) Jasper anticlinorium ($124^{\circ} 70^{\circ} \text{SW}$), with other minor antidiels ($124^{\circ} 70^{\circ} \text{SW}$ ^{and/or plunging anticline}) and synclines ($124^{\circ} 70^{\circ} \text{SW}$) as well. There are some even smaller folds ("S"/"M" - folds) and chevron folds found at the anticline's (2nd) nose. All of these tectonic features occurred from the same disturbance.

The Formation then experienced a period of erosion. This erosion affected the units in a differential manner. The slate units, being friable,

and less resistant, were eroded to a much greater extent than the conglomerate/breccia unit. This differential erosion accounts for the ridges (of conglomerate) that are found at the Old Fort Point site. Finally, completing the history (will be dealt with later at field school), is the deposition of glacial sediment that is found throughout the area except at the exposed outcrops.

⑧ As part of the tectonic disturbance, the units also underwent major faulting (015° 85° NW) and minor faulting (045° 84° NW), (038° 86° NW) in a system.

SUMMARY

1) Deposition of Unit A

Unit B

45/6.0

Unit C

Unit D

2) Regional Metamorphism

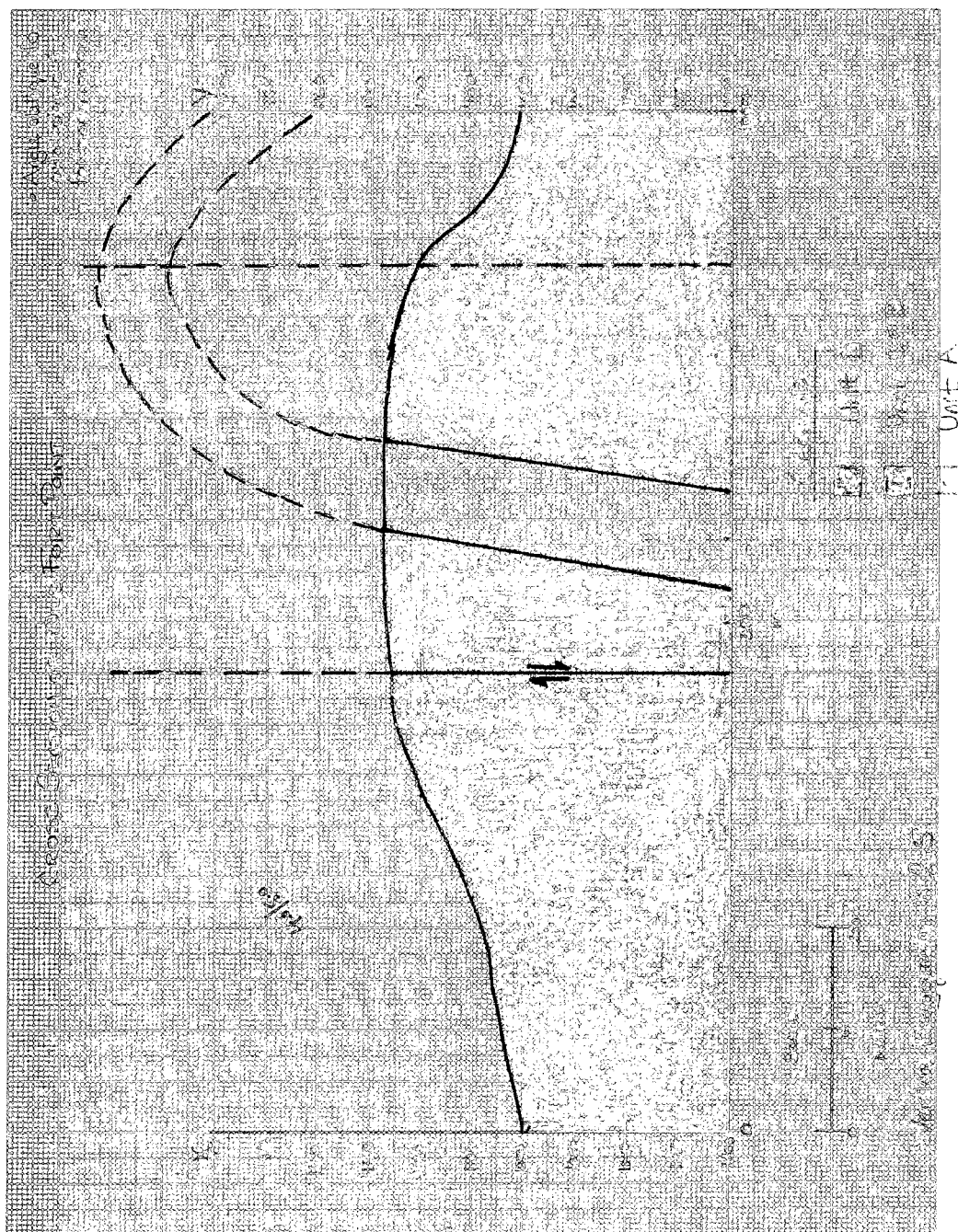
3) Tectonic Activity

-Folding

-Faulting

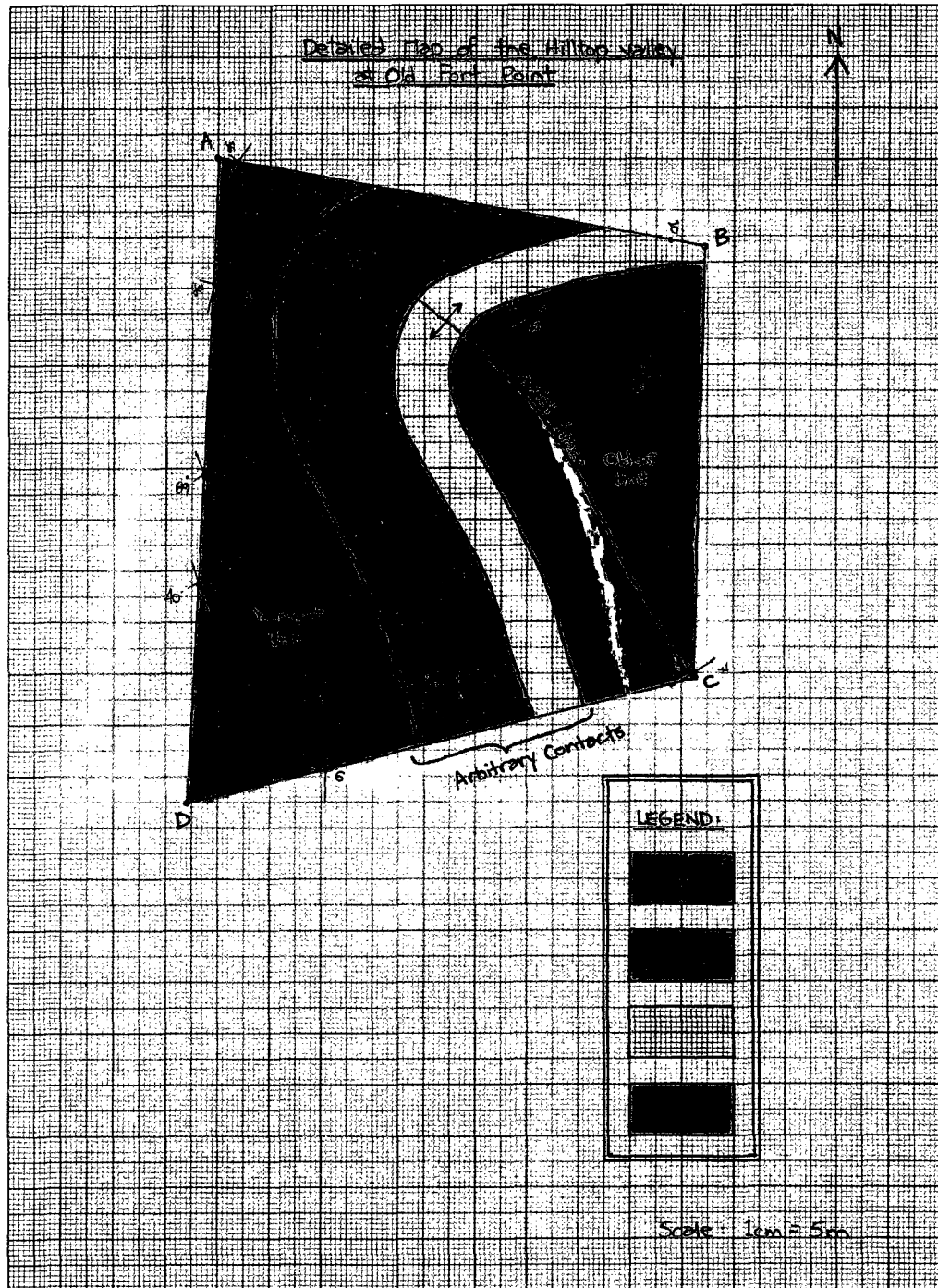
4) Differential Erosion

5) Deposition of Glacial sediments



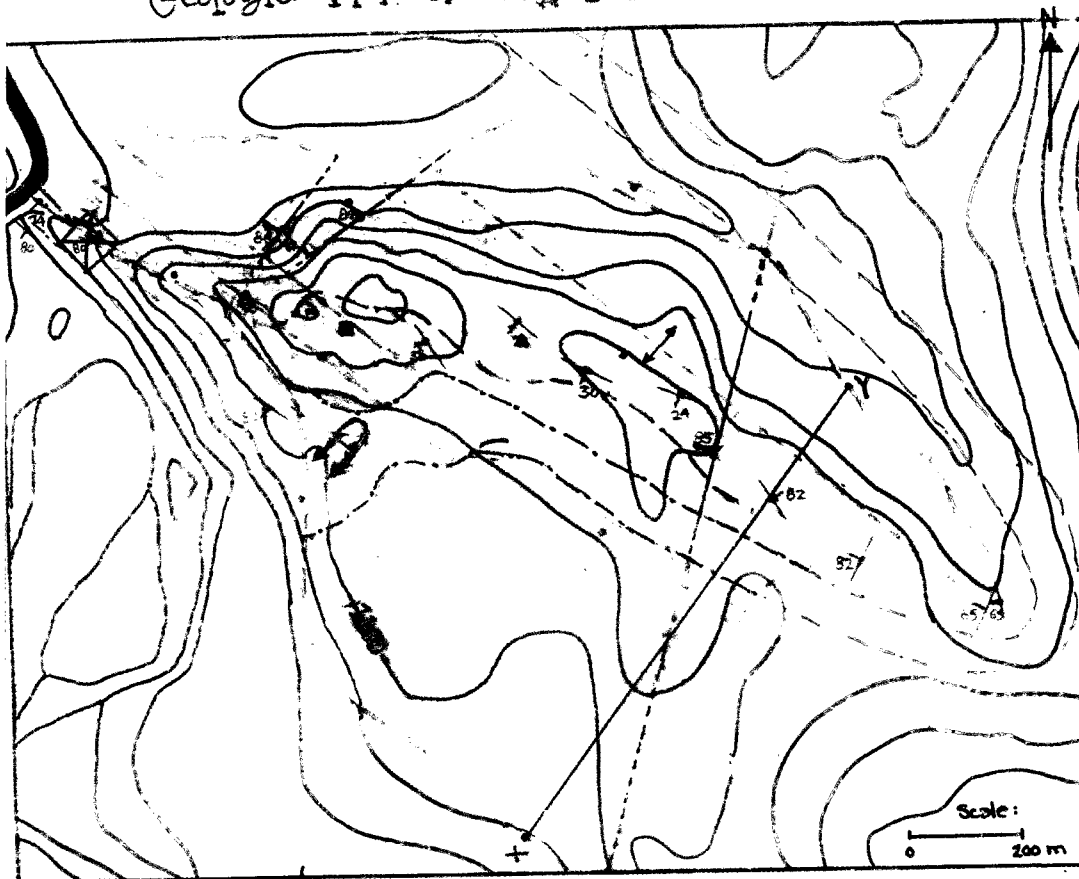
- elevation?

4.0/5.0



10 Millimeters to the Centimeter

Geologic Map of Old Fort Point



LEGEND:

D

B+C

A

CONTOUR
INTERVAL: 20m

Geologic boundaries