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**STRATIGRAPHY AND SEDIMENTOLOGY OF THE
CHANCELLOR SUCCESSION (MIDDLE AND UPPER CAMBRIAN)
SOUTHEASTERN CANADIAN ROCKY MOUNTAINS**

By
WILLIAM DOUGLAS STEWART

A Thesis
Presented to the School of Graduate Studies and Research
in Partial Fulfillment of the Requirements for the
Degree of Doctor of Philosophy
in
Geology

Ottawa-Carleton Geoscience Centre
and University of Ottawa
Ottawa, Ontario, Canada



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DEDICATION



This thesis is dedicated to the memory of Dr. Brian Rust, who supervised this project prior to his tragic death in June 1990. In addition to his many talents, Brian had a keen intellect, a fine sense of humour, and an insatiable curiosity about the natural world.

"Because of structural complexity, lithic monotony, penetrative cleavage, and a dearth of fossils, the Chancellor, like many other detrital formations, has been a stratigrapher's Gordian Knot."

- J.D. Aitken

ABSTRACT

The Chancellor succession accumulated in a deep-water trough bordering a wide, epeiric shelf during Middle and Late Cambrian time. Due to structural complexity and poor biostratigraphic control, the stratigraphic and sedimentological relationships in the zone of facies change have long been poorly understood. Clarification of these relationships at the level of the lower and middle Chancellor has provided new insights into large-scale depositional and erosional processes at the critical juncture between the shelf margin and upper slope.

The Chancellor is divisible into seven major lithostratigraphic units, which are correlative with an eastern shelf assemblage comprising eight carbonate and siliciclastic formations. Two of the Chancellor units have already been designated as formations (Naiset and "basinal" Stephen formations), and the remainder are new units deserving of that rank (Takakkaw Tongue, McArthur unit, Duchesnay unit, Oke unit, and upper Chancellor sequence). The Chancellor must therefore be elevated from formation to group status. The McArthur unit is further divisible into the Tokumm and Vermilion sub-units, both of which merit the rank of member.

The deep-water carbonate and siliciclastic sediments in the Chancellor are divisible into five basic lithofacies, each of which has several variants due to a variety of depositional and diagenetic factors. Sediments in the **argillite lithofacies** were deposited by dilute, muddy and silty turbidity currents and hemipelagic settling. The **ribbon calcilutite lithofacies** was probably deposited in a similar manner, but owes its final appearance to diagenetic enhancement of rhythmic, primary variations in sediment composition. Both of these lithofacies contain a variety of syndepositional deformation structures indicative of

slope instability. The **ribbon calcisiltite** lithofacies is composed of interbedded silty carbonate and terrigenous mud turbidites. The **calcarenite lithofacies** is the product of high-concentration turbidity flows. It locally occupies large, channel-like features ("megachannels"), which are inferred to be slide scars incised into the upper slope. Most of the sediments assigned to the **conglomerate lithofacies** show evidence of matrix strength, and were laid down by debris flows. This lithofacies includes spectacular megaconglomerates containing Epiphyton boundstone blocks up to 50 m in maximum dimension. Periplatform talus blocks of similar size are scattered throughout the Chancellor.

The Naiset Formation, "basinal" Stephen Formation and Duchesnay unit are predominantly fine-grained terrigenous turbidite sequences that accumulated during periods of widespread siliciclastic sedimentation on the adjoining shelf (represented by the Mount Whyte, "platformal" Stephen and Arctomys formations, respectively). The Takakkaw Tongue, Tokumm sub-unit and Oke unit are laterally extensive carbonate aprons that were deposited during periods of predominantly shallow-water carbonate sedimentation on the shelf (represented by the Cathedral, Eldon-lower Pika and Waterfowl formations, respectively). During most of Chancellor time, silt- and sand-sized material either bypassed the upper slope or was confined to the shelf. The high proportion of carbonate and siliciclastic turbidites in the Duchesnay and Oke units (middle Chancellor) is a direct reflection of an abrupt, regressive shift in the position of the cratonal shoreline.

Spectacular cross-strike exposures have revealed that the Eldon-Pika margin and adjoining upper slope strata (Tokumm and Vermilion sub-units) are traversed by at least three **megatruncation surfaces**. These are sharp, relatively smooth erosional surfaces that visibly truncate up to 215 m of outer platform strata. Most are demonstrably listric in form, and are onlapped by deep-water sediments. Platformward, they either merge imperceptibly

with platform bedding or terminate in near-vertical headwalls. The megatruncation surfaces are inferred to be the upper parts of regional submarine gravity slide structures produced by large-scale, outer platform collapse. The debris generated by these large-scale collapse events is presumably incorporated in olistostromes lying well beyond the limits of current exposure. In contrast, the megaconglomerates observed in the study area were generated by margin failures an order of magnitude smaller.

Comparisons with modern and ancient analogues indicate that the megatruncation surfaces probably have areal extents greater than the entire study area, and that they profoundly affect regional stratigraphy. Three, laterally continuous megatruncation surfaces are inferred to traverse the platform margin and upper slope strata, and thus different stratigraphic successions are encountered, depending on where along a cross-sectional profile a particular stratigraphic section has been measured. Based on this premise, all of the key stratigraphic relationships in the study area can be distilled into a single, comprehensive stratigraphic model.

The recognition that the Middle Cambrian carbonate margin was prone to large-scale collapse, and the discovery of a new exposure of the Cathedral Escarpment, have provided fresh insight into the origin of that enigmatic feature. The truncation of platform bedding, and the presence of a major megabreccia at the foot of the new exposure, provide the most explicit evidence of a collapse origin. This interpretation reaffirms that the Burgess Shale was deposited at the base of a Middle Cambrian submarine cliff, and implies the presence of a subtle, bedding-parallel megatruncation surface in the extensive cross-strike exposures near Field.

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It is traditional in a thesis to acknowledge first the organizations and individuals who financed and supervised the study. This is an injustice, as it is the family of the author that makes the greatest sacrifice. After all, it is they who must endure the prolonged absences, the chronic absent mindedness, and the ever elusive deadlines. For that reason, I would like to express my deepest gratitude to my partner Clare, who endured it all through boundless patience, love and understanding. My daughter Jeneba never failed to bring joy into each day, and taught me that there is more to life than writing a book that is, in any case, absolutely useless as a bedtime story. Even little Kaia, born in the closing weeks of the writing, contributed by thoughtfully sleeping through the night at an early age.

The field component of this project was generously funded by the Institute of Sedimentary and Petroleum Geology (Geological Survey of Canada). Without GSC support, the author would have lacked the mobility and resources necessary to unravel the Chancellor. Don Cook and Jim Aitken of the ISPG initiated this study, and both provided valuable advice and assistance throughout. All fossils collected during this study were identified at the GSC in Ottawa by Bill Fritz, who readily shared his extensive knowledge of Cambrian stratigraphy and biostratigraphy. Don, Jim and Bill also critically read the pre-final draft of this thesis.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL STATEMENT

Deep-water carbonate slopes have recently become the focus of intense research, partly as a result of significant hydrocarbon discoveries in this geological setting in Mexico (e.g. Poza Rica Trend; Enos and Moore, 1983), the southwestern United States (Permian Basin; Hobson *et al.*, 1985), and other areas (see Cook and Mullins, 1990). Current concepts about carbonate slopes have come largely from a small, but rapidly expanding number of well documented ancient examples (e.g. Cook *et al.*, 1972; various papers in Cook and Enos, 1977a; Pfeil and Read, 1980; James and Stevens, 1986 and related papers). Increasingly, however, this data base is being supplemented by studies of modern deep-water carbonate slopes in the Gulf of Mexico, Caribbean and Bahamas regions. Seismic reflection methods have proven especially valuable in identifying large-scale depositional and erosional features and establishing three-dimensional deposit geometry. Collectively, these studies have revealed many sedimentary features unique to carbonate margin and slope settings, such as spectacular megabreccias and large-scale erosional structures associated with wholesale platform margin collapse (e.g. Mountjoy *et al.*, 1972; James and Stevens, 1986; Mullins *et al.*, 1986; Bosellini, 1989).

The **Chancellor Formation** is a carbonate slope and basin succession of Middle to Late Cambrian age. The distal parts of this succession are structurally deformed and remain largely undeciphered. Prior to this study, the gross lithostratigraphic units that had been

mapped near the zone of facies change with coeval shelf strata had never been studied in detail. More importantly, the character of the platform-to-basin transition had never been satisfactorily resolved on a regional scale, despite intensive studies at specific stratigraphic levels (e.g. McIlreath, 1977a). This zone is relatively undeformed, exposed at mountain scale, and readily accessible. The facies relationships and large-scale erosional features found within it are the subject of this thesis.

1.2 LOCATION AND ACCESS

The study area is situated immediately southwest of the Continental Divide in southeastern British Columbia. It is about 130 km long and less than 10 km wide, and lies mainly within the borders of Yoho and Kootenay National Parks and Mount Assiniboine Provincial Park (Figs. 1, 2).

The northern part of the study area is traversed by the Trans-Canada Highway and the Canadian Pacific rail line. Both follow the Kicking Horse Valley and pass through the town of Field (Fig. 3), which serves as the administrative headquarters for Yoho National Park. The southern part of the study area can be reached along Highway 93, which follows the Vermilion and Kootenay River valleys (Fig. 4). A well maintained mining road in the Cross River valley provides access to the southeastern extremity of the study area.

Although the lower altitude exposures are generally accessible from early June onward, conditions are generally wet, and the canyons tend to be choked with snow early in the season. The higher altitude sections, particularly those on north-facing slopes, are better suited to examination in late July or August.

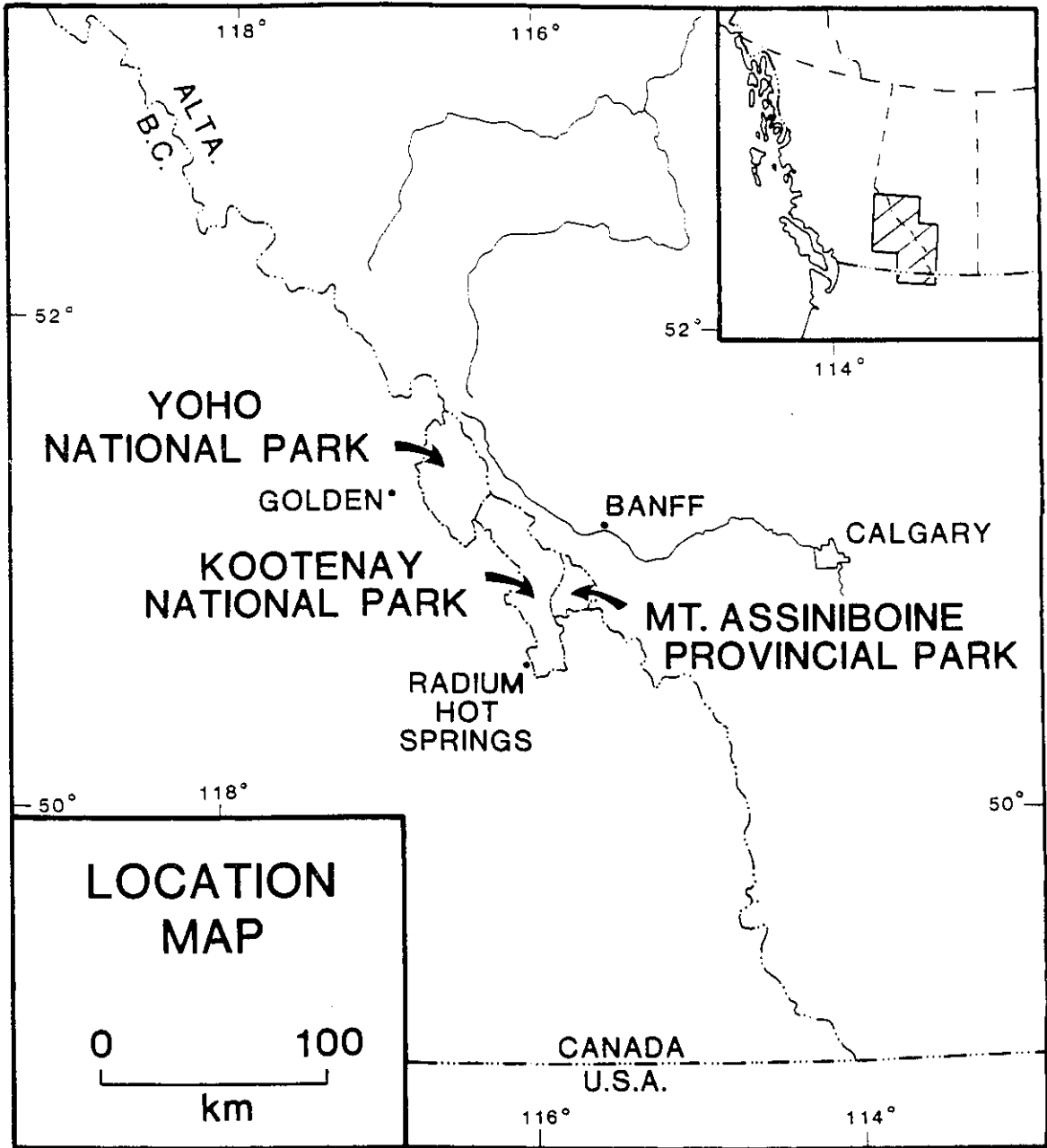


Figure 1. Location map for Yoho and Kootenay National Parks and Mount Assiniboine Provincial Park.

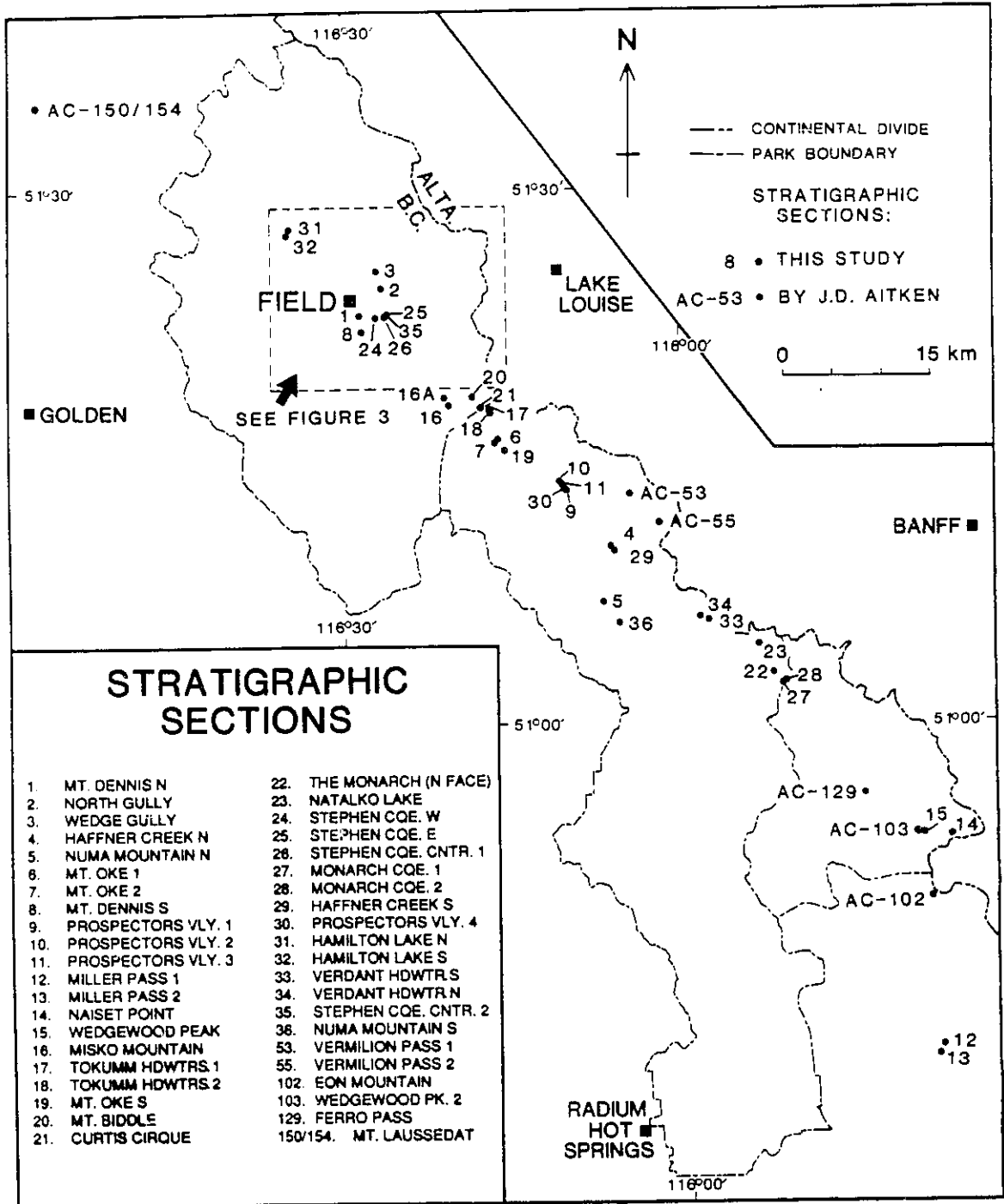
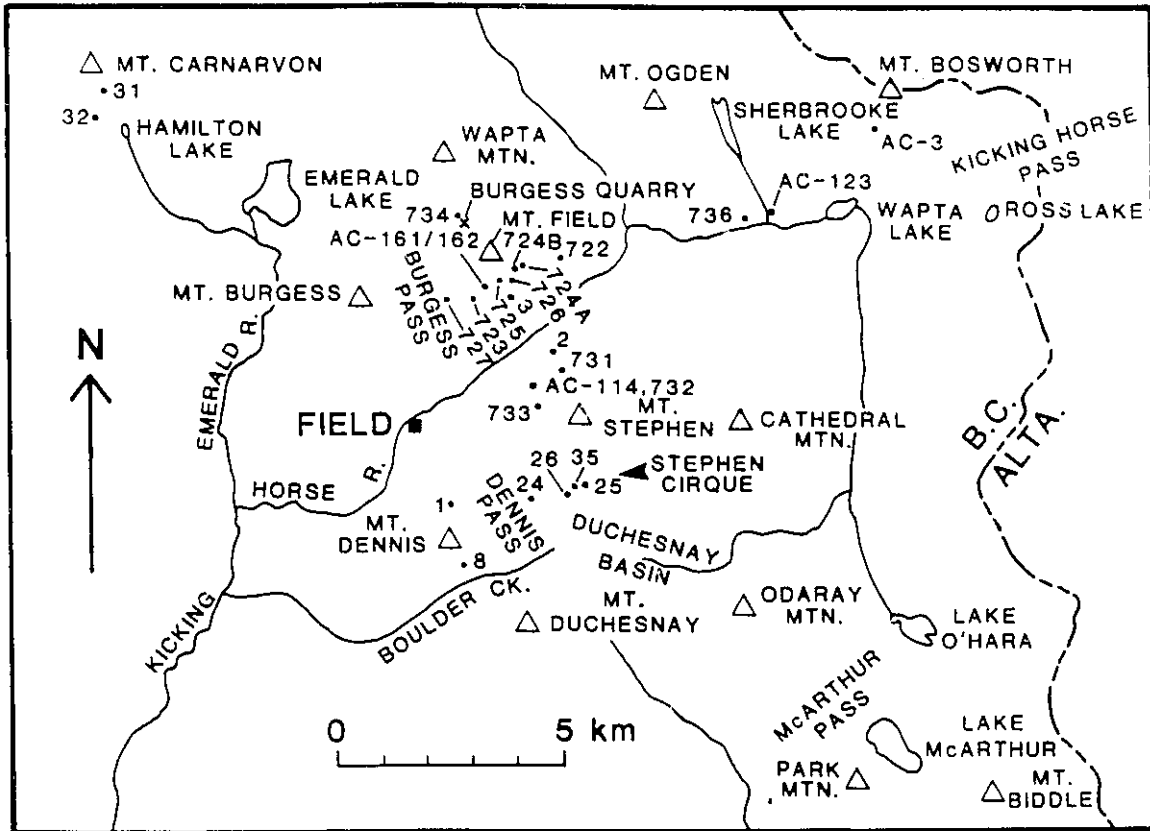


Figure 2. Locations of stratigraphic sections measured during the present study, and key sections measured by J.D. Aitken.



INDEX TO STRATIGRAPHIC SECTIONS

1. MT. DENNIS N	AC-3 MT. BOSWORTH	MJA-722 CHALET GULLY
2. NORTH GULLY	AC-114 MT. STEPHEN, NORTH	MJA-723 AVALANCHE SECTION
3. WEDGE GULLY	FACE	MJA-724A CAMP GULLY E
8. MT. DENNIS S	AC-123 KICKING HORSE PASS	MJA-724B CAMP GULLY W
24. STEPHEN CIRQUE W	ROADCUTS	MJA-725 WEDGE GULLY (UPPER)
25. STEPHEN CIRQUE E	AC-161/2 MT. FIELD	MJA-728 DRY GULLY
26. STEPHEN CIRQUE CENTRE 1		MJA-727 BIG FLY GULLY
31. HAMILTON LAKE N		MJA-731 STEPHEN GLACIER
32. HAMILTON LAKE S		MJA-732 FOSSIL GULLY (LOWER)
35. STEPHEN CIRQUE CENTRE 2		MJA-733 FOSSIL GULLY (UPPER)
		MJA-734 PARADOX SECTION
		MJA-736 WAPTA LAKE

Figure 3. Detailed map of the Field area, showing stratigraphic sections measured by I.A. McIlreath (MJA prefix), J.D. Aitken (AC prefix), and the author (no prefix).

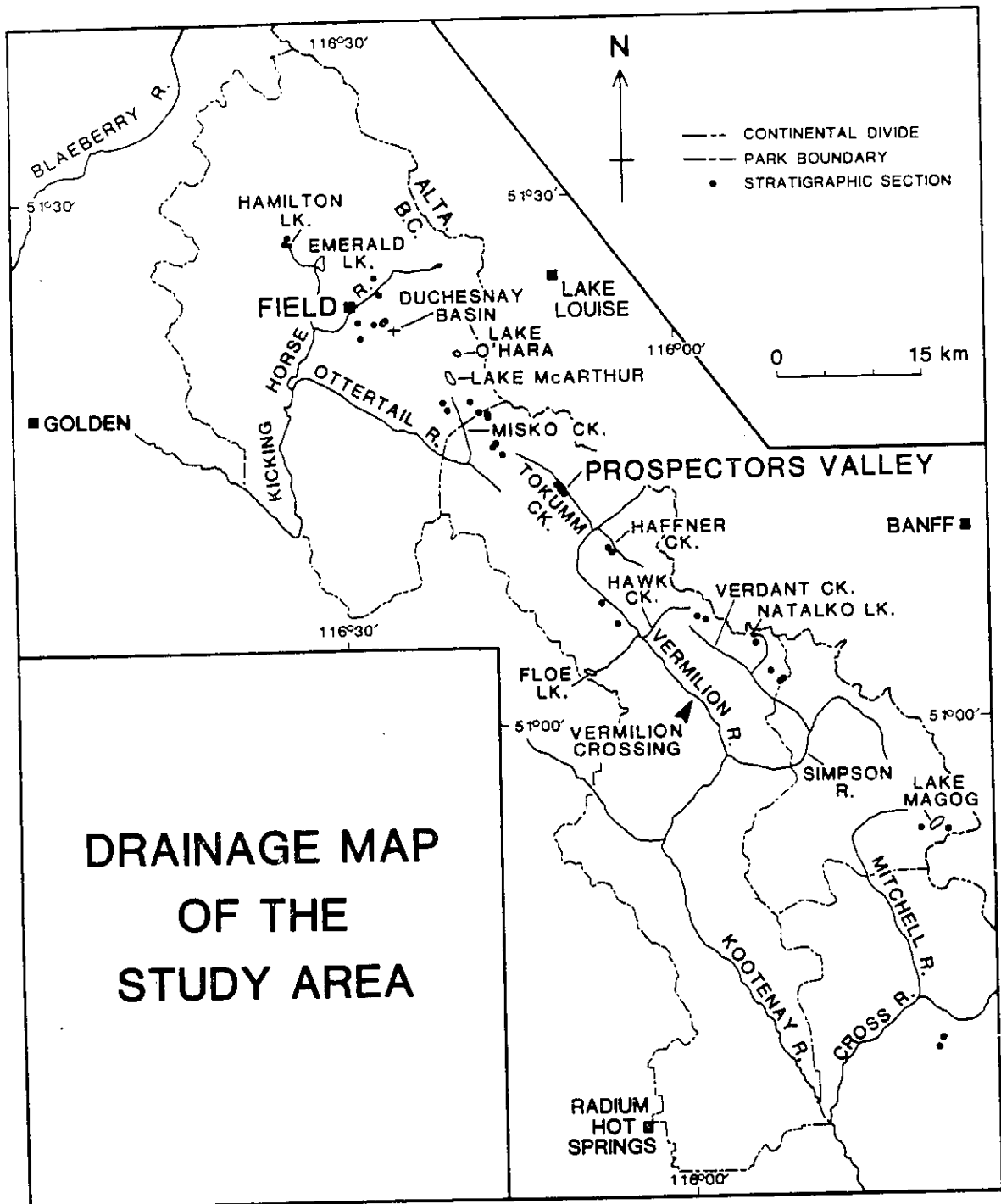


Figure 4. Drainage map of the study area.

Several of the stratigraphic sections measured during this study could be reached on foot in less than 2 hours along excellently maintained National Parks hiking trails. Light camps were packed in to more distant localities. Sections located at higher altitudes (7500-8000 ft.) were sufficiently remote to warrant the use of fly camps supplied by helicopters based in Banff or Canmore.

This project was greatly enhanced by the use of helicopters. Helicopter reconnaissance located most of the crucial cross-strike exposures of the Middle Cambrian facies change. In addition, remote exposures could be more thoroughly examined from helicopter fly camps than would otherwise have been possible. Flights were approved on a case-by-case basis, using Park guidelines to minimize impacts on the natural environment and tourism. Efficient use was made of air time by splitting helicopter charters with Parks personnel, particularly trail maintenance crews. The success of this study suggests that helicopters can be used prudently and with minimal impact to conduct beneficial research in the National and Provincial Parks.

1.3 FIELD WORK

Eight months of field work were carried out during the summers of 1987, 1988 and 1989. During that time, 37 stratigraphic sections, totalling about 10.3 km of Chancellor and equivalent strata, were measured in as much detail as time permitted. More than 600 hand specimens were collected, of which about 340 were examined in thin section to supplement field descriptions. All of these specimens are the property of the National and Provincial Parks, and are currently being stored on their behalf at the Institute of Sedimentary and Petroleum Geology (Geological Survey of Canada) in Calgary.

Most of the stratigraphic sections are located in the core part of the study area, defined as the 70 km-long zone from Mt. Carnarvon in the northwest to The Monarch in the southeast (Fig. 5). The entire study area was also reconnoitered by helicopter to locate additional stratigraphic sections, and to assess the lateral variability and mappability of the stratigraphic units measured on the ground.

Most stratigraphic sections were measured along a series of NW-SE trending valleys oriented sub-parallel to original depositional strike (Misko Valley, Prospectors Valley, Haffner Creek, and Verdant Creek; Fig. 4). The platform margin is visible at a few, key cross-strike exposures at certain stratigraphic levels. These cross-strike exposures permitted direct correlation of stratigraphic units across the zone of facies change. They also revealed the style of platform margin and the nature of downslope facies changes at various stratigraphic levels. These relationships were recorded in the field on enlarged photographs. The line drawings from these photographs provide a striking visual record of the margin at different times in its history (Plates 39-42; 46; 49-54).

The most startling revelation of the cross-strike exposures was the presence of large-scale erosional features, herein termed **megatruncation surfaces**, which represent the wholesale removal of hundreds of metres of platform margin and upper slope strata. The recognition of these features led to the realization that significant, yet subtle disconformities were present in the stratigraphic sections measured along strike. Perplexing correlation problems amongst these sections were thus resolved. With the acquisition of more stratigraphic evidence, it soon became clear that the observed megatruncation surfaces are but small segments of features much larger in scale than the mountainsides on which they are exposed. This necessitated a mental readjustment to a scale more familiar to seismic

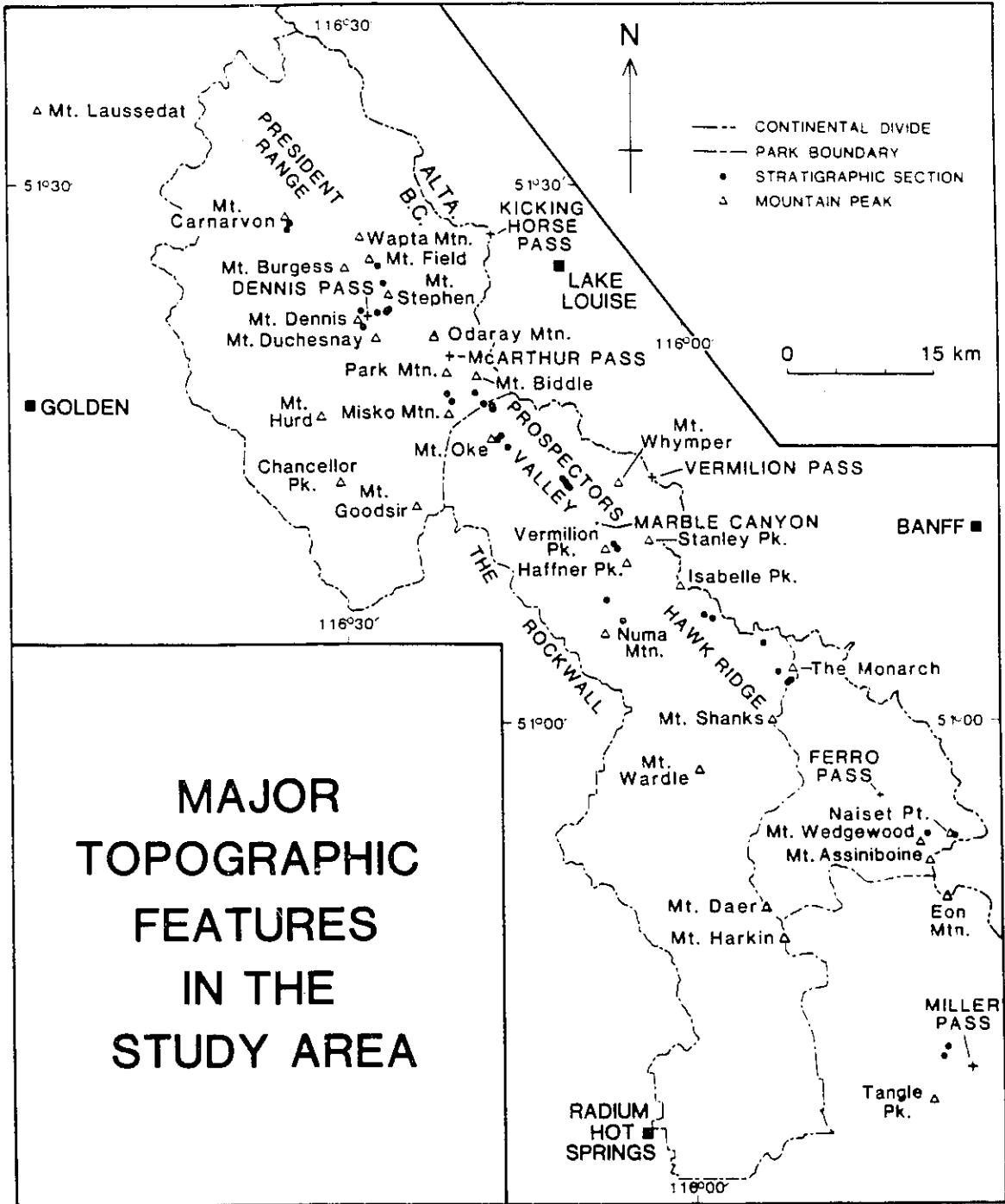


Figure 5. Major topographic features in the study area.

stratigraphers than outcrop geologists, before the style of the Middle to Upper Cambrian facies change could be reconstructed.

1.4 OBJECTIVES, SCOPE AND CONTRIBUTIONS OF THIS STUDY

The primary goal of this study was to establish the stratigraphic and sedimentological relationships across the zone of facies change between a Middle and Upper Cambrian shelf assemblage and its slope and basin equivalent, the Chancellor Formation. To achieve this goal, considerable effort was put into establishing a regional stratigraphy for the Chancellor sequence to facilitate correlation at the formation level with the shelf succession. In keeping with this emphasis on stratigraphy and physical sedimentology, no attempt was made to delve into the diagenesis of these sediments beyond a superficial level.

This study has made a number of contributions towards understanding the Middle to Upper Cambrian facies change:

1. **Refinement of Chancellor stratigraphy:** the refinement of Chancellor stratigraphy should facilitate regional mapping and correlations with strata along strike to the northwest. As a thesis is not the proper forum for defining formal nomenclature, informal stratigraphic names have been used throughout (see also Stewart, 1989). It is writer's intention to formalize these names in a future Geological Survey of Canada Bulletin.
2. **Establishment of platform-to-basin correlations:** this study resolved long-standing correlation problems between the shelf and slope strata (Cook, 1975;

McIlreath, 1977a), chiefly through the application of physical stratigraphic principles, supplemented in part by sparse biostratigraphic control.

3. **Documentation of the style of facies change:** extensive, along-strike exposures of the upper slope sequence and a small number of cross-strike exposures of the platform margin at key stratigraphic levels have permitted the recognition of different margin styles, including ramps, depositional margins, and collapsed margins. These have been incorporated into a new regional model for the Middle to Upper Cambrian facies change.
4. **Documentation of physical sedimentary processes:** the six major lithofacies documented in this thesis provide important insights into the range of sedimentary processes operative in the upper slope environment. This provides a basis for comparison with other ancient and modern examples.
5. **Documentation of large-scale depositional and erosional processes on carbonate slopes:** this thesis documents large-scale depositional and erosional processes that are probably widespread in carbonate slope environments. Examples include wholesale outer platform collapse, the establishment of upper slope sediment bypass channels, and megaconglomerate shedding by minor margin failures. Thus, the spectacular outcrops described in this thesis are an important, accessible resource for geologists wishing to gain hands-on experience in this particular sedimentary environment.
6. **A new interpretation of the Cathedral Escarpment:** an unexpected outcome of this study was the discovery of a new example of the Cathedral Escarpment. Key

elements of this exposure have led to the conclusion that, throughout the study area, the Cathedral Escarpment is the headwall of a large-scale collapse feature (megatruncation surface). This reaffirms the classic contention that the Burgess Shale accumulated at the foot of a submarine escarpment.

1.5 FORMAT OF THESIS

This thesis is organized into eight chapters. Chapter 2 outlines the regional structural and stratigraphic framework and depositional setting of the study area. Chapter 3 summarizes the contributions of previous workers in and around the study area, and describes the regional platform stratigraphy. In Chapter 4, all deep- and shallow-water lithofacies encountered in the study area are described and interpreted. Chapter 5 provides the first comprehensive account of Chancellor stratigraphy. The megatruncation surfaces that traverse the Middle to Upper Cambrian margin and upper slope succession are documented in Chapter 6. Chapter 7 describes and reinterprets the Cathedral margin, with special reference to the Cathedral Escarpment. Finally, the depositional history of the Middle and Upper Cambrian slope succession is summarized in Chapter 8.

CHAPTER 2

REGIONAL GEOLOGICAL AND PALEOGEOGRAPHICAL CONTEXT

2.1 REGIONAL STRUCTURAL FRAMEWORK

The study area is situated in the southern Rocky Mountain Fold and Thrust Belt, one of five morphogeological terranes in the Canadian Cordillera (Fig. 6). This belt contains tectonically compressed strata of a northeast-tapering wedge of sedimentary rocks deposited in the platform, miogeocline and foreland basin domains of the Western Canada Sedimentary Basin (Fig. 7).

The southern Rocky Mountain Belt ranges from 150-250 km in width, and is dominated by easterly verging thrust faults and associated flexural slip folds (Fig. 8). Regionally, these faults form a penetrative array of laterally discontinuous slip surfaces, the spacing and orientation of which are affected by lateral and vertical changes in the stratigraphy and the level of exposure (Price, 1981; McMechan and Thompson, 1989). At the latitude of the Trans-Canada Highway (51°N), this belt has been traditionally subdivided into five structural provinces, each displaying a distinctive structural style and physiographic expression (North and Henderson, 1954; Price and Mountjoy, 1970).

The study area straddles the boundary between two of these provinces, the Eastern and Western Main Ranges (Cook, 1975). In the **Eastern Main Ranges**, the lower Paleozoic succession is predominantly composed of structurally competent carbonate strata, which are

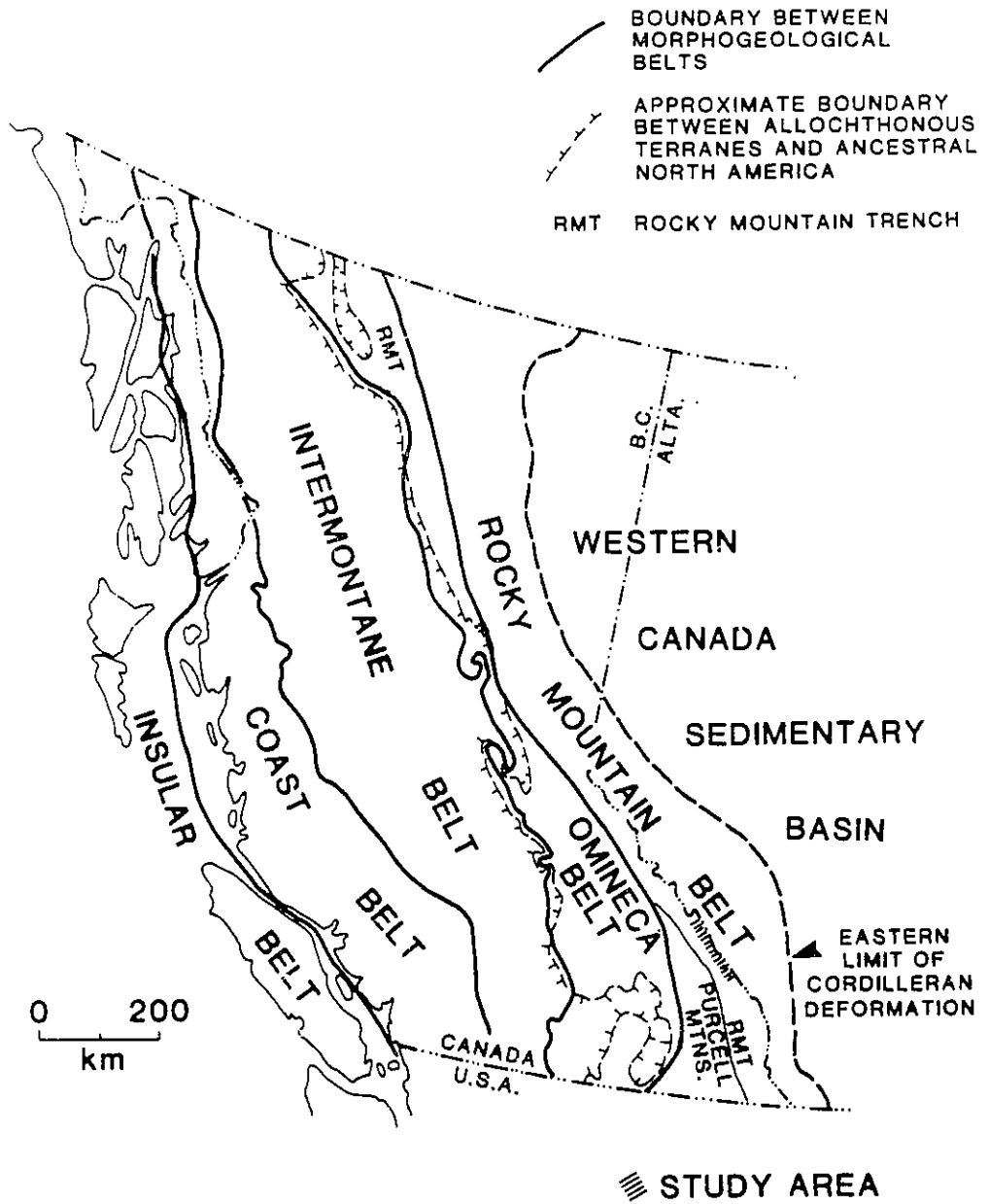


Figure 6. Morphogeological belts of the Canadian Cordillera (redrawn from McMechan and Thompson, 1989).

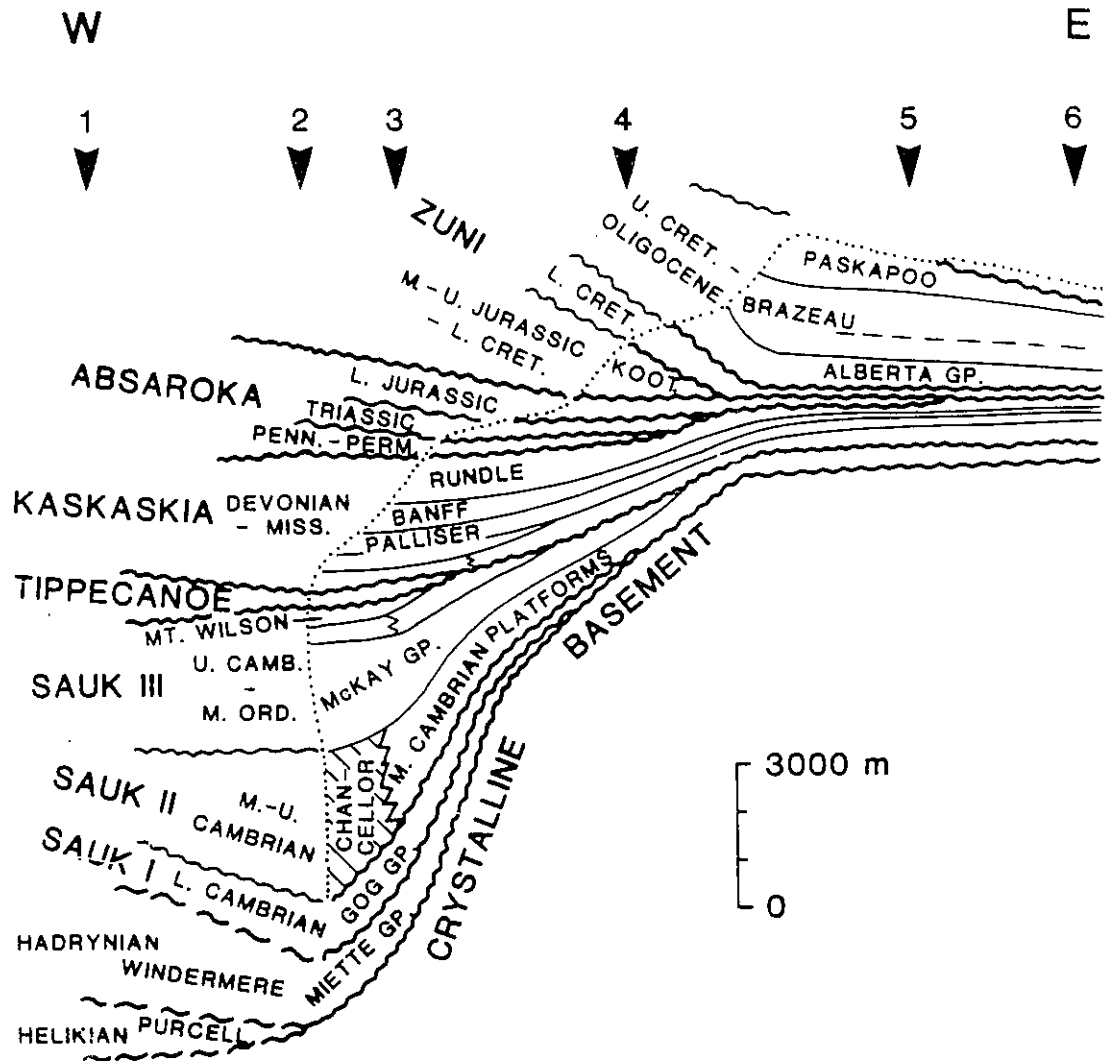


Figure 7. Generalized stratigraphic cross-section of the miogeocline-platform and foreland basin succession, showing the main, unconformity-bounded tectonostratigraphic assemblages. The Chancellor Formation is wholly contained in the Sauk II sub-sequence. 1: Rogers Pass; 2: Rocky Mountain Trench; 3: Field; 4: Banff; 5: Calgary; 6: Cypress Hills (redrawn from Ricketts, 1989b).

LEGEND

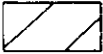
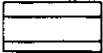
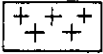








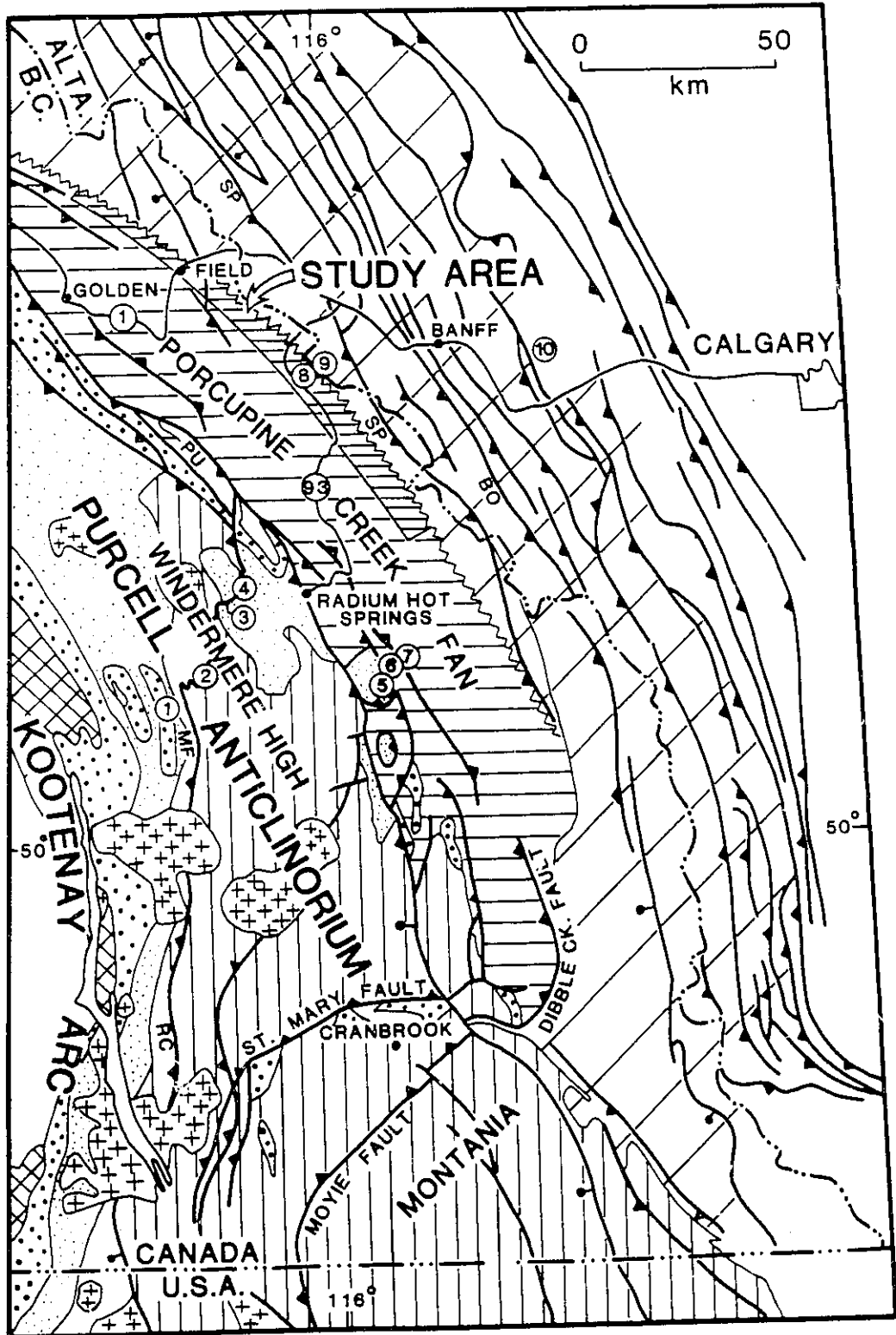
	MAINLY CAMBRO-ORDOVICIAN SHELF STRATA
	CAMBRO-ORDOVICIAN DEEP-WATER STRATA
	MIDDLE JURASSIC - MIDDLE CRETACEOUS PLUTONS
	LOWER PALEOZOIC LARDEAU GROUP
	LOWER CAMBRIAN HAMILL GROUP
	UPPER PROTEROZOIC WINDERMERE SUPERGROUP
	MIDDLE PROTEROZOIC PURCELL SUPERGROUP
	THRUST FAULT
	NORMAL FAULT
	FAULT, UNDEFINED DISPLACEMENT
	LOWER PALEOZOIC FACIES CHANGE

Figure 8. Generalized geological map of the southern Canadian Rocky Mountains fold and thrust belt, showing principal structural elements in the region of the study area (simplified from Tipper *et al.*, 1981, with modifications based on Root, 1987). The circled numbers correspond to the locations of the stratigraphic sections illustrated in Figure 10. SP: Simpson Pass Thrust; BO: Bourgeau Thrust; RC: Redding Creek Fault; MF: Mount Forster Fault; PU: Purcell Thrust. Map legend is shown above.



incorporated in a small number of enormous, folded thrust plates. These strata are cut by west-dipping normal faults and a few imbricate thrust sheets, and tend to form high, castellated peaks (Cook, 1975; McMechan and Thompson, 1989). In contrast, the structural style of the coeval argillaceous, deep-water succession in the **Western Main Ranges** is one of complex, disharmonic folding and penetrative cleavage (Cook, 1970, 1975; McMechan and Thompson, 1989). The most important feature in this structural province is the Porcupine Creek Anticlinorium, a regional, upward-diverging fan structure (Fig. 8; Balkwill, 1972). Physiographically, the mountains tend to be more rounded and subdued, and their internal stratigraphy is often obscured by complex deformation.

The **Purcell Anticlinorium** occurs farther southwest (Fig. 8), on the opposite side of the Rocky Mountain Trench. This feature is a broad, northward-plunging box fold cored by Middle Paleozoic strata, and is composed of stacked, folded thrust sheets. According to Price (1981), the anticlinorium is a crustal-scale example of a hanging wall anticline localized over a footwall ramp and flat formed by the attenuated edge of autochthonous, North American basement. The Lower Paleozoic sedimentary record has been largely stripped off this feature by erosion.

The west flank of the Purcell Anticlinorium is occupied by the **Kootenay Arc**, a narrow belt of complexly deformed, westerly facing, metasedimentary and metavolcanic rocks of Upper Proterozoic and lower Paleozoic age (Fig. 8). This feature marks the boundary between Proterozoic and Paleozoic strata of the pre-orogenic, western North American margin, and the tectonic collage of terranes that were accreted during mid-Jurassic time (Archibald *et al.*, 1983). It contains pericratonic rocks that are generally inferred to have been deposited on attenuated crust in continental slope and rise settings. Notably, these

rocks contain scattered records of mid-Paleozoic and Permo-Triassic contractional deformation and intrusive events that are not represented farther east (Monger, 1989).

Palinspastic reconstructions by Price (1981) indicate that prior to Late Cretaceous-Paleocene contractional deformation, strata now found northeast of the study area in the Bourgeau thrust sheet (Fig. 8) were formerly situated near the edge of the non-attenuated craton, close to the present day position of Kootenay Arc. Thus, all strata in and southwest of the Bourgeau thrust sheet, including those in the study area, are thought to have accumulated on attenuated continental crust (Fig. 9; see also Bond *et al.*, 1984). The lower Paleozoic facies change ("carbonate bank margin" of Price, 1981) studied in this thesis is therefore thought to have been detached from its original depositional basement and transported some 200 km northeastward onto the craton in response to the accretion of exotic superterranes during the Mesozoic and Tertiary (Price, 1981).

2.2 REGIONAL STRATIGRAPHIC SETTING

The rocks of the study area form a tiny part of a northeast-tapering wedge of sediments deposited along the western margin of ancestral North America. This wedge contains a series of unconformity-bounded, tectonostratigraphic assemblages ranging from Proterozoic to Tertiary in age (Fig. 7).

Southwest of the study area, the lowest tectonostratigraphic assemblage is composed of Middle Proterozoic quartzite, carbonate and argillite of the **Purcell Supergroup** (Fig. 8). These sediments have a maximum thickness of 11 km in the Purcell Anticlinorium, and are inferred to have been deposited between 1.5-1.2 Ga in basinal, shallow marine and continental environments (Ross *et al.*, 1989).

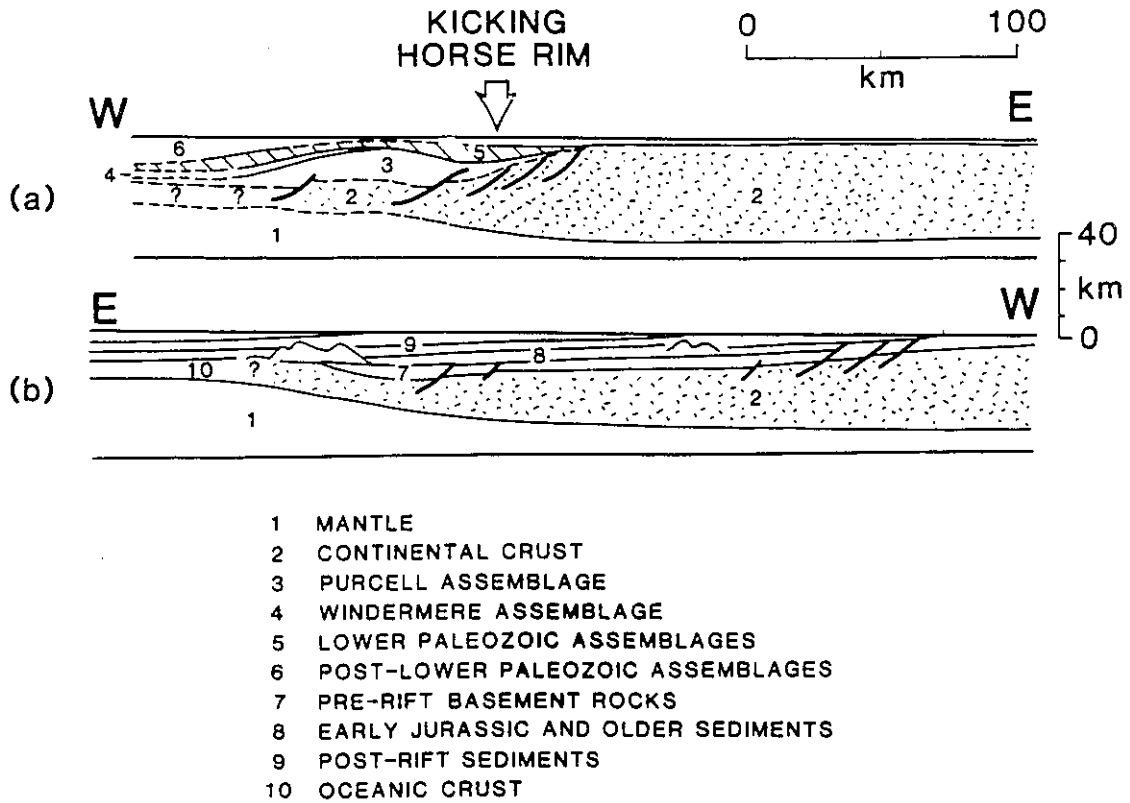


Figure 9. Comparison between a palinspastic reconstruction of the western Canadian continental margin at the end of Jurassic time (a), and a crustal section through the Atlantic margin of Canada (b). The Lower Paleozoic assemblage (5) is crosshatched. Note the position of the Kicking Horse Rim well inboard of the underlying edge of continental crust (redrawn from Price, 1981, with modifications from James and Mountjoy, 1983).

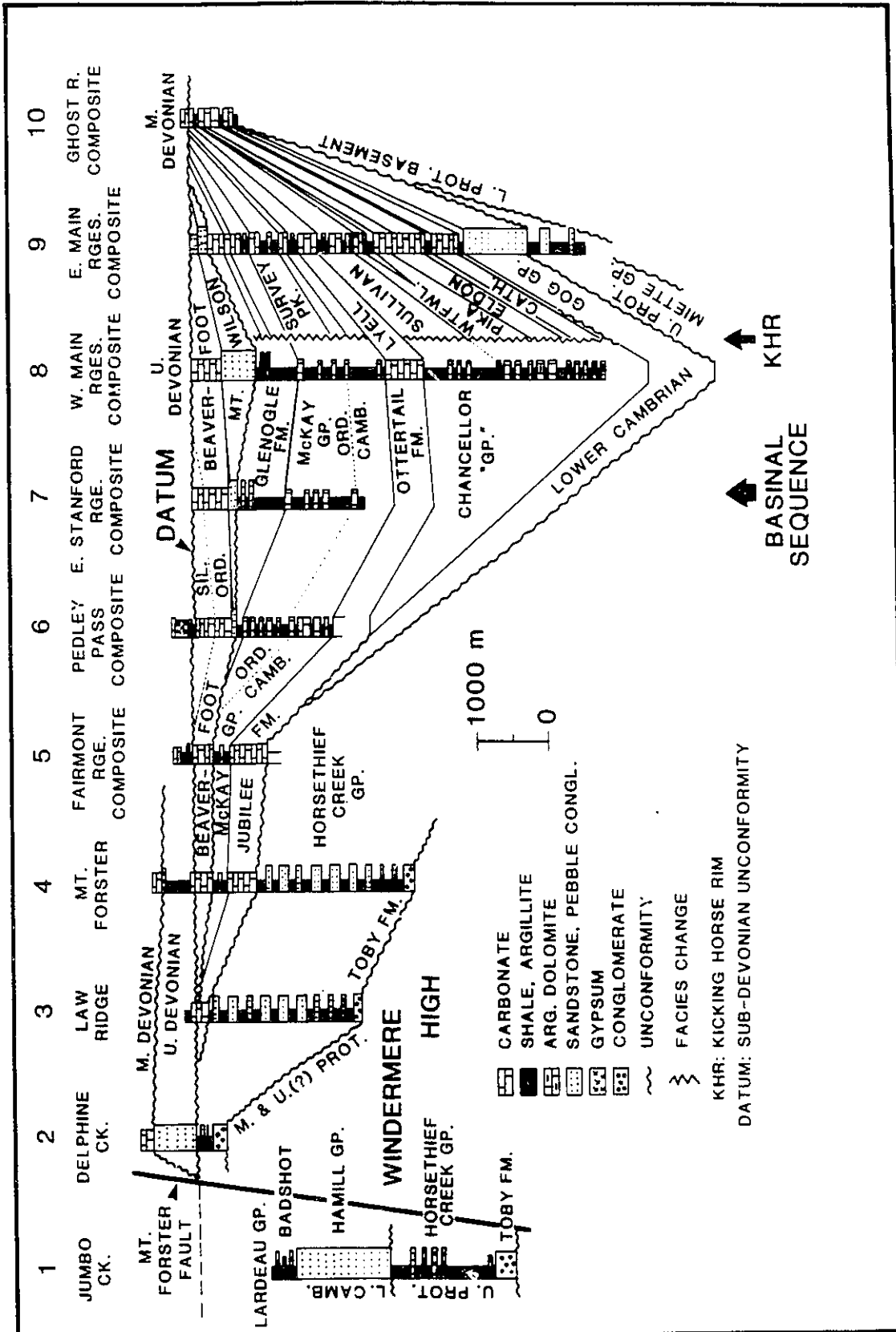
The second tectonostratigraphic assemblage is the Late Proterozoic **Windermere Supergroup**. In Canada, this assemblage crops out almost continuously from the 49th parallel to the Yukon-Alaska border. Exposures of the Windermere Supergroup have been assigned to the **Miette Group** near the study area, and to the **Horsethief Creek Group** in the Purcell Mountains to the southwest. Sparse radiometric age determinations suggest that Windermere sedimentation commenced between 728 and 760 Ma, and fossil evidence indicates that it ended during the Late Proterozoic (Ross *et al.*, 1989 and references therein).

The third tectonostratigraphic assemblage contains Early Paleozoic platformal and miogeoclinal rocks assigned to the Sauk sequence (Fig. 7; Sloss, 1963). This sequence thickens from about 1 km or less in the Front Ranges to about 5 km in the Eastern Main Ranges. The rocks of the study area occur in the lower part of this wedge.

In the Eastern Main Ranges, the lower part of the assemblage contains a thick, unconformity-bounded sequence of quartz sandstone and subordinate pelite belonging to the **Gog Group** (Fig. 10). These sediments were deposited mainly in shallow marine settings in and near the study area (e.g. Palonen, 1976; Hein, 1987), and in both marine and non-marine environments north of Jasper (Young, 1979). The Gog Group has a maximum thickness of at least 2000 m (Aitken, 1981a).

Partly coeval siliciclastic strata of the **Hamill Group** are found along the eastern margin of Kootenay Arc (Figs. 8, 10). The Hamill Group is composed of feldspathic and quartzose arenites and conglomerates, and contains locally abundant extrusive volcanic rocks (Devlin and Bond, 1988). Archeocyathid-bearing, shallow-water limestones of the Badshot Formation (late Early Cambrian age) are found stratigraphically above this sequence (Fig.

Figure 10. Stratigraphic section from the Front Ranges to the Purcell Anticlinorium (redrawn from Root, 1987). Section locations are shown in Figure 8. Note the significant thickening of stratigraphic units into the deep-water trough, and the disappearance of the Chancellor succession against the northeastern flank of the Windermere High.



KHR: KICKING HORSE RIM
 DATUM: SUB-DEVONIAN UNCONFORMITY

10; Fritz, in press). The sediments of the Hamill Group are inferred to have been deposited in fluvial and shallow marine environments sourced from nearby rift flank uplifts (Devlin and Bond, 1988).

The remainder of the Lower Paleozoic tectonostratigraphic assemblage contains the great carbonate platforms and intervening shale formations of Cambro-Ordovician age. With the exception of two formations, this entire stratigraphic succession changes facies southwestward into deep-water argillaceous strata at the "carbonate bank margin" mentioned earlier (Fig. 10; Price, 1981; Aitken, 1971, 1981a). Partly equivalent distal sediments in the Kootenay Arc consist of dark pelites, feldspathic grits, feldspathic wackestones, and basic volcanic rocks, all of which have been assigned to the Lardeau Group (Reesor, 1973; Price, 1981).

The remaining tectonostratigraphic assemblages in the sedimentary wedge have been assigned to the Middle to Late Paleozoic Tippecanoe and Kaskaskia assemblages, and the Triassic to Middle Jurassic Absaroka sequence (Fig. 7). The Absaroka assemblage records the final, pre-orogenic phase of sedimentation along the western North American margin. These assemblages have been described in summary form by Porter *et al.* (1982), and more recently by various authors in the volume edited by Ricketts (1989a).

2.3 ORIGIN AND EVOLUTION OF THE WESTERN NORTH AMERICAN MARGIN

2.3.1 Introduction

The wedge-shaped geometry of individual chronostratigraphic units, the well defined proximal to distal trends, and the lack of evidence for a westerly source area are all

compatible with a general passive margin setting for the Lower Paleozoic succession (Aitken, 1981a, in press, c; Bond *et al.*, 1989). This interpretation has recently been reinforced by quantitative subsidence analysis of the Lower Paleozoic sequence (Armin and Mayer, 1983; Bond and Kominz, 1984). Tectonic subsidence curves generated by this technique are comparable in form to those of modern passive margins (Sleep, 1971; Watts and Ryan, 1976; Steckler and Watts, 1978).

Although an overall divergent margin setting seems certain, important questions remain as to the timing, nature, and duration of rifting, the style of passive margin (see Sheridan, 1981), and the origin and nature of tectonic processes affecting parts of the trailing margin following continental separation. In addition, the tectonic setting of the Lower Paleozoic "shale basin" (Price, 1981) requires clarification.

2.3.2 Paleogeographical setting

During the Cambrian, continents were distributed latitudinally, with most land areas occurring within 60° of the paleoequator (Scotese, 1986). Polar icecaps were absent, and very broad, shallow epeiric seas covered large parts of the smaller paleocontinents (Bambach *et al.*, 1980).

During the Middle and Late Cambrian, the Cordilleran miogeocline was situated along the northern margin of Laurentia. Paleogeographic reconstructions indicate that the miogeocline was oriented roughly east-west, and was situated at low latitudes. The study area lay within the belt of northeasterly tradewinds, about 10° north of the Middle Cambrian paleoequator (Fig. 11; Scotese, 1986; Drewry *et al.*, 1974; Dalrymple *et al.*, 1985).

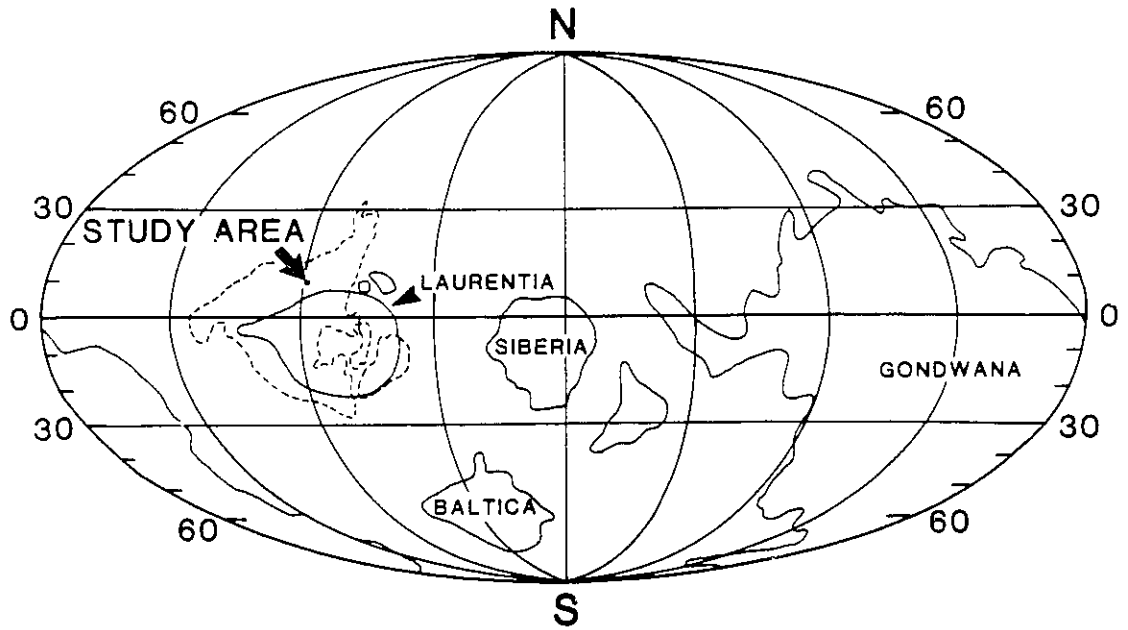


Figure 11. Latitudinal distribution of the continents during the Middle Cambrian (modified from Scotese, 1986).

2.3.3 Initiation of the passive margin

Some authors have suggested that rifting of the western North American margin occurred prior to or during deposition of the Middle Proterozoic Purcell Supergroup (e.g. Monger et al., 1972; McMechan, 1981; Thompson et al., 1987). It now seems likely, however, that the Purcell Supergroup accumulated in an intracratonic basin setting (Stewart, 1972, 1976; Winston et al., 1984; Root, 1987), and that rifting did not commence until the Late Proterozoic.

Most workers, particularly those in the northern Canadian Cordillera, cite irrefutable evidence of synsedimentary tectonism and volcanism near the base of the Windermere Supergroup (e.g. Eisbacher, 1985; Root, 1987; Jefferson and Parrish, 1989; Mustard, 1990). These events are generally inferred to have been related to a widespread, diverse igneous event dated at about 780-730 Ma (Jefferson and Parrish, 1989). Similar events are recorded by basal Windermere strata in the western United States (Christie-Blick and Levy, 1989 and references therein). This tectonism is attributed by most authors to the rifting that ultimately led to continental breakup and the formation of the western North American passive margin.

Much disagreement exists over the events that followed. Some authors have suggested that continental separation followed during later Windermere time (e.g. Stewart and Suczek, 1977; Thompson et al., 1987). However, several workers have pointed out that the thermal anomalies significantly earlier than about 590 Ma cannot account for the great thickness of post-rift, Lower Paleozoic strata found along the length of the North American Cordillera (e.g. Bond et al., 1985; Devlin and Bond, 1988; Christie-Blick and Levy, 1989; Ross et al., 1989). This suggests that the rifting may have been protracted and episodic (Eisbacher, 1985; Pell and Simony, 1987; Root, 1987). A potential analogue is the East

Greenland rifted margin, where multiple extensional phases during the Mesozoic did not culminate in actual continental separation until Early Tertiary time (Surlyk *et al.*, 1981). Alternatively, the rifting may have involved at least two discrete events of widely separated age: a Late Proterozoic event that determined the eventual shape of the western North American margin, and a final, short-lived rift event at about the Precambrian-Cambrian boundary that led directly to continental breakup (Bond and Kominz, 1984; Bond *et al.*, 1985; Jefferson and Parrish, 1989). It is unclear whether the breakup occurred well inside a Proterozoic supercontinent (Piper, 1982; Bond *et al.*, 1984), or whether it involved narrow continental slivers (Bond *et al.*, 1985; Thompson *et al.*, 1987).

At the latitude of the study area, the Hamill Group contains the best evidence for the final rift event that led directly to continental breakup (Devlin and Bond, 1988). Extensional tectonism is suggested by: (1) the local occurrence of thick, mafic volcanic rocks; (2) an unconformable base suggestive of widespread uplift; (3) petrological evidence for nearby, uplifted crystalline basement sources; and (4) rapid, vertical facies changes suggestive of syndepositional faulting (Devlin and Bond, 1988). With the exception of the basal unconformity, these effects have not been observed in partly coeval strata of the Gog Group to the east.

The unconformity underlying the Hamill and Gog groups is the product of large-scale tilting and erosion of upper Windermere strata (Aitken, 1969; Arnoit and Hein, 1986; Devlin and Bond, 1988), and is postulated by some to be the "breakup unconformity" (*sensu* Falvey, 1974). The fact that the unconformity marks a change in subsidence patterns and separates strata laid down in different depositional settings is compatible with this interpretation (Bond and Kominz, 1984; Root, 1987). However, as pointed out by Aitken (in

press, c), the unconformity consistently bevels older units cratonward, the opposite of what would be expected on thermally elevated rift shoulders.

The evidence for rift-related tectonism near the Precambrian-Cambrian boundary in the southeastern Canadian Cordillera is minor compared to the extensive synsedimentary faulting, deposition of coarse conglomerates, and widespread igneous activity recorded by basal Windermere strata in the north (Christie-Blick and Levy, 1989; Mustard, 1990). Thus, there is a significant discrepancy between the amount of crustal extension indicated for the younger event, and the considerable, thermally-driven, Early Paleozoic subsidence suggested by the subsidence curves (Christie-Blick and Levy, 1989).

In summary, although the evidence generally supports a passive margin setting for the western North American margin, many important questions remain unresolved and continue to be the focus of research. The simple thermo-mechanical passive margin models currently proposed are only a first approximation, and do not account for all aspects of this potentially complex margin.

2.3.4 Early history of the passive margin

Thermo-mechanical modelling has become an important tool for understanding and predicting post-rift subsidence and sedimentation patterns on modern passive margins. Similar techniques have been applied to the Lower Paleozoic margin by Bond *et al.* (1988, 1989). A brief synopsis of their conclusions is presented below to illustrate tectonic controls on the origin and development of the carbonate platform, and possible eustatic controls on gross sedimentation patterns during the Middle and Late Cambrian. Similar analyses have

been provided by Read (1989) and James *et al.*, (1989) for the Appalachian margin on the opposite side of the North American craton.

According to Bond *et al.* (1989), the primary controls on the growth of the Early Paleozoic passive margin were thermally-controlled subsidence, time-dependent flexure of the cooling lithosphere, and both long-term and short-term eustatic changes of sea level. Due to the interplay of these factors, initial (Early Cambrian) subsidence and sedimentation patterns differed substantially from those during subsequent, more mature stages of passive margin development.

The early post-rift stage was dominated by areally extensive siliciclastic sedimentation (Gog and Hamill groups in the southeastern Canadian Cordillera). These sediments are inferred to have been derived from rift flank uplifts (Root, 1987; Devlin and Bond, 1988; Bond *et al.* 1989). Subsequent cooling, accompanied by a progressive increase in the flexural rigidity of the lithosphere, had two effects: (1) the volume of siliciclastic sediment declined as the flanking uplifts subsided; and (2) flexural bending of the craton edge shifted landward, thereby extending subsidence well into the adjoining craton to create an "inner flexural wedge" (see also Watts, 1982). The latter process initiated progressive onlap of the siliciclastic shoreline onto the craton, and was followed by cratonward expansion of the Middle Cambrian carbonate platforms.

Systematic misfits between the calculated tectonic subsidence curves and best-fit exponential cooling curves are considered to reflect two orders of eustatic sea level change superimposed on the thermally controlled subsidence (Bond *et al.*, 1983, 1988, 1989). The long-term eustatic event spans more than 40 m.y., and corresponds temporally with the Sauk transgression and regression on the craton. The short-term eustatic events have wave lengths

of 2-6 m.y., and correspond to large-scale carbonate-shale cycles (Grand Cycles of Aitken, 1966, 1978) in the Middle Cambrian and younger platform sequence. These cycles have been physically correlated by Bond *et al.* (1989) with broadly similar, short-term cycles in the Great Basin and Virginia-Tennessee Appalachians.

Bond *et al.* (1989) subdivided carbonate platform growth into three stages: (1) an initial, Middle Cambrian stage characterized by high, but rapidly declining subsidence rates combined with eustatic sea-level rise; (2) a middle, Late Cambrian to earliest Ordovician stage characterized by lower, slowly declining tectonic subsidence rates accompanied by eustatic sea level fall; and (3) a final, mature, Middle Ordovician to Middle Devonian stage, characterized by near-zero thermally controlled subsidence approximating that of the stable craton.

During the initial Middle Cambrian stage, subsidence associated with flexural bending of the craton acted in concert with long-term relative sea level rise to eliminate basement highs, diminish the supply of siliciclastic sand, and shift the shoreline substantially cratonward to the centre of present-day Saskatchewan (Fig. 12). The reduction in net subsidence rates during the middle and final stages is cited by Bond *et al.* (1988, 1989) as a primary cause for the continued expansion of the carbonate platforms onto the craton, and as a contributing factor to the marked, southwestward progradation of part of the Late Cambrian platform (the Lyell-Ottertall-Jubilee carbonate lithosome) into the adjoining deep-water basin (Fig. 10).

Although the model by Bond *et al.*, (1983, 1988, 1989) provides a gross tectonic framework for the development of the Cambro-Ordovician platforms at the latitude of the study area, it oversimplifies the development of the western North American margin. North

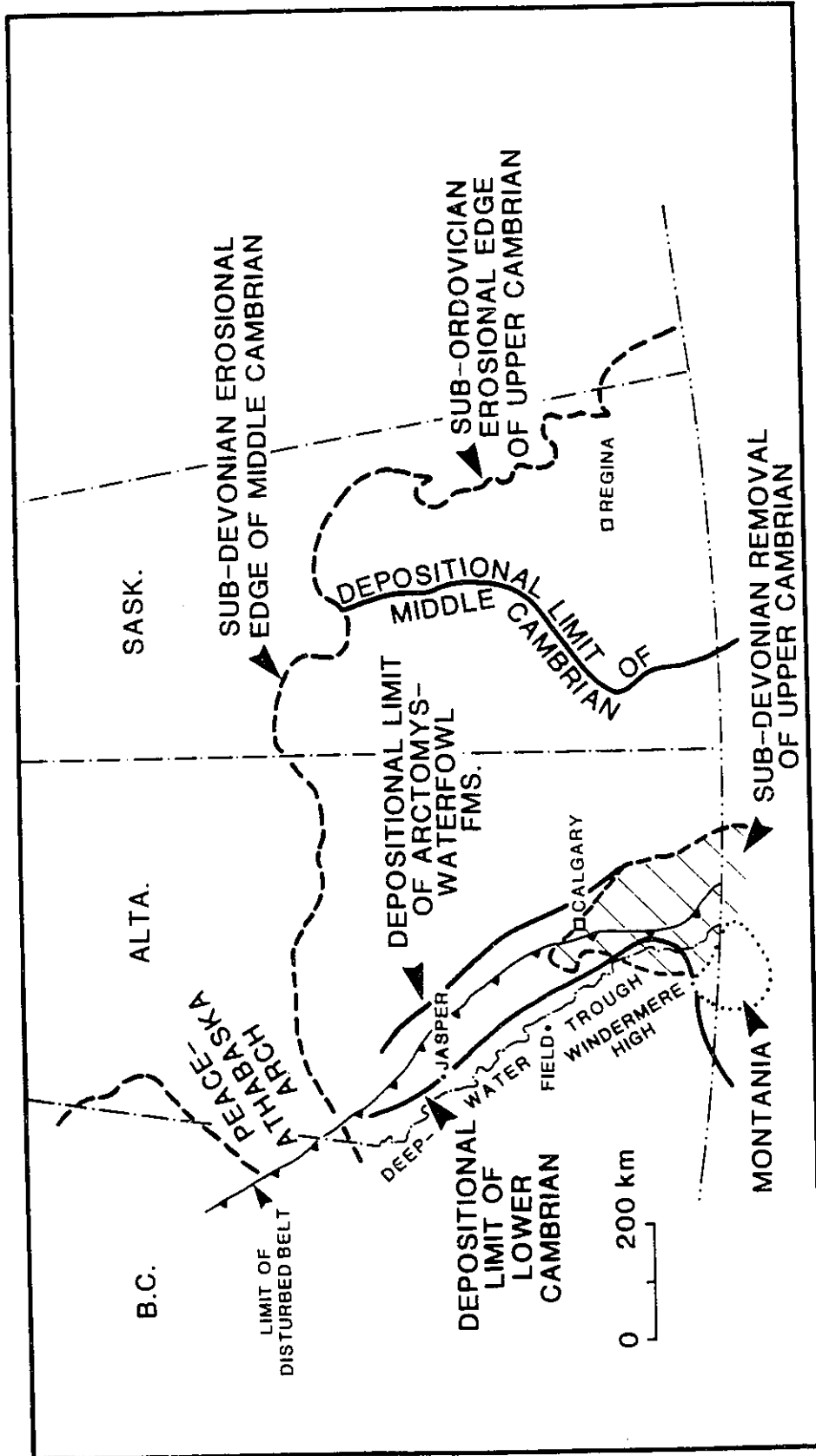


Figure 12. Depositional and erosional limits of Cambrian strata in southwestern Canada (based on van Hees, 1964; Aitken, 1968; Pugh, 1971; Waters, 1986; Aitken, in press, b).

of the study area, for example, the margin continued to experience considerable synsedimentary extensional tectonism that does not fit simple passive margin models. In northeastern British Columbia, widespread horst and graben tectonics reached a peak during the Middle Cambrian (Aitken, in press, b). Farther north in Selwyn Basin, extensional faulting created the Misty Creek Embayment during the Early to Middle Cambrian, and is linked to alkalic volcanism commencing in the Middle Ordovician (Cecile, 1982). These complexities will have to be accounted for in future margin models.

2.3.5 Depositional setting of the Chancellor formation

2.3.5.1 Structural setting

The Chancellor Formation was deposited in an elongate trough or depression that was the site of persistent, deep-water sedimentation during most of Middle and Late Cambrian time and much of the Ordovician (Fig. 12). This feature was at least partly bounded on all sides by positive regional structural elements.

To the northeast, the deep-water trough was bounded by the **Kicking Horse Rim**, a persistent, NNW-SSE trending paleotopographic high that affected sedimentation patterns during most of the Middle and Upper Cambrian, and probably part of the Ordovician (Aitken, 1971). The Kicking Horse Rim controlled the position of the facies change between predominantly shallow-water, carbonate-producing environments in the northeast, from deep-water slope environments in the southwest. During the Middle Cambrian, it was the site of persistent, peritidal carbonate shoals (Aitken, 1978). Stratigraphic evidence suggests that the Kicking Horse Rim formed during the latest Early Cambrian (Aitken, 1971), and was rejuvenated periodically by subsequent, Early Paleozoic tectonism. Palinspastically restored

isopach maps of Middle Cambrian formations indicate that it was significantly offset in places, most probably by syndepositional faulting (Aitken, in press, a).

To the southeast, the trough was bounded by **Montania**, a NE-SW trending paleohigh straddling the International Boundary south and east of Cranbrook (Figs. 8, 12; Deiss, 1941; Norris and Price, 1966). Windermere strata are missing from this feature, and the Purcell Supergroup is directly overlain by an anomalously thin Middle Cambrian section with greater affinity to the platform succession beneath the Plains than to the miogeoclinal succession in the north (Norris and Price, 1966).

Montania was a positive element during the Late Proterozoic and Early Cambrian, and only became shallowly submerged during the Middle Cambrian. Coarse, Lower Cambrian conglomerates along its flanks testify to significant erosion at least as late as Early Cambrian time (Norris and Price, 1966). Immediately northwest of this feature, the antecedent of the St. Mary Fault (Fig. 8) is inferred to have been a northwest-side-down structure with up to 13 km of stratigraphic separation across it during Windermere time (Lis and Price, 1976). Montania was thus probably part of a prominent, structurally-controlled bulge in the continental margin.

A second, structurally controlled bulge in the continental margin forms the northwestern boundary of the trough. North of Jasper, the Middle Cambrian succession thins, and its character assumes a more proximal aspect. Cumulative evidence indicates a westward deflection in depositional strike (Aitken, in press, b), paralleling a similar deflection in the subsurface to the east (Pugh, 1975). This deflection is an early, southwestward expression of the **Peace-Athabasca Arch** (Fig. 12; Aitken, in press, b). The

southern margin of this feature follows transverse, basement-controlled structures that formed during Late Proterozoic rifting (McMechan, 1990).

The southwestern boundary of the trough is poorly defined. At the latitude of the study area, the trough was bounded by a paleotopographic feature known as the **Windermere High** (Figs. 8, 10, 12; Reesor, 1973).¹ Although the Windermere High was most probably a regional feature, its study is hampered by structural complications and a paucity of Lower Paleozoic exposures. A series of palinspastically restored isopach maps prepared by Root (1987) indicate that the high had a NW-SE trend, sub-parallel to the Lower Paleozoic facies change. In the region of the study area, Lower Paleozoic strata thin southwestward towards the crest of this feature (Fig. 10). Southwest of the Windermere High, the Early Paleozoic Hamill and Lardeau groups accumulated in a structurally controlled basin bounded by southwest-side-down, synsedimentary normal faults (Purcell-Mount Forster-Redding Creek faults; Figs. 8, 10; Root, 1987). These faults were subsequently reactivated during Mesozoic tectonism, obscuring their original nature and form.

The lateral extent of the Windermere High is unknown. According to Root (1987), it may have extended tens or hundreds of kilometres to the NNW. This is not evident in outcrop, as strata formerly situated in distal areas southwest of the high have since been structurally juxtaposed with strata deposited northeast of that feature. To the southeast, the Windermere High may well have merged with Montania. This cannot be proven due to the paucity of Early Paleozoic exposures over the southern part of the Purcell Anticlinorium. If the Windermere High was a regional feature as Root (1987) suggests, the deep-water trough

¹ This feature has also been termed the Purcell Platform and Purcell Arch by other authors.

in which the Chancellor Formation accumulated may well have been bounded on the southwest by a positive or shallowly submergent feature over much of its length.

As defined above, the deep-water trough was about 600 km long and about 40 km wide at the latitude of the study area. Palinspastic restoration of this feature is not feasible due to the widespread development of penetrative cleavage and the intense deformation of primary features (Price, 1981). If it is assumed that the degree of structural shortening in the deep-water trough was similar to that in the carbonate-dominated platformal and miogeoclinal assemblages to the east, the trough may originally have been about 2-3 times wider.

2.3.5.2 The stratigraphic succession in the deep-water trough

The deep-water trough was clearly a significant repository for deep-water sediments from Middle Cambrian through Ordovician time. About 6000 m of predominantly deep-water, argillaceous sediments are estimated to have been deposited in it, almost double the thickness of correlative platform strata in the Eastern Main Ranges (Balkwill, 1972). It is sobering to note that this study examines only a small part of the overall succession, high on the northeastern flank of this feature.

Although stratigraphic relationships must be inferred from scattered, incompletely exposed stratigraphic sections (Fig. 8), it is clear that the Cambrian and Ordovician formations thin southwesterly onto the northeastern flank of the Windermere High (Fig. 10). Root (1987) concluded that much of this thinning was due to depositional attenuation, although certain stratigraphic units are known to have been erosionally truncated as well (e.g. McKay Group, Glenogle Formation; Fig. 10). Available stratigraphic evidence suggests that

the Windermere High formed during the Early Cambrian, and was probably emergent during deposition of the Hamill Group, Chancellor Formation, McKay Group, Glenogle Formation and Mt. Wilson Quartzite. It was probably shallowly submerged during deposition of the Jubilee and Beaverfoot formations.² Significantly, these two periods of shallow submergence coincided with the only times when platformal strata expanded westward over the former deep-water trough without changing facies at the Kicking Horse Rim (Root, 1987).

2.3.5.3 Origin of the deep-water trough

The deep-water trough is asymmetric in form. It experienced large-scale syndepositional tilting, as indicated by the southwesterly depositional and erosional thinning of Lower Paleozoic units against the Windermere High (Price, 1981; Root, 1987). Price (1981) attributed the origin of this feature to deep-seated, southwest-side-down listric faulting. In his model, the Windermere High was designated as the high-standing side of a large-scale, rotated fault block. However, Root (1987) pointed out that the laterally monotonous lithological character and lack of abrupt, southwesterly thickness changes in Lower Paleozoic strata of the Main Ranges is incompatible with the notion of crustal-scale faulting near the trend of the Kicking Horse Rim. Moreover, he noted, the intermittent reactivation of the Windermere High and Kicking Horse Rim is not explained by this concept.

Root (1987, p. 353-354) further rejected the possibilities that the Windermere High represents an outer continental high (sensu Schuepbach and Vail, 1980) or an isolated fragment of non-attenuated continental crust (cf. Sheridan, 1981). He proposed instead that

² The Jubilee Formation is the lateral equivalent of the Ottertail Formation, which caps the Chancellor succession in the study area.

intermittent, extensional tectonism was responsible for the formation of both the Windermere High and Kicking Horse Rim..

In Root's (1987) interpretation, the Windermere High is considered to be a rift flank uplift, bounded on the southwest by large-displacement, southwest-side-down normal faults. Movement along these faults permitted significant subsidence in the structural basin to the southwest, where the Hamill Group and younger siliciclastic sediments were accumulating. Northeast of the Windermere High, subsidence is thought to have been controlled by small-displacement, deep-seated normal faults. Lateral heat flow associated with periodic, extensional tectonism near the continental margin contributed to uplift of the high, and simultaneously enhanced cooling and subsidence in the southwestern basin. At the same time, movements along the smaller scale faults underlying the deep-water trough promoted subsidence southwest of the Kicking Horse Rim, thus maintaining relatively deep-water conditions.

Root's (1987) model is attractive in that it provides a mechanism for localizing and maintaining the zone of facies change along the Kicking Horse Rim over an extended period of time. It also provides for periodic suppression of this feature and a slowing of subsidence rates in the adjoining trough during times of tectonic quiescence. This could account, in part, for the abrupt, westward progradation of the Lyell-Ottertail-Jubilee and Beaverfoot carbonate platforms (Fig. 10). A corollary of this model, also noted by Root (1987), is that an emergent Windermere High would have been a significant contributor of fine-grained siliciclastic sediments to the deep-water trough during periods of lithospheric extension.

2.4 STRUCTURAL GEOLOGY OF THE STUDY AREA

The structural geology of the northern part of the study area has been investigated in detail by Cook (1970, 1975). Additional structural information is available from the maps and cross sections authored by Price and Mountjoy (1972), Price *et al.* (1978a, b; 1979, 1980), Leech (1979) and Balkwill *et al.* (1980).

The study area straddles the boundary between the Eastern and Western Main Ranges, and lies entirely within a single, huge thrust plate underlain by the Simpson Pass Thrust (Figs. 8, 13). The structure of the Eastern Main Ranges is dominated by broad, open folds with associated en-echelon normal faults. The faults tend to abut or merge with the narrow, complex belt of thrust faults and folds that mark the zone of facies transition. One of these regional folds, named the Cathedral Crags Anticline by Cook (1975), parallels the zone of facies change in the northwestern half of the study area (Fig. 13). The west limb of this fold constitutes an abrupt, westward downturn of the Simpson Pass Thrust plate.

The core part of the study area occurs in Cook's (1975) southeastern zone of tight folds. Large thrust faults originating in a complex belt of tight folds and thrust faults northwest of the study area coalesce and die out near Field. Major thrust faults are lacking at the surface southeast of Field, where the structure of the Chancellor Formation is dominated by tight, disharmonic folds. The folds are confined to a steeply-dipping zone that transects progressively higher stratigraphic units in a southwesterly direction. According to Cook (1975), they are the surface expression of an underlying backlimb thrust, localized by the favorably oriented, southwest-dipping limb of the Cathedral Crags Anticline. The folds reflect plastic deformation of the incompetent argillaceous rocks of the Chancellor Formation, which were carried eastward by the thrust fault and crushed against a rigid

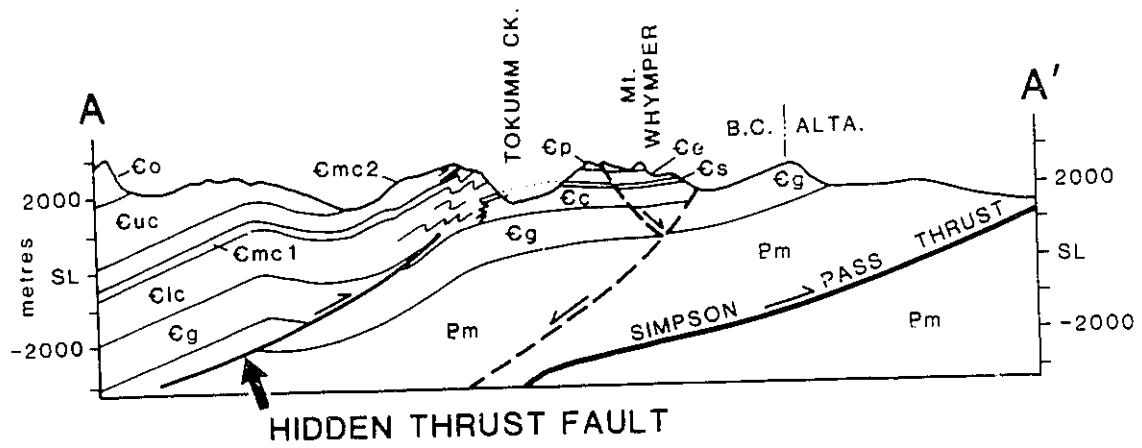
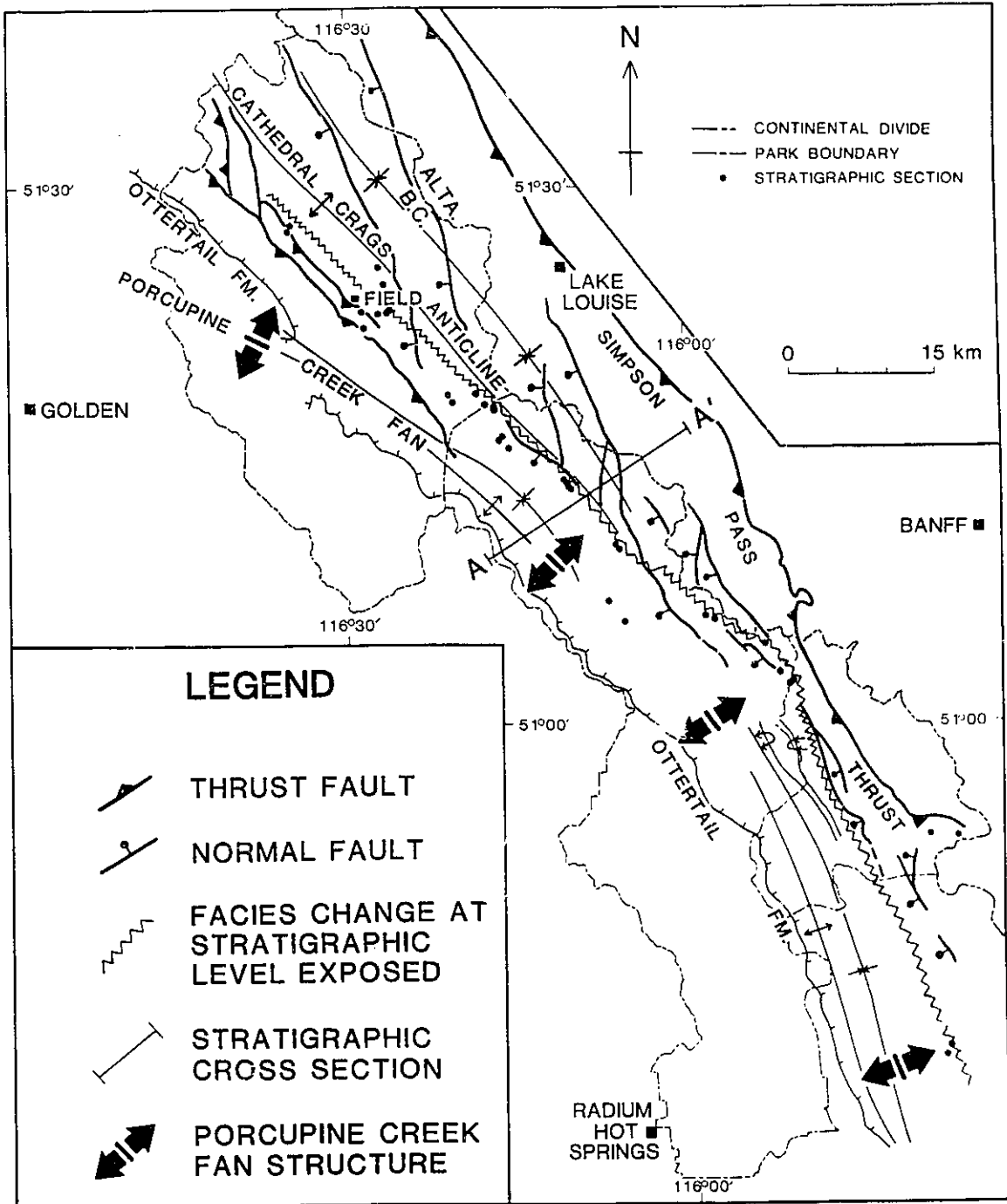


Figure 13. Major structural elements and general trend of the Middle and Upper Cambrian facies change in the study area (based on Cook, 1975 and Frey, 1989). Cross-section A-A' is shown above.



buttress of platform carbonate rocks. The cleavage patterns in these rocks have been analysed in detail by Cook (1975). A similar style of deformation also prevails in the southeastern half of the study area, where the zone of deformation is somewhat broader.

The study area is bounded on the southwest by a southwest-dipping homocline, in which predominantly middle and upper Chancellor strata are exposed (cross-section; Fig. 13). Relatively undeformed lower Chancellor strata also crop out along this feature southwest of Highway 93 near Vermilion Crossing. Broad folds are superimposed on the homocline (Cook, 1975; Leech, 1979), which is also cut by a few, laterally extensive thrust faults. Complex, overturned folds occur locally.

CHAPTER 3

REGIONAL STRATIGRAPHIC PERSPECTIVE AND PREVIOUS WORK

3.1 OVERVIEW OF PREVIOUS STRATIGRAPHIC STUDIES

Previous stratigraphic studies in and near the study area concentrated mainly on the well exposed, shallow-water equivalents of the Chancellor Formation. Thus, the stratigraphy of the Chancellor sequence remained, until this study, largely unknown, except for gross subdivisions established during regional reconnaissance mapping. Direct correlations were inhibited by a lack of continuous exposures across the zone of facies change, and by poor fossil control in the deep-water succession.

A comprehensive historical summary of stratigraphic work in the region has been written by Aitken (in press, a). This chapter presents only an overview of previous studies that contributed significantly to resolving the stratigraphy in and adjacent to the study area.

The earliest worker to recognize the Middle Cambrian facies change near Field was McConnell (1887). More detailed studies were subsequently conducted in the area by C.D. Walcott and J.A. Allan. Walcott is best known for his discovery of the Burgess shale, but he also left a legacy of lithostratigraphic nomenclature (e.g. Walcott, 1928) that has been used and modified by all workers since. Mapping slightly further west, Allan (1911, 1912, 1914) was the first to name and describe the Chancellor and Ottetail formations, although he

mistakenly considered them to be younger than the platform succession exposed immediately to the east.

Deiss (1939, 1940) studied the platform stratigraphy at Castle Mountain (northeast of Lake Louise), in the Kicking Horse Pass area, and near Mount Assiniboine (Fig. 5). In the last area, he named and described the basal Middle Cambrian Naiset Formation, which is assigned herein to the basal Chancellor Formation.

Rasetti (1951) published much of the classical biostratigraphy still in use in the study area, and provided the first evidence for a sub-Middle Cambrian unconformity. He also recognized an apparent, westward facies change in the Eldon Formation near Park Mountain and Mt. Biddle (Fig. 5; Rasetti, 1951, p. 34), but did not relate this in a broader context to the Chancellor Formation, which was still considered to be Late Cambrian in age. This mistaken age assignment was eventually rectified by North and Henderson (1954).

Rasetti (1951, p. 45) also recognized platform-derived boulders in the deep-water equivalent of the Cathedral Formation, and was the first to speculate on the existence of a steep, Middle Cambrian margin nearby. Ney (1954, p. 124) soon followed with the first published description of the Cathedral Escarpment on Mount Stephen and Mount Field. Although this feature has since been intensively studied (Aitken and Fritz, 1968; Fritz, 1971; McIlreath, 1977a; Aitken and McIlreath, 1981, 1984; Aitken, 1989, in press a), its interpretation remains highly controversial (Ludvigsen, 1989, 1990; Fritz, 1990; Aitken and McIlreath, 1990).

Stratigraphic control in and around the study area was brought up to a modern standard by the combined efforts of J.D. Aitken and W.H. Fritz. Their work forms the basis

for all of the platform stratigraphy referred to in this thesis (Aitken 1966, 1968, 1971, 1978, 1981a, 1981b, 1989, in press, a; Fritz 1971, 1981).

Mapping specifically aimed at unravelling the structural and stratigraphic relationships in the zone of facies change was carried out by D.G. Cook (Cook, 1967, 1970, 1975). His regional breakdown of the Chancellor Formation and proposed correlations with the eastern platform sequence were vital prerequisites for the present study. Cook's work has been incorporated (in a somewhat modified form) in the 1:50,000 geological map series covering most of the study area (Price and Mountjoy, 1972; Price *et al.*, 1978a, 1978b, 1979, 1980; Balkwill *et al.*, 1980). The southernmost part of the study area, not covered by this map series, has been mapped at 1:126,720 scale by Leech (1979).

Other studies have expanded regional stratigraphic control northwest and southeast of the study area, as well as in the Plains subsurface to the east. Cambrian strata have been mapped north of Jasper by Mountjoy (1962), and the platformal succession has been described as far north as Pine Pass (about 55° 30' N latitude) by Slind and Perkins (1966). These and other exposures of the Sauk sequence in the northern Rockies and Mackenzie Mountains have been described in summary form by Aitken (in press, b). Southeast of the study area, Norris and Price (1966) have described the Middle Cambrian platform succession mantling Montania. In the subsurface east of the deformed belt, the Cambrian has been studied on a regional basis by Pugh (1971, 1973), utilizing ties that Aitken (1968) established with the surface stratigraphy. This work is currently being expanded and improved with additional well control for an upcoming geological atlas of the Western Canada Sedimentary Basin (Slind *et al.*, 1990).

Metamorphosed and structurally complex Chancellor strata northwest of the study area have been the focus of local mapping projects by graduate students from the University of Calgary. These include studies in the Blackwater Range by Ferri (1984), the Solitude Range by Meilliez (1972) and the Park Range by Craw (1977; see also Klein and Mountjoy, 1988). The first two areas are also included in the regional map compiled by Wheeler (1963).

3.2 REGIONAL STRATIGRAPHIC PERSPECTIVE

The Chancellor Formation and equivalent platform strata form part of the Sauk II sub-sequence (Fig. 14; Aitken, in press b). This stratigraphic package is bounded at the base by a sub-Middle Cambrian unconformity, and at the top by a regional disconformity corresponding to about the base of the Franconian Stage (except in the Canadian Rocky Mountains; see below).

The sub-Middle Cambrian unconformity is readily recognizable at the top of the Gog Group on the basis of missing stratigraphy, local erosional relief, and locally developed paleoregoliths (Rasetti, 1951, p. 54; Palonen, 1976; Aitken, in press, a). Along the crest of the Kicking Horse Rim at The Monarch (Fig. 5), it is clearly expressed as a westward-dipping angular unconformity (Plate 37c).

The regional "sub-Elvinia disconformity" at the top of the Sauk II sub-sequence is recognizable in Montana and parts of the Great Basin (Palmer, 1981 a, b), Texas and Oklahoma (J.L. Wilson in Chow and James, 1987). It has never been identified in the Canadian Rockies, although an abrupt contact overlain by Elvinia-bearing strata is reported to occur in the uppermost Lyell Formation (Aitken, 1981a, p. 23). According to Westrop

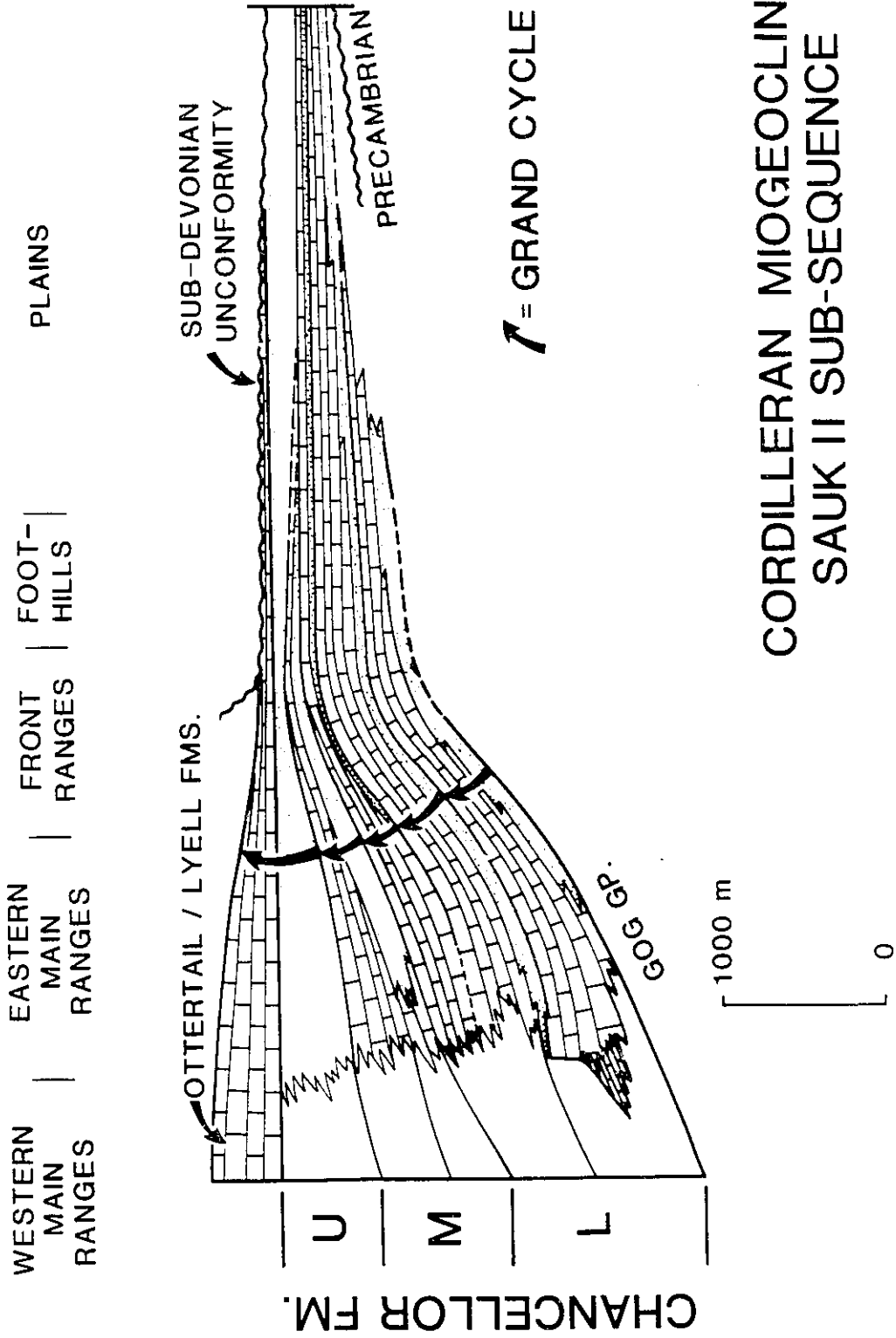


Figure 14. Restored diagrammatic cross-section of the Sauk II sub-sequence in the southern Rocky Mountains and western Plains. In ascending stratigraphic order, the five Grand Cycles indicated by the arrows are composed, respectively, of the Mount Whyte/Cathedral, Stephen/Eldon, Pika, Arctomys/Waterfowl, and Sullivan/Lyell formations (modified from Aitken, 1981a).

(1989, p. 2300), however, this boundary records relative sea level rise, and is not disconformable.

3.3 PLATFORM STRATIGRAPHY

3.3.1 Introduction

The Middle and Upper Cambrian platform stratigraphy in and adjacent to the study area has been described principally by Aitken and Greggs (1967) and Aitken (in press, a). The trilobite biostratigraphy of these formations has recently been summarized by Fritz (1981, in press). A review of this classic stratigraphy is presented below to clarify regional stratigraphic, sedimentological and paleogeographical relationships.

The summary descriptions that follow cover formation lithology, contacts, thickness and age. Other details, including the derivation of stratigraphic nomenclature and the selection of type and reference sections, are given in the above-named publications.

3.3.2 Grand Cycle concept

In 1966, J.D. Aitken popularized the concept of Grand Cycles as a means of synthesizing Cambrian lithostratigraphy in the southeastern Canadian Rocky Mountains (Aitken, 1966). The idea stemmed from the identification of persistent, laterally shifting facies belts analogous to those recognized some years earlier in the Great Basin by Robison (1960) and Palmer (1960). Grand Cycle analysis has since been applied to Cambrian strata throughout much of the Cordilleran Miogeocline (Fritz, 1975; Palmer and Halley, 1979; Palmer, 1981a), and more recently to Middle and Upper Cambrian strata in southwestern

Newfoundland (Chow and James, 1987). The concept is, however, undergoing re-evaluation in the latter area (Cowan and James, 1990).

In the region of the study area, Middle and Late Cambrian sedimentation took place in three mega-environments (Aitken, 1978; Fig. 15): (1) a shallow to moderately deep "inshore" (intrashelf) basin, estimated to be about 1900 km long (parallel to depositional strike), and 700-1100 km wide; (2) a peritidal shoal complex, usually confined to a narrow zone a few tens of kilometres wide over the Kicking Horse Rim (Aitken, 1971); and (3) a deep-water basin. In this general paleogeographical context, five Grand Cycles were deposited during the Middle and Late Cambrian (Fig. 14). Aitken (1966, 1978) defined Grand Cycles as large-scale, asymmetrical depositional cycles spanning 1 to 3 trilobite zones, and with thicknesses on the order of 90-600 m.¹ Each Grand Cycle has a lower shaly half-cycle and an upper carbonate half-cycle.² As the shaly and carbonate half-cycles have been conventionally mapped as separate formations, a typical Grand Cycle is composed of two formations. Grand Cycles have traditionally been named after the lower, shaly half-cycle of each couplet.

This classic configuration is generally inferred to be the result of large-scale, cyclical shifts of the boundary between an "inner detrital belt" and a "middle carbonate belt". During the Middle Cambrian, the middle carbonate belt consisted of a zone of peritidal shoals at the platform margin, and a contiguous belt of predominantly subtidal carbonate sedimentation in the seaward part of the inshore basin. The inner detrital belt was an area of peritidal to moderately deep-water siliciclastic sedimentation bordering the craton.

¹ Thinner examples of Grand Cycles have been reported by Palmer and Halley (1979) from the Great Basin.

² The "essential characteristics" of these features have been summarized by Aitken (1981b).

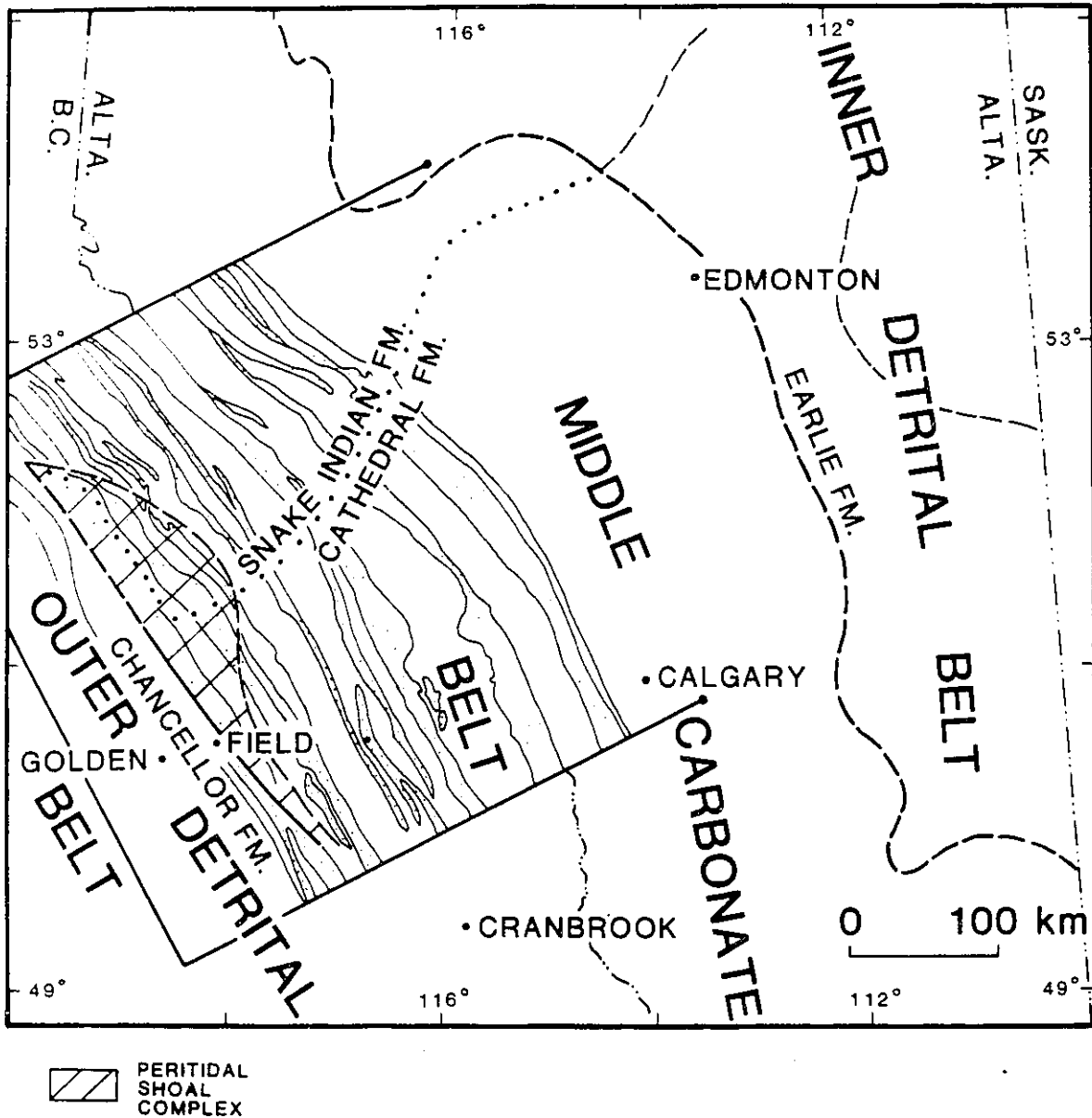


Figure 15. Distribution of major facies belts during late Cathedral time, shown on a palinspastic base (modified from Aitken, 1989). The boundaries of the inner detrital and middle carbonate belts shifted substantially through time, but the position of the outer detrital belt remained essentially fixed on the seaward side of the peritidal shoals developed over the Kicking Horse Rim. The Snake Indian Formation is equivalent to the entire Mount Whyte-Cathedral-Stephen succession, and reflects a northward thickening of siliciclastic units at the expense of the carbonate units (Mountjoy and Aitken, 1978).

The origin of Grand Cycles is still being debated, but many authors favour eustasy as a primary mechanism, in conjunction with tectonics and climate (e.g. Aitken, 1978, in press, a; Mount and Rowland, 1981; Chow and James, 1987; Read, 1989; James *et al.*, 1989). Attempts at inter-regional correlation of Grand Cycle tops (e.g. Palmer, 1981a) have had mixed success, and are complicated by the poor biostratigraphic resolution currently available. The eustatic argument has recently been revitalized by the modelling of the Early Paleozoic Cordilleran and Appalachian passive margins by Bond *et al.* (1988, 1989).

3.3.3 Mount Whyte Grand Cycle

The Mount Whyte Grand Cycle is composed of the Mount Whyte Formation (lower shaly half-cycle) and the Cathedral Formation (upper carbonate half-cycle). The base of the Grand Cycle is the sub-Middle Cambrian unconformity, and its top is the regionally conformable contact between the Cathedral and Stephen formations. The Grand Cycle is entirely Middle Cambrian in age (*Plagiura*-*"Poliella"* through *Glossopleura* zones; Fritz, 1981), and is coeval with the lowermost Chancellor (Naiset Formation and Takakkaw Tongue; Fig. 16).

The **Mount Whyte Formation** is largely composed of intensely burrowed shale, siltstone and very fine-grained sandstone. Small-scale, shoaling-upward cycles capped by various types of carbonate rocks occur in its upper part (Aitken, in press, a). The formation has a maximum thickness of about 190 m. It thins to extinction over the Kicking Horse Rim, where the Cathedral Formation rests directly on Gog Group quartzites (e.g. at Odaray Mountain, Vermilion Pass, and The Monarch; Fig. 5; Plate 37b-d). Elsewhere, the upper contact of the Mount Whyte Formation is gradational, and becomes younger cratonward (Aitken, 1989).

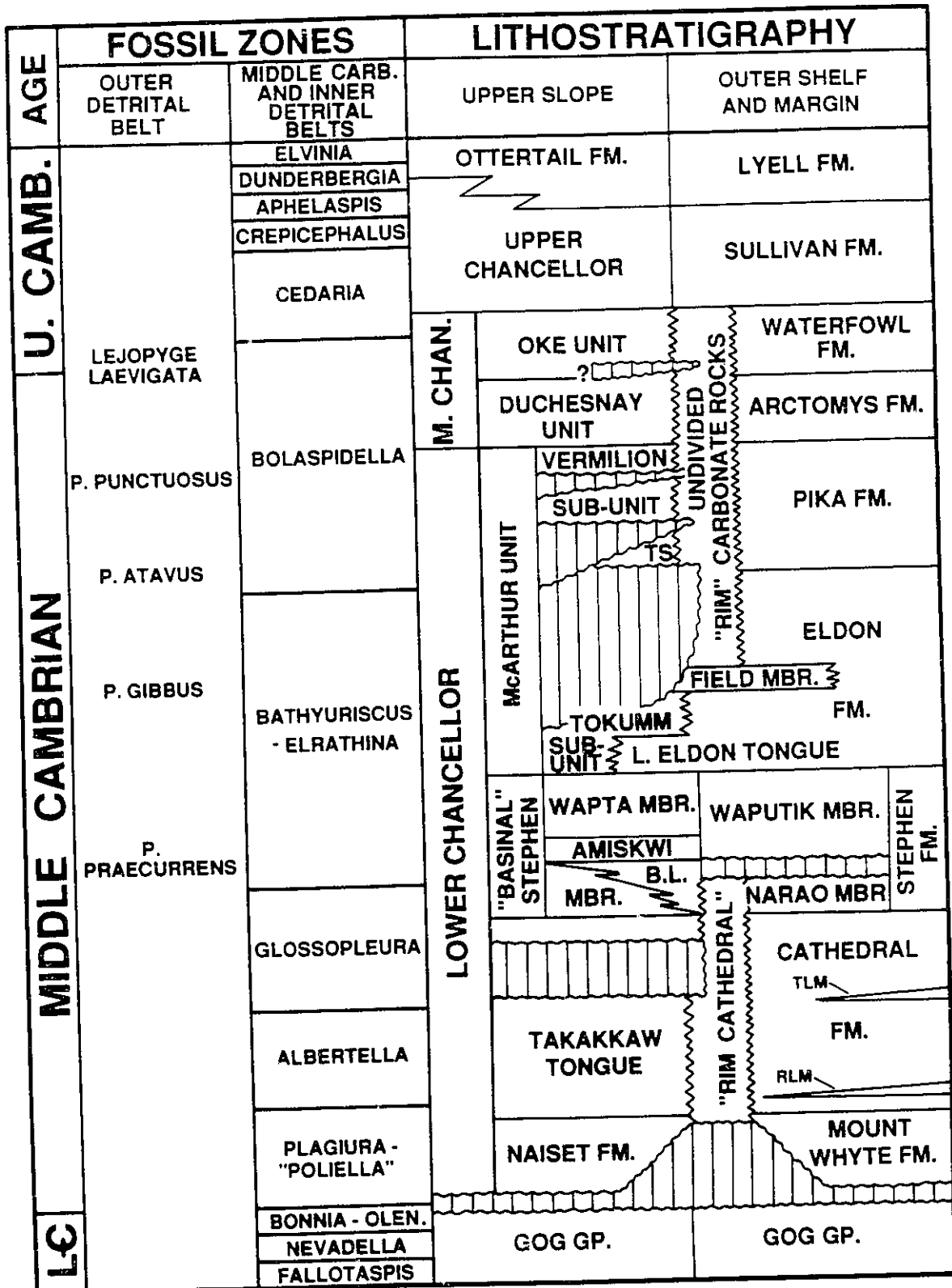


Figure 16. Stratigraphic correlation chart for upper slope and outer shelf/margin successions in and near the study area. TS: Tokumm sub-unit; B.L.: Boundary Limestone; TLM: Trinity Lakes Member; RLM: Ross Lakes Member.

The **Cathedral Formation** is a major carbonate lithosome that extends from a relatively abrupt western limit to a highly attenuated eastern limit in the Alberta subsurface (Aitken, 1989). The lower contact of the lithosome is markedly diachronous over this distance, but its upper contact is thought to be quasi-synchronous over most of the platform region (Aitken, 1981b; in press, a).

Along the Kicking Horse Rim, the Cathedral Formation is composed mainly of bedded, peritidal carbonate strata, which have been fully described by McIlreath (1977a) and Aitken (in press, a).³ Eastward, this zone passes into monotonous burrow-mottled limestones of subtidal origin. The lithosome is interrupted twice by westward-pinching shaly tongues (Ross Lakes and Trinity Lakes members; Fig. 16). Both are composed of shale-based, shallowing-upward cycles (Aitken, in press, a).

Near Field, the Cathedral platform margin is vertically segregated into two components. The lower two thirds of the lithosome are bounded by a narrow, massive, destructively dolomitized zone (Plate 39c). Periplatform talus blocks preserved in the adjoining slope sequence reveal that the platform was formerly rimmed by calcified algal buildups constructed by Epiphyton, Girvanella and Renalcis (McIlreath, 1977a). In contrast, the upper third of the lithosome is bounded by the Cathedral Escarpment (Plates 38a; 39a). This feature has also been identified by McIlreath (1977a) on Mt. Stephen (Plate 38b), Odaray Mountain, and Park Mountain (Plate 38e), and by the author in the Natalko Lake/Monarch area (Plates 38d; 40; 41). The nature and history of the Cathedral margin will be discussed in detail in Chapter 7.

³ Summary descriptions of these rocks will be presented in Sections 4.8.3 and 4.8.4.

The most westerly sections of the Cathedral Formation average about 365 m in thickness (Aitken, 1989). A notable exception is the anomalously thick succession near Field, estimated to be 600 m thick (Aitken, in press, a).

3.3.4 Stephen Grand Cycle

The Stephen Grand Cycle consists of the platformal ("thin") Stephen Formation (lower shaly half-cycle) and the Eldon Formation (upper carbonate half-cycle). The base of the Grand Cycle is probably locally disconformable over the Kicking Horse Rim.⁴ The top of the Grand Cycle is the conformable contact between the Eldon and Pika formations (Fig. 16). The Grand Cycle is entirely Middle Cambrian in age (Glossopleura to lowermost(?) Bolaspidella zones; Fritz, 1981), and correlates with part of the lower Chancellor succession ("basinal" Stephen Formation and Tokumm sub-unit; Fig. 16).

The **Stephen Formation** has been subdivided by Aitken (in press, a) into two members (Fig. 16). The **Narao Member** (46 m at the type section) is composed of two, shale-based, shallowing-upward cycles, each dominated by burrow-stratified limestone with thin, interbedded trilobite coquinas. This member changes facies to cryptalgal laminite and fenestral dolostone over the Kicking Horse Rim, where it has been included in the uppermost Cathedral Formation during regional mapping. The overlying **Waputik Member** (56 m at the type section) is similarly composed of shale-based, shallowing-upward cycles. However, shale with interlaminated and interbedded siltstone is more prominent, and calcarenite interbeds are common throughout.

⁴ The controversial contact relationships of the Stephen Formation will be discussed in Section 5.4.6.

The Waputik Member is an important stratigraphic marker in Misko and Prospectors valleys (Fig. 4), and has been traversed by a number of stratigraphic sections (sections 10, 12, 17, 20, 24; Appendix 2). In all sections, it is composed of lightly burrowed argillite with common lenses and layers of crosslaminated siltstone and calcisiltite (Plate 36a)⁵. Both horizontal and vertical cylindrical burrows (Palaeophycus and Skolithos) are present. The argillaceous units are commonly capped by thin, massive, burrow-mottled limestones, forming repetitive cycles up to 12 m thick. The sequence is further punctuated by decimetre-scale calcarenite beds, containing various proportions of coliths, oncoids, and bioclasts (mostly trilobite skeletal debris). Sections lying some distance (500-1500 m?) inboard of the shelf break contain a thick, basal unit of unburrowed argillite, characterized by fine lamination and rarely, syndimentary overfolds (sections 10, 17; Plate 35d, e).

In the reference section on Mt. Bosworth (Fig. 3), the Stephen Formation is about 103 m thick. The formation thickens northwestward along depositional strike at the expense of the overlying Eldon Formation (Aitken, in press, a). Sections are anomalously thin over the Kicking Horse Rim, largely because of the westward disappearance of the Narao Member by facies change. The formation averages 30 m in thickness in Misko and Prospectors valleys (sections 20, 9, 10, 17; Fig. 2), and thins southeastward to as little as 16 m at Mt. Eon (section AC-102, Fig. 2; Aitken, in press, a).

The **Eldon Formation** is predominantly massive, burrow-mottled limestone and its dolomitized equivalent. Two departures from this monolithic character have produced useful marker units in the vicinity of the study area. In the Eastern Main Ranges, the dark grey to black, thin-bedded limestones of the "**basal black limestone band**" constitute as much as the lower 80 m of the formation, and stand in marked contrast to the overlying, pale coloured

⁵ Descriptions of these rock types and lithofacies are provided in Chapter 4.

dolostones (Plate 37d). Near the middle of the formation, an eastward-pinching tongue of outer detrital sediments known as the **Field Member** (Aitken, in press, a) separates the Eldon into lower and upper parts. At its type section on Mt. Field, this member is about 50 m thick, and is composed of a lower ribbon limestone (40.8 m) and an upper argillite (9.1 m). It has also been identified on Mount Stephen (Plate 38b), in the headwaters of Prospectors Valley (section 17; Appendix 2), at Vermilion Pass (section AC-55; Aitken, in press, a), and near the headwaters of Verdant Creek (Plate 52).

The nature of the Eldon platform margin is poorly understood due to destructive dolomitization, common inaccessibility, and the fact that much of the original margin is missing due to catastrophic collapse during the Middle Cambrian (Chapter 6). Regionally, where remnant textures have been observed, intraclast rudstone, fenestral lime mudstone, cryptalgal laminite, and minor thrombolites and algal stromatolites have been recognized (Aitken, in press, a). Thick, dolomitized oolite beds have also been reported in the lower Eldon on Mt. Field and at other localities to the northwest (Aitken, in press, a). Peritidal strata, comparable to those observed in the Cathedral Formation near Field (Sections 4.8.3, 4.8.4), have been observed by the writer behind the truncated Eldon margin near the headwaters of Verdant Creek (Fig. 4). Similar, but very poorly preserved fabrics have also been reported in equivalent rocks on Mt. Eon (section AC-102; Fig. 2; Aitken, in press, a).

The westernmost exposures of the Eldon Formation range in thickness from 417 - 487 m (Aitken, in press, a). Along the Kicking Horse Rim, the upper Eldon and Pika Formations are lithologically similar, and must be treated as a single, undivided unit. In the Prospectors Valley area, the lower 100 m of the Eldon Formation project basinward as a recognizable tongue, which is gradationally overlain by deep-water carbonate sediments of the lower Chancellor (Tokumm sub-unit; sections 9, 10, Appendix 2; Fig. 16).

3.3.5 Pika Grand Cycle

The Pika Grand Cycle is mapped as a single formation, as the shaly half-cycle is not as thick or areally extensive as in other Grand Cycles. Despite this modest beginning, the Pika Formation has the greatest areal extent of all the Middle Cambrian formations. The Grand Cycle is entirely Middle Cambrian in age (Bolaspidella Zone; Fritz, 1981), and is correlative with the uppermost lower Chancellor (Fig. 16).

The **Pika Formation** is composed predominantly of burrow-stratified lime mudstone.⁶ Shale-carbonate cycles up to 10.7 m thick occur in the lower half of the formation. These sediments reflect the maintenance of deeper subtidal conditions over the platform than had been the case during Cathedral or Eldon time. Cryptalgal laminite, algal stromatolites, and thrombolites are abundant only on, or near, the Kicking Horse Rim (Aitken, in press, a). Much of the original platform margin is missing due to large-scale collapse during the Middle Cambrian. Periplatform debris indicates that the truncated margin was rimmed by Epiphyton buildups and carbonate sand shoals (Chapter 6).

The Pika Formation is about 240 m thick near the study area, and thins markedly towards the northeast. Its upper contact is marked by the abrupt appearance of evaporitic redbeds of the Arctomys Formation (Aitken, in press, a). Over the Kicking Horse Rim, the upper Pika contact becomes indefinite due to westward facies change of the Arctomys Formation into carbonate rocks.

⁶ This lithofacies will be described in Section 4.8.2.

3.3.6 Arctomys Grand Cycle

The Arctomys Grand Cycle consists of the Arctomys Formation (lower "shaly" half cycle) and the Waterfowl Formation (upper carbonate half cycle). It is aberrant, in that the Arctomys Formation records marked shallowing and at least intermittent subaerial exposure, in contrast to the generally subtidal conditions that were previously maintained in the inshore basin. The Arctomys Grand Cycle straddles the Middle-Upper Cambrian boundary (Bolaspidella and Cedaria zones; Fritz, in press), and is correlative with the Middle Chancellor (Duchesnay and Oke units; Fig. 16).

The **Arctomys Formation** is a lithologically heterogeneous unit composed of varicoloured shales and dolomitic siltstones exhibiting mudcracks, halite casts, ripple marks, horizontal laminae, and small-scale crosslaminae (Aitken and Greggs, 1967). Other features include solution collapse breccias (Aitken, 1981a), silty and argillaceous dolostone, and stromatolite layers (Aitken and Greggs, 1967). These rock types are commonly arranged into small-scale cycles capped by cryptalgal laminite (Aitken, 1978). A very shallow marine, evaporitic setting is favoured by Aitken (1978), although Waters (1986, p. 30-31) has proposed that sedimentation may have occurred at least partly in playa lakes.

The Arctomys Formation is 235 m thick at its type section in Banff National Park. Due to westward facies change into the Waterfowl Formation over the Kicking Horse Rim, it is much thinner in and near the study area. For example, the Arctomys is only 70.1 m thick in Vermilion Pass (Aitken and Greggs, 1967; Fig. 5). To the east, the Arctomys and Waterfowl formations are missing in the Plains subsurface (Aitken, 1968). Hence, the depositional limits of these formations lie as much as 600 km southwest of the depositional

and erosional limits of formations above and below, implying marked displacement of the cratonal shoreline (Fig. 12).

According to Aitken (1981a), the **Waterfowl Formation** is composed mainly of flaggy lime mudstone and calcisiltite with dolomitic partings, and massive, burrow-mottled limestone. Other prominent rock types include dolomitic siltstones and silty dolostones exhibiting ripple crosslaminae and desiccation cracks. Subsidiary lithologies include algal laminite, oolitic grainstone, stromatolites and thrombolites.⁷ The platform margin is thought to have been occupied by some form of continuous barrier (now destructively dolomitized), which was bounded on its inner edge by cryptalgal laminite laid down in a restricted, supratidal environment (Waters, 1986, p. 182). In general, Waterfowl deposition alternated between periods of repeated, tidal flat progradation over a shallow, aggraded platform, and subtidal carbonate sedimentation in a platform lagoon some 50-80 km wide and perhaps more than 10 m deep (Waters, 1986).

The Waterfowl Formation is about 120 - 200 m thick in the Main Ranges, and thins markedly eastward towards the mountain front. Its upper contact with the Sullivan Formation is abrupt, but appears to be regionally conformable (Aitken and Greggs, 1967). Locally, however, this contact is erosional (J.D. Aitken, oral communication, 1991).

3.3.7 Sullivan Grand Cycle

The Sullivan Grand Cycle consists of the Sullivan Formation (lower shaly half-cycle) and the Lyell Formation (upper carbonate half-cycle). The Grand Cycle is entirely of Late Cambrian age (Cedaria through Elvinia zones; Fritz, 1981). The Sullivan and Lyell

⁷ Detailed facies descriptions and stratigraphic sections have been provided by Waters (1986).

formations are correlative with the Upper Chancellor and Ottertail formations respectively (Cook, 1975; Fig. 16).

The **Sullivan Formation** is composed mainly of shale, but also contains thin to thick beds of skeletal grainstone, oolite, calcisiltite, lime mudstone, thrombolites and lesser stromatolites (Aitken and Greggs, 1967; Aitken, 1981a). Siltstone and silty beds increase in proportion towards the craton (Aitken, 1978). Small-scale sedimentary cycles have been reported (Aitken, 1966, p. 430), but not documented in detail. The Sullivan Formation is 424 m thick at its type section in Banff National Park, and thins towards the northeast, northwest, and southeast (Aitken, 1981a). It is 156 m thick at Mt. Ogden (Fig. 3), and 165 m thick at Vermilion Pass (Aitken and Greggs, 1967). The upper contact of the formation is gradational by interbedding.

The **Lyell Formation** is characterized by a basal, massive oolite, which is overlain by a series of metre-scale, shoaling-upward carbonate cycles (Aitken, 1978, 1981; Sargent, 1975). The formation is 345 m thick at its type section in Banff National Park, and thins eastward (Aitken, 1981a). No complete sections have been measured near the study area, but thicknesses are probably comparable (Aitken and Greggs, 1967).

The Lyell, unlike all other carbonate half-cycles, records the rapid expansion of a peritidal shoal complex both seaward and cratonward from its nucleation site along the Kicking Horse Rim. The ultimate cross-strike width of this complex apparently exceeded 400 km (Aitken, 1978). The upper contact with the overlying Bison Creek formation is abrupt, and records a change to storm-dominated, subtidal shelf conditions following a rapid relative sea level rise (Westrop, 1989).

3.4 SLOPE STRATIGRAPHY: BACKGROUND

3.4.1 Original definition and historical usage

The name "Chancellor Formation" was introduced by Allan (1912) for a predominantly slate sequence exposed on the east and north slopes of Chancellor Peak (Fig. 5).⁸ He subsequently included two additional rock units in this formation: (1) a thin-bedded limestone unit exposed on Mt. Dennis and at other localities along strike to the southeast; and (2) a stratigraphically lower, argillaceous limestone unit cropping out between Mt. Duchesnay and Prospectors Valley.⁹ No type section has ever been designated for the Chancellor Formation.

Regional mapping and detailed structural analysis by D.G. Cook (Cook, 1967, 1970, 1975) subsequently clarified the gross stratigraphy of the Chancellor Formation between Blaeberry River and Vermilion Pass (Figs. 4, 5). Cook subdivided the Chancellor sequence into lower, middle and upper divisions, and correlated the entire succession with the Mount Whyte through Sullivan formations inclusively (Fig. 16). Gross lithological descriptions of the three divisions, together with descriptions of apparent facies changes along depositional strike, have been summarized by Cook (1975, p. 16-24).

Like Rasetti (1951) before him, Cook recognized, this time in Eldon/Pika-equivalent rocks, "huge blocks or lenses, a few hundred feet long, of massive grey limestone . . . in brown, thin-bedded argillaceous limestone". He suggested that these were large slide

⁸ Recent maps show that this particular exposure contains the upper Chancellor Formation and a separate, transitional unit to the overlying Ottertail Formation (Price *et al.*, 1978a, 1979).

⁹ These units are now recognized respectively as the upper middle Chancellor and part of the lower Chancellor (Cook, 1975; Price *et al.*, 1980).

blocks derived from the Eldon carbonate bank to the east (Cook, 1975, p. 17). During the same period, J.D. Aitken measured the first stratigraphic sections through part of the lower Chancellor near the headwaters of Tokumm Creek (section AC-160, Aitken, in press, a)¹⁰, and part of the upper middle Chancellor on Mt. Duchesnay (section AC-130, Aitken, unpubl. data). He also measured the only known complete section through the upper Chancellor (950 m), immediately north of Mt. Laussedat (section 150/154, Aitken, unpubl. data; Figs. 2, 5, 31). Other stratigraphic sections have been measured in units now assigned to the Chancellor sequence by Deiss (1941), Fritz (1971) and McIlreath (1977a).

3.4.2 Correlation of shelf and slope stratigraphy

Cook (1975) correlated the various Chancellor divisions with the eastern shelf succession on the basis of gross lithology, sparse fossil information (summarized in Cook, 1975, p. 68-73), and essentially continuous exposures across the zone of facies change at a few key localities. These correlations were subsequently contested by McIlreath (1977a), based mainly on stratigraphic and structural observations at one of Cook's (1967, 1970) cross-strike exposures in Stephen cirque (Fig. 3).

McIlreath (1977a) correlated the Field Member of the Eldon Formation with what he considered to be lower middle Chancellor slates overlying lower Eldon carbonate rocks immediately to the west. This crucial correlation had important implications. Acknowledging that Cook's (1967, 1970) correlation between the Sullivan Formation and the upper Chancellor division was firmly established on paleontological grounds, McIlreath concluded that the upper Eldon, Pika, Arctomys and Waterfowl formations must be equivalent to the upper middle Chancellor division (Oke unit of this thesis). He then

¹⁰ This section also corresponds with section MJA-735 of McIlreath (1977a), and section 17 of this thesis.

restricted the term "lower Chancellor division" to the deep-water equivalents of the lower Eldon Formation.

McIlreath's (1977a) correlations effectively excluded the slope equivalents of the Mount Whyte, Cathedral and Stephen formations from the Chancellor sequence. This was consistent with his observation, subsequently confirmed during this study, that the visible transition to the "classical" Chancellor Formation, from Dennis Pass southeastward to Vermilion Pass, takes place in Eldon and younger strata. This situation is, however, an artifact of exposure, and has no regional significance. McIlreath's (1977a) pivotal correlations in Stephen cirque have been shown by this study to be incorrect (Section 6.2.2). The correlations proposed here (Fig. 16) correspond closely to those originally suggested by Cook (1975), and were deduced through a combination of: (1) lithological and sedimentological relationships; (2) sparse paleontological control, marginally improved from earlier work by new fossil collections (Appendix 1); and (3) lateral facies relationships observed at a few, critical, cross-strike localities (Chapter 6).

3.4.3 Proposed definition for the Chancellor sequence

Clearly, all strata of "deep-water" or "basinal" aspect should be mapped separately from the classic platform sequence in view of their differing physical aspects and contrasting depositional styles. In addition, the Chancellor should be defined with reference to regional, rather than local, geological relationships, in a manner consistent with existing geological maps of the area (Allan, 1914; Cook, 1975; Leech, 1979; Price *et al.*, 1972, 1978a, 1978b, 1979, 1980; Balkwill *et al.*, 1980).

The Chancellor is a stratigraphic unit of Middle to Late Cambrian age (Plagiura - "Poliella" through lower Dunderbergia trilobite zones), that:

1. is composed of fine-grained siliciclastic rocks and various types of carbonate rocks that show evidence of having been deposited near or below maximum storm wave base in a slope and basin environment;
2. unconformably overlies the Gog Group;
3. is conformably and gradationally overlain by the Ottertail Formation; and
4. partly demonstrably and partly by inference passes eastward into eight formations of shallow-water origin that were laid down on a major, pericratonic shelf.

Under this proposed definition, the Chancellor contains at least seven, mappable stratigraphic units (Fig. 16). Some of these have already been designated as formations, and the remainder are deserving of that rank. In ascending stratigraphic order, these units are:

1. **Naiset Formation** (Deiss, 1940; Aitken in press, a);
2. **Takakkaw Tongue** (Aitken, in press, a; Fritz, 1971; McIlreath, 1977a);
3. **"Basinal" Stephen Formation** (Rasetti, 1951; Fritz, 1971; McIlreath, 1977a; Aitken, in press, a);
4. **McArthur unit** (new name);
 - (a) **Tokumm sub-unit** (new name);
 - (b) **Vermilion sub-unit** (new name);
5. **Duchesnay unit** (new name);

6. **Oke unit** (new name);
7. **Upper Chancellor**, undivided (Cook, 1975).

The incorporation of units of present or potential formational rank necessitates that the Chancellor Formation be formally elevated to Group status. This must, however, await publication of the results of this study. To avoid nomenclatural conflicts, the deep-water sequence will be informally referred to as "the Chancellor" or "Chancellor succession" in the chapters that follow.

CHAPTER 4

DESCRIPTION AND INTERPRETATION OF LITHOFACIES

4.1 INTRODUCTION

The Chancellor succession is composed of five basic lithofacies: (1) argillite; (2) ribbon calcilutite; (3) ribbon calcisiltite; (4) calcarenite; and (5) conglomerate (including megaconglomerate). Due to a combination of diagenetic and depositional factors, each lithofacies has several variants.

The Chancellor closely resembles ancient carbonate slope successions in the southwestern United States (Cook and Taylor, 1977; Yurewicz, 1977), the Canadian Rockies (Cook *et al.*, 1972; Mountjoy *et al.*, 1972; Hopkins, 1977; Cook, 1979); the Mackenzie Mountains (Krause and Oldershaw, 1979), the Canadian Arctic (Davies, 1977), the southern Appalachians (Pfeil and Read, 1980; Demicco, 1985; Barnaby and Read, 1990), and the northern Appalachians (Hubert *et al.*, 1977; James and Stevens, 1986; Coniglio, 1986; Coniglio and James, 1985, 1990; Hiscott and James, 1985). The Chancellor sediments are also similar in many respects to deep-water sediments on modern carbonate slopes (e.g. Schlager and Chermak, 1979; Crevello and Schlager, 1980; Mullins, 1983; Mullins *et al.*, 1984).

The sedimentary environments recorded by these sediments have become reasonably well understood over the past 20 years, although models of carbonate slope

sedimentation are still at an early stage of development (Cook and Mullins, 1983; Cook, 1983; McIlreath and James, 1984; Mullins and Cook, 1986). Together, the case histories and preliminary facies models cited above provide a valuable framework for interpreting the range of sedimentary processes responsible for deposition of the Chancellor succession.

4.2 METHODS OF STUDY

The facies descriptions that follow are based on careful field observations, the examination of standard thin sections, and, where indicated, the study of etched slabs. The thin sections were stained with Alizarin Red-S and potassium ferricyanide to differentiate between ferroan and non-ferroan dolomite and calcite.

In keeping with the focus of this study on regional stratigraphy and physical sedimentology, the diagenesis of these sediments has not been investigated. For an excellent study covering the diagenesis of a very similar suite of facies, the reader is referred to the thorough and detailed Ph.D. thesis by M. Coniglio on fine-grained sediments in the Cow Head Group of western Newfoundland (Coniglio, 1985).¹ Various aspects of Coniglio's thesis have recently been published, and serve as an invaluable guide to the observation and interpretation of ancient, deep-water carbonate settings (Coniglio, 1986, 1987, 1989; Coniglio and James, 1985, 1988, 1990).

¹ Coniglio's study utilized stained thin section petrography, cathodoluminescence observations, microprobe analyses, and stable isotope analyses.

4.3 ARGILLITE LITHOFACIES

4.3.1 Definition, variability and stratigraphic distribution

An **argillite** is defined by Bates and Jackson (1987, p. 36) as a "compact rock, derived either from mudstone (claystone or siltstone) or shale, that has undergone a somewhat higher degree of induration than mudstone or shale". It is "less clearly laminated than shale and without its fissility, and . . . lacks the cleavage distinctive of slate." The **argillite lithofacies** encompasses a spectrum of rock types, with protoliths ranging from essentially pure claystone to siltstone. Thus, the argillites range from rocks composed almost exclusively of clay minerals, to rocks composed mainly of quartz and/or dolomite silt. The term "argillite" is also broadened in this thesis to encompass finely laminated argillaceous rocks, even though this contradicts the letter of the foregoing definition.²

Depositional, diagenetic and structural factors have further contributed to the heterogeneity of this lithofacies. While many of the rock types assigned to the argillite lithofacies meet the requirements of the above definition, a variety of other argillaceous rocks are also included to simplify the nomenclature. These include **shale, slate, nodular argillite, ribbon argillite**, and the dolomitic or dolomitized versions of all of the above rock types.

Most of the true **shale** seen in the Chancellor is stratigraphically confined to the "basinal" Stephen Formation in the Field area (Plate 3a). Fissile shale is also known from other parts of the stratigraphy, but is volumetrically insignificant in comparison with argillite, cleaved argillite, and slate.

² Aitken (in press, a) applied the term "shale" to argillaceous strata exhibiting lamination and/or fissility, and reserved the term "mudstone" for non-fissile, non-laminated rocks. The former term is not used here, as true shale is actually quite rare in the Chancellor. The latter term is avoided in the case of terrigenous rocks to prevent confusion with lime mudstones.

Slate is the most abundant rock type in the Chancellor as a whole. It is also the most visible for the casual observer travelling the main access routes through the study area. Upper Chancellor slate is extensively exposed in the Porcupine Creek Anticlinorium southwest of Field (Balkwill, 1972). It is also prominent in contiguous exposures of the middle Chancellor. Both successions are traversed by the Trans-Canada Highway (Fig. 8). Distal lower Chancellor slate crops out along Highway 93 near Vermilion Crossing (Fig. 4), and middle and upper Chancellor slate is also exposed high on the mountainsides overlooking that highway. Thus, there is little wonder why the overwhelming impression of the Chancellor has been, until recently, one of monotonous, indecipherable slate.

In the zone of facies change, argillite predominates over slate. Notably, however, there is a continuous intergradation between these two rock types. Throughout the lower and middle Chancellor, at least an incipient slaty cleavage is commonly developed. Thus, from a structural standpoint, the argillite lithofacies is characterized by a spectrum of rock types, ranging from shale, through massive argillite, to pervasively cleaved slate.

Depositional and diagenetic factors are responsible for the remaining rock type variations in this lithofacies. **Nodular argillite** is argillite containing carbonate nodules.³ **Ribbon argillite** contains subordinate, planar or wavy carbonate interbeds (Fig. 17), and is compositionally gradational to ribbon limestone.

A final, distinctive suite of rocks assigned to the argillite lithofacies is herein termed the **bioturbated argillite sub-facies**. These rocks are typically highly argillaceous, and contain interlaminated and interbedded siltstone, sandstone or calcarenite (Plates 1d; 2a, b, d;

³ The term "nodular" is strictly descriptive, and has no genetic connotation.

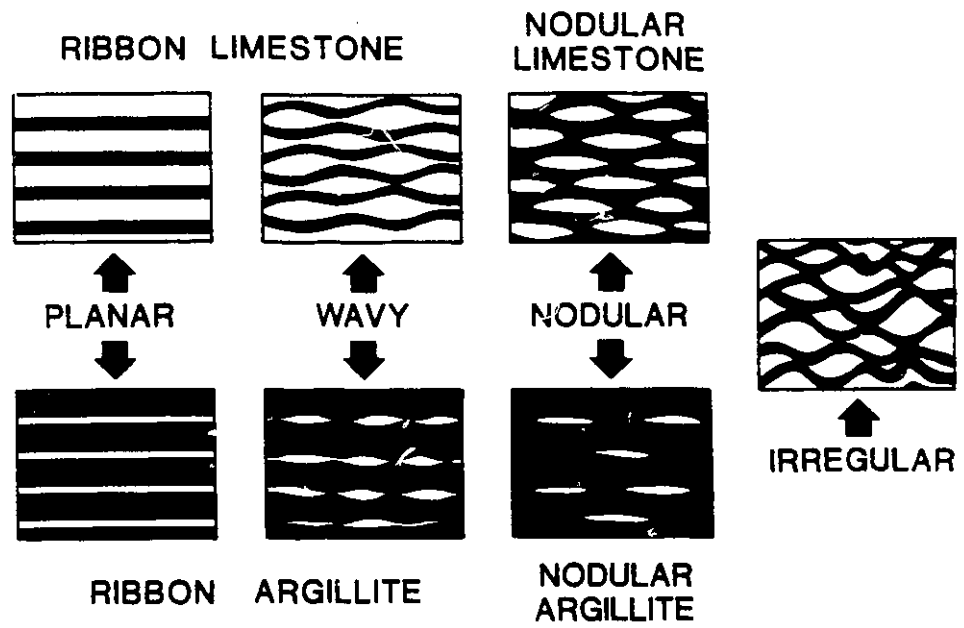


Figure 17. Descriptive terminology for ribbon limestones and argillites in the Chancellor sequence.

9c). They contain Palaeophycus-like and Skolithos-like horizontal and vertical burrows, and cap large-scale shallowing-upward sequences. These rock-types are akin to the shales and siltstones described by Aitken (1966, 1978, in press, a) in facies of relatively shallow-water origin on the adjoining shelf.

All of the above rock types are commonly dolomitic to some degree. The dolomitization can be expressed by lightly disseminated dolomite rhombs throughout the rock, or it can be much more pervasive. Argillaceous siltstone is the most commonly and pervasively dolomitized rock type.

The argillite lithofacies occurs throughout the Chancellor. It is the predominant lithofacies in the Naiset Formation, "basinal" Stephen Formation, Duchesnay unit, and upper Chancellor (Fig. 16). It is also volumetrically significant in the Vermilion sub-unit, and forms two important markers in the Tokumm sub-unit.

4.3.2 General description

4.3.2.1 Colour

At the more argillaceous end of the spectrum, rocks of the argillite lithofacies are commonly grey, brownish grey, greenish grey, or dark green on fresh surfaces. Weathering colours range from greenish and greyish brown to dark brown, with dolomitic varieties varying from tan to rust. Chloritic varieties commonly exhibit greenish or blue-green spots (Plate 1b), and pervasively chloritized sediments are usually a uniform, deep green colour.

4.3.2.2 Sediment composition

The clay mineralogy of the argillite lithofacies has not been investigated. Where determinations have been made on equivalent, fine-grained siliciclastic rocks (Mt. Whyte Formation, Hockley, 1973; Stephen Formation, McIlreath, 1977a), illite and chlorite are the predominant minerals. Petrographic relationships indicate that most, if not all of the chlorite probably originated during incipient metamorphism. Notably, illite and chlorite also predominate in the fine-grained siliciclastic sediments of the Cow Head Group (Coniglio and James, 1990).

Other components in the argillite lithofacies include silt-sized quartz, feldspar, ferroan and non-ferroan dolomite (the former being most abundant), and pyrite. Laminae and interbeds of very fine to fine sand are also found in the Naiset Formation (Plates 1c, d; 2a).

4.3.2.3 Sedimentary structures and bedding

The highly **argillaceous argillite** commonly contains alternating, millimetre-scale, dark and light laminae (Plates 3c; 5a, e). There are no systematic variations in colour on a larger scale. Compacted horizontal burrows, bioclasts, and other carbonate grains occur rarely.

The dark laminae are sharply defined to rather diffuse, and are generally black or dark grey. The light laminae range through shades of green and brown, and are tan-coloured in dolomitic varieties. Where dark laminae are absent or poorly defined, primary lamination is often indicated by slight colour contrasts. This texture is commonly accentuated in

dolomitic varieties. The laminae are attributed to subtle variations in grain size and/or composition.

In some cases, the dark laminae contain minor disseminated silt or silt lenses (siliciclastic silt and silt-sized dolomite), together with stringy, opaque to brown or yellow-brown translucent material (Plate 9e). The translucent material is probably undifferentiated organic matter. The light laminae are composed of homogeneous clay minerals, and contain little or no siliciclastic silt, dolomite, and organic matter (Plate 10a). Faint, internal stratification is rarely visible. The dark laminae commonly grade upward into the light laminae. Very similar "millimetre cycles" have been described by Coniglio and James (1990) in the shale lithofacies of the Cow Head Group.

The lamination style just described, though fairly common, is not typical of the more argillaceous argillite as a whole. No consistent pattern could be discerned. Some lower, graded laminae contain little or no organic matter. Instead, the organic matter is either finely disseminated, or occurs as continuous to discontinuous layers in the overlying clay lamina. In these examples, colouration is reversed: the lower, silty layer has a light colour, and the overlying clay or silty clay layer is dark. In other examples, organic-rich, ungraded laminae alternate with homogeneous clay laminae on a millimetre-scale, and no size grading is visible.⁴ In still other examples, siliciclastic silt is lacking from the lower, graded lamina, and grading is expressed by upward dilution of ferroan dolomite crystals.

The more argillaceous argillite tends to be unbedded, although some laminated varieties may break into platy beds less than 2-3 cm thick. There are considerable

⁴ In an interesting and unique example, argillites of the distal "basinal" Stephen Formation west of Mt. Field are completely pervaded by organic matter, imparting a sooty appearance to the rock. Laminae, apparently defined by relative concentrations of organic matter, are very subtly expressed.

thicknesses of apparently massive, structureless argillite, for example, in parts of the "basinal" Stephen Formation in the Nataalko Lake/Monarch area (Plate 3d), and in the Duchesnay unit of the Mt. Dennis area (Plate 7a).

The reasons for this apparently massive character are not always obvious. On some weathered surfaces, laminae appear to be absent or only vaguely defined. Nearby, wet, stream-washed surfaces show that the rock is, in fact, finely laminated. Some lamination is obscured by cleavage, but usually the cause is primary. Some apparently structureless rocks may exhibit a very vague, wispy texture. Remnants of contorted laminae are visible in some instances. These textures suggest that the original lamination was lost due to complete or nearly complete homogenization of an unlithified or only slightly cohesive sediment. This conclusion is supported by the preservation of convolute laminae and/or bedding in laterally equivalent rocks.

With increasing siltiness, lamination becomes accentuated, other sedimentary structures appear, and dolomitization generally becomes more pervasive. Two intergradational rock types have been recognized: finely laminated **silty argillite**, which is common in the Vermilion sub-unit, and **laminated/crosslaminated argillaceous siltstone**, which is largely confined to the Duchesnay unit.

Laminated silty argillite is generally even parallel-laminated throughout (Plate 6b). It commonly stands out as orange-weathering units intercalated with ribbon argillite and ribbon/parted limestone (Plate 6a). Most units are composed of alternating dark and light laminae about 1-5 mm thick. The dark laminae are generally rich in siliciclastic silt and dolomite, and commonly contain abundant stringers, streaks, and semi-continuous layers of opaque to dark brown, probable organic matter. All three components tend to decrease in

quantity upwards into the overlying light-coloured laminae, which are more homogeneous and composed mainly of homogeneous clay minerals (Plates 9d, 10d).

Laminated/crosslaminated argillaceous siltstone occurs mainly in the Duchesnay unit, where it is compositionally gradational to ribbon calcisiltite (described in Section 4.4.3). In this unit, rocks are incipiently metamorphosed, and the argillaceous laminae tend to be pervasively cleaved on a microscopic scale (Plate 10c). Like the laminated silty argillite, the laminated/crosslaminated argillaceous siltstone is largely composed of alternating dark and light laminae, though on a more variable scale. The dark laminae tend to be slightly more resistant than the light laminae, imparting a fine, ribbed appearance to weathered outcrops (Plate 7c).

The light laminae are composed of dolomitic siltstone (siliciclastic silt and silt-sized dolomite crystals). They contain minor argillaceous material and local stringy, discontinuous layers of probable organic matter. Microscopic load or scour structures are sometimes seen along lamina bases. The proportion of silt decreases upward into the overlying dark laminae, which are often characterized by pervasive, microscopic cleavage planes lined with clay and possible organic matter (Plate 10c). Where cleavage is absent, the dark laminae are composed predominantly of aligned stringers of clay minerals, together with various quantities of siliciclastic silt, dolomite, and organic matter (Plate 10e). Faint, internal stratification is visible in some cases.

Close inspection reveals consistent structural sequences, ranging from less than 1 cm to more than 2 cm thick. Light coloured, parallel-laminated and/or crosslaminated dolomitic siltstone commonly occurs at the base. Microscopic load and/or scour structures are present locally. The siltstone ultimately passes upward into dark, argillaceous laminae up

to a centimetre or more thick. The transition is commonly marked by discontinuous to continuous, millimetre- to sub-millimetre-scale, graded laminae (*sensu* Piper, 1972b). Each is composed of a lower, light, silty layer, which grades upward into a dark, argillaceous layer. The graded laminae progressively thin and contain less silt-sized material upward. Some overlying argillaceous laminae are differentiated into dark lower and light upper portions.

Starved, asymmetric ripple trains are also commonly found in the siltstone units (Plate 7d). Some of the ripple forms have deformed or oversteepened crosslaminae. Individual ripple sets are up to 4 cm thick, and occur at horizons several centimetres or tens of centimetres apart. The ripple foresets consistently face southwestward, and are oriented approximately perpendicular to the regional paleoslope.⁵

4.3.2.4 Ribbon and nodular argillite

In the argillite lithofacies, lime mudstone commonly occurs as well defined, tabular interbeds, as wavy beds, or as randomly distributed nodules (Fig. 17). As the proportion of tabular and wavy interbeds increases, these rock types grade compositionally into ribbon calcilutite. Petrographic relationships are basically the same as for the ribbon calcilutite lithofacies, and will be discussed in Section 4.4.2.

Ribbon argillite contains interbeds of grey-weathering lime mudstone (Plates 5b; 8d). The argillite interbeds are commonly dolomitic, and are usually composed of millimetre-scale cycles identical to those described earlier. The lime mudstone interbeds are generally structureless, although subtle, fine lamination can be discerned locally. Dolomitic

⁵ Paleocurrent measurements were unobtainable as the exposures were almost exclusively two-dimensional.

varieties weather orange-brown or orange. The argillite interbeds are usually more resistant than the carbonate interbeds, resulting in a pronounced, ribbed appearance on weathered surfaces (Plate 5b). The limestone interbeds are tabular or wavy, and typically 0.5 to 3 cm in thickness. Many extend hundreds of metres laterally, and sharp boundaries are the norm. Some tabular lime mudstone interbeds pinch out, then reappear laterally along the same horizon.

In **nodular argillite**, the nodules either occur along specific stratigraphic horizons (Plate 5j), or are randomly distributed. The nodules are lenticular in cross-section, and are typically 0.5 to 20 cm long, and 1 to 4 cm thick.

Although nodular argillite overwhelmingly contains structureless lime mudstone nodules, other nodule types are present locally. These include: (1) wavy laminated limestone; (2) ripple crosslaminated limestone (starved ripples); (3) graded calcisiltite and calcarenite, capped by horizontally laminated limestone; and (4) massive calcisiltite/calcarenite.

4.3.2.5 Evidence for syndimentary deformation

The argillite lithofacies contains abundant evidence of syndimentary deformation. Features indicative of this process include intrafolial recumbent folds, disrupted and irregular bedding, and intraformational truncation surfaces.

Intrafolial recumbent folds are present at all scales. They occur in stratigraphic intervals ranging from a few centimetres to at least 3 m thick (Plates 2d; 4c, d; 6d, e) In some, the lower fold limb is truncated along the lower bounding surface (Plate 6d). Most

examples are sharp-peaked, and have the geometry of similar folds. The preservation of individual laminae, despite visible thickening and stretching of the argillaceous beds, implies plastic deformation of a cohesive sediment. In contrast, fracturing of the carbonate interbeds in the fold hinges indicates that they were lithified at or close to the sediment-water interface (cf. Cook, 1979).

Intrafolial folds are common locally, and some pass laterally into seemingly undeformed beds or laminae. Some large folds may also pass laterally into chaotic, smaller scale folds, or other types of disturbed bedding (see below). Similar relationships have been documented by Coniglio (1986) and Gibling and Stuart (1988).

Disrupted and irregular bedding is ubiquitous in the argillite lithofacies, and occurs in zones a few tens of centimetres to several metres in thickness. In relatively pure argillaceous argillite, these irregularities are generally expressed by convolute or reoriented laminae. With more advanced internal deformation, only remnants of these laminae can be seen, and in extreme cases, the rock appears homogeneous (Plates 3d; 4a; 7a). These textural irregularities are commonly enhanced by differential weathering in ribbon and nodular argillites (Plate 6c). In sediments originally containing carbonate interbeds or dispersed nodules, advanced deformation is indicated by a chaotic mixture of carbonate nodules surrounded by a highly irregular or stringy argillite matrix (Plate 6c).

Some of the recumbently folded zones and zones of disrupted and irregular bedding are bounded below by surfaces obviously truncating underlying bedding (Plates 4b, 6c). These **intraformational truncation surfaces** truncate anywhere from a few centimetres to several metres of strata, and are defined as "small-to-large-scale surfaces, normally concave up, which truncate underlying strata until they merge tangentially with underlying beds and

lose their identity" (Cook and Enos, 1977b, p. 1). All are inferred to be slide scars or shear surfaces of various scales. Although intraformational truncation surfaces are fairly common in the argillite lithofacies, they are not as prevalent as in the ribbon calcilutite lithofacies.

Zones of folded and/or irregular bedding bounded below by intraformational truncation surfaces probably form part of discrete, internally deformed slide masses, like those described in modern and ancient environments elsewhere (Mullins and Neumann, 1979; Cook and Mullins, 1983; Gawthorpe and Clemmey, 1985; Coniglio, 1986; Gibling and Stuart, 1988). Commonly, however, discrete, basal shear planes cannot be discerned, and other mechanisms, such as shear related to overlying intraformational truncation surfaces, cannot be invoked to explain the observed deformation (Plates 2d; 4d; 6e). In such cases, the folds and disturbed bedding probably originated in subsurficial shear zones, developed in response to downslope creep of an overlying package of sediments (cf. Coniglio, 1986).

The interpretation of zones of disturbed bedding several metres to several tens of metres thick is less straightforward. The problem is likely one of scale. Modern slide masses in carbonate and siliciclastic settings are enormous relative to the scale of a typical outcrop (e.g. Mullins and Neumann, 1979; Prior and Coleman, 1984; Jacobi, 1984). The same is apparently true of large bodies of sediment moving downslope under the influence of creep (Hill *et al.*, 1982). Thus, many of the thicker examples of heterogeneously deformed sediment may be small parts of much larger slide masses. Others may be thick sequences that have suffered various degrees of large-scale creep deformation.

4.3.2.6 Dolomitization and other diagenetic aspects

Dolomite is ubiquitous in the argillite lithofacies. Almost every specimen examined in thin section had at least some disseminated dolomite crystals. The proportion of dolomite invariably increases with increasing siliciclastic silt content. However, pervasive dolomitization is also quite common in the non-silty (argillaceous) argillite.

Most of the dolomite observed in the more argillaceous argillite is silt-sized, subhedral to euhedral, and ferroan. The dolomite crystals stain uniformly, and inclusions, where present, are uniformly distributed throughout the crystal. In some more pervasively dolomitized examples, these dolomite crystals account for 50% or more of the rock. Clay minerals, minor siliciclastic silt, organic matter, and pyrite make up the remainder. This type of dolomite is probably entirely authigenic, and resembles the uncored "conglomerate matrix" dolomites described by Coniglio and James (1988) in the Cow Head Group.

At the silty end of the spectrum, the character of much of the dolomite is different. Again, euhedral and subhedral dolomite is most common, and most crystals are silt-sized. Significantly, however, a large proportion of these crystals have cloudy, inclusion-rich cores and clear, inclusion-poor rims (Plate 10b). The cores are typically non-ferroan, whereas the clear rims are ferroan (as determined by staining with potassium ferricyanide solution). Ovoid, spherical, and rhomb-shaped cores have been observed. This dolomite almost certainly corresponds to the cloudy core, clear rim (CCCR) dolomite documented by Coniglio (1985) and described by Coniglio and James (1988) in the Cow Head Group.

The petrographic similarities with the Cow Head CCCR dolomites are close enough to infer a similar origin, pending further study. In the Cow Head Group, this type of

dolomite is thought to have originated in two ways: (1) diagenetic enlargement of detrital dolomite, derived from erosion of older carbonate terrains, or from aeolian transport of penecontemporaneously formed dolomite; and (2) replacement of pre-existing peloids in the sediment, followed by continued crystal growth to form an inclusion-poor rim (Coniglio and James, 1988, p. 1040). More intensive study, including cathodoluminescence work and stable isotope geochemistry, will be necessary to confirm the origin and timing of this dolomitization.

Peloids and bioclasts have also been replaced by other minerals in the "basinal" Stephen Formation near Field and Natalko Lake (Fig. 4). The argillites are composed of graded silt/mud couplets, identical in form to those described earlier (Plate 9d). However, siliciclastic silt is actually quite rare. All of the silt to very fine sand-sized material, including trilobite and bivalve fragments, has been replaced by phyllosilicates. Most of the unidentifiable grains were probably originally calcium carbonate peloids of various origins. Similar observations have been published by Whittington (1980), who reported the complete replacement of an Olenoides trilobite exoskeleton by chlorite and illite in the Burgess Shale (also part of the "basinal" Stephen Formation).

4.3.3 Interpretation of the argillite lithofacies

4.3.3.1 Interpretation of argillaceous and laminated silty argillites

The sedimentary structures observed in the **argillaceous and laminated silty argillites** are actually quite simple. Where depositional fabrics have not been obscured by primary or secondary processes, millimetre-scale cycles are the norm (Section 4.3.2.3). These regularly laminated, graded muds and silty muds are best interpreted in the context of facies models for fine-grained turbidites in similar slope settings. They do not resemble the

deposits of muddy, contour-following currents, at least as described by Stow and Lovell (1979) and Stow (1986).

The alternating dark and light laminae (millimetre-scale cycles) in the argillaceous argillites are inferred to correspond to the Bouma E_{turbidite} and Bouma E_{hemipelagite} divisions, respectively, of the standard Bouma (1962) sequence (cf. Coniglio and James, 1990, p. 222). The almost total lack of biogenic structures in the latter division indicates an environment inhospitable to burrowing organisms. This is presumably attributable to oxygen-deficient conditions on the upper slope.

The reason for the inconsistent nature of these millimetre-scale cycles is not clear. Where dark, organic-rich laminae grade consistently upward into light, essentially homogeneous clay laminae, a mechanism similar to that proposed by Coniglio and James (1990) for shales in the Cow Head Group is probably applicable. Based on a comparison with DSDP cores from the northwest African continental margin (Dean *et al.*, 1977), they argued that organic matter was preserved in the lower, terrigenous turbidite due to rapid burial. The paucity of organic matter in the overlying hemipelagic layer was attributed to oxidation as the organics settled through the water column.

The above mechanism does not explain why organic matter is preserved in the upper, clayey layer in many argillite units. The inconsistent distribution of organic matter in these sediments possibly reflects variations in the intensity and/or vertical position of an oxygen-minimum zone impinging on the slope.

The interpretation of fine-grained turbidites in the argillite lithofacies is not new. Piper (1972a) inferred that the thin, graded silt and terrigenous mudstone beds in the Burgess

Shale were turbidites. A similar conclusion was reached by McIlreath (1977a) for graded silt and terrigenous mud in the lowermost "basinal" Stephen Formation.

There has recently been some discussion as to whether the fine-grained sediments in the "basinal" Stephen Formation should be classified as turbidites or tempestites (Ludvigsen, 1989; Aitken and McIlreath, 1990). In the opinion of the writer, this discussion verges on the esoteric. The laminated argillite and shale of the "basinal" Stephen Formation, like those in other parts of the Chancellor, were deposited below maximum storm wave base. This is indicated by the preservation of fine lamination, and the absence of features such as lags, wave ripples, or hummocky cross-stratification. Below storm wave base, offshore-directed, storm-generated currents would in all probability evolve into density currents (cf. Hamblin and Walker, 1979; see also Dott and Bourgeois, 1982). Distal tempestites deposited in this manner would thus be no different than fine-grained turbidites, as the sedimentary process is the same.

4.3.3.2 Interpretation of laminated/crosslaminated argillaceous siltstone

Most of the **laminated/crosslaminated argillaceous siltstone** can similarly be interpreted in the context of fine-grained turbidite deposition. Suitable models have been proposed by Piper (1978) and Stow and Shanmugam (1980) for silt and mud turbidites (Fig. 18; see also summary in Stow and Piper, 1984).

The parallel-laminated and crosslaminated dolomitic siltstone units are best interpreted as Bouma BC sequences in the context of Piper's (1978) silt turbidite model. The underlying Bouma A division is rarely seen. The overlying graded silt laminae correspond to the Bouma D division, and pass upward into $E_{\text{turbidite}}$ (dark) and $E_{\text{hemipelagite}}$ (light)

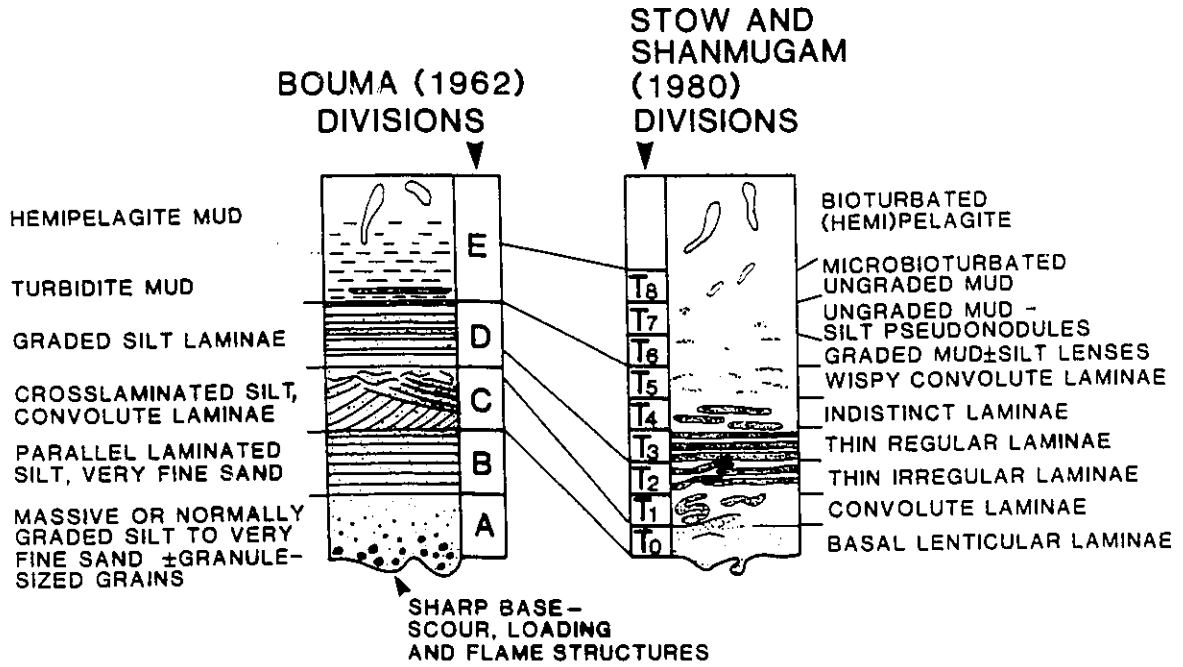


Figure 18. Left: schematic sequence of sedimentary structures in laminated/crosslaminated silty argillites and ribbon calcisiltites in the Chancellor. Right: sedimentary structures documented in terrigenous mud turbidites by Stow and Shanmugam (1980). Correlations and diagram format based on Coniglio and James (1990).

muds.⁶ Commonly, only parts of this sequence are preserved. More extensive sampling and slab study would undoubtedly uncover a more complete sequence of sedimentary structures, similar to that documented by Stow and Shanmugam (1980) in terrigenous mud turbidites.

Various processes are thought to be capable of generating low density turbidity currents (Stow, 1986, p. 408). In this case, the turbidity currents probably originated from storm activity on the shelf, assuming that storm-generated waves and currents contributed to net, offshore-directed sediment transport. Alternatively, the turbidites could have evolved from sediment slides or debris flows.

The starved, asymmetric ripple trains do not fit into the above interpretation. They are clearly different in form and size from the Bouma C division crosslaminae, and were deposited by unidirectional, southeasterly-directed currents operating under conditions of limited sediment supply. The direction of flow was approximately perpendicular to the regional paleoslope. The currents were only able to introduce and/or redistribute sediment periodically, as indicated by the widely separated occurrences of the ripples. Overall, these features suggest a sedimentary process superimposed upon a background of silty turbidite deposition.

The starved ripples were most likely deposited by contour-following currents that cannibalized silt- to very fine sand-sized sediment from the substrate. The currents were only periodically intense enough to cross the threshold of sediment movement. A similar origin has also been proposed for nearly identical ripple forms in the upper slope sediments of the lower Hales Limestone (Upper Cambrian) in Nevada (Cook and Taylor, 1977; Cook and Mullins, 1983).

⁶ The E_{hemipelagite} division is referred to as the "F" division in the model by Piper (1978).

These deposits are not contourites in the classic sense, as they were not deposited by deep, thermohaline currents operating on the lower continental slope and rise. They were instead deposited on the upper slope, and were thus probably associated with wind-driven surface circulation. Contour-following currents of this type have been very effective in transporting bank-derived slope sediments in the northern Straits of Florida off the Bahama Banks (Mullins and Neumann, 1979; Mullins *et al.*, 1980).

4.4 RIBBON LIMESTONES

4.4.1 Terminology

The carbonate-dominated parts of the Chancellor are typically composed of grey-weathering limestone with brown- to tan-weathering, argillaceous/dolomitic interbeds and interlaminae (Plates 11, 12). Successions such as these are termed **limestone rhythmites** or **ribbon limestones**, and have been described from a large number of ancient carbonate slope successions (e.g. Wilson, 1969; Cook and Taylor, 1977; Pfeil and Read, 1980; James and Stevens, 1986).

Two main types of ribbon limestone can be distinguished, based on the composition of the limestone interbeds: **ribbon calcilutite**, with predominantly lime mudstone interbeds, and **ribbon calcisiltite**, composed mainly of silt- to very fine sand-sized carbonate grains. In the Chancellor, ribbon calcilutite is an important constituent in the Takakkaw Tongue, Tokumm sub-unit, and Vermilion sub-unit, whereas ribbon calcisiltite is largely confined to the Duchesnay and Oke units.

In a very thorough study, Coniglio and James (1990) differentiated between **ribbon** and **parted** limestones (see also James and Stevens, 1986). In their terminology, ribbon limestones are successions in which the limestone and argillaceous/dolomitic beds are roughly equal in thickness. Predominantly shale successions with similar limestone interbeds are also given the same name. Parted limestones are defined as predominantly limestone successions in which the argillaceous/dolomitic layers are less than 1 cm thick.

The term "parted limestone" has also been applied to rocks of shallow-water origin on the platform in and adjacent to the study area (Aitken, 1966, p. 411). In these rocks, the argillaceous or dolomitic partings "invade" the adjoining carbonate beds, largely as a result of extensive burrowing. The irregular partings have also been attributed to dolomitization following syneresis cracks and spreading outward from burrows (Aitken, in press, a).

To avoid confusion with Aitken's (1966, in press, a) terminology, the term "parted limestone" will not be used. The term "ribbon limestone" will be applied to successions in which the thickness of the interbedded and interlaminated argillaceous/dolomitic material is roughly equal to or less than that of the limestone.

4.4.2 Ribbon calcilutite lithofacies

4.4.2.1 General description

The **ribbon calcilutite lithofacies** consists of continuously bedded lime mudstone, which is rhythmically interbedded and interlaminated with argillaceous and/or dolomitic

material (Plate 11a-d). In general, rocks of this lithofacies are very thin- to thin-bedded, with most beds in the 2-3 cm range. Medium bedding is much less common.⁷

Individual limestone beds commonly extend hundreds of metres along depositional strike without significant changes in thickness or geometry. They are dark grey, and usually weather light to medium grey. The intervening argillaceous/dolomitic material is as little as a millimetre thick. It usually weathers brown to tan, depending on the degree of dolomitization (Plates 11a, b, d; 12a). Fresh surfaces are dark grey to black (Plate 12b). Bedding is commonly accentuated by differential weathering. Contacts are generally planar in undeformed successions.

Nodular and irregular ribbon calcilutites are also very common (Fig. 17), and can be interbedded or intercalated in any proportion with planar bedded ribbon calcilutite. A "fitted nodular" fabric (*cf.* Coniglio and James, 1990, p. 224) is common where the intervening argillaceous/dolomitic material is very thin (Plate 11e). Irregular ribbon calcilutite consists of more chaotic mixtures of lime mudstone nodules surrounded by stringy masses of argillaceous/dolomitic material. The lime mudstone in both these rock-types is identical to that in the continuously bedded ribbon calcilutite.

In the field, most lime mudstone interbeds appear to be structureless. Some contain subtle, continuous or discontinuous laminae, made visible by slight colour variations or differential weathering. Well-laminated limestones invariably turn out to be graded, peloidal calcisiltite (Plate 19c), but occur rarely. "Stromatactoid structure" (Aitken, 1966, p. 414) is also locally developed in this lithofacies (Plate 36d).

⁷ Throughout this thesis, the following bedding terminology will be used: thin bedding: 1-10 cm; medium bedding: 10-30 cm; thick bedding: 30-100 cm; very thick bedding: >100 cm. The term "lamina" will be applied to layers less than 1 cm thick.

The argillaceous/dolomitic interbeds and interlaminae are compositionally variable, and a number of varieties can be distinguished in the field. A complete compositional spectrum is present, from essentially pure argillite, to variably dolomitized argillite, to argillaceous dolomite, to nearly pure dolomite. These rock types are generally finely laminated (Plate 12b). In more dolomitic examples, the laminae tend to be accentuated by differential weathering (Plate 12a).

4.4.2.2 Thin section petrography

In thin section, the lime mudstones generally consist of non-ferroan microspar and pseudospar mosaics.⁸ Some examples contain a mixture of ferroan and non-ferroan calcite, which is detectable by staining. Disseminated non-ferroan, subhedral to euhedral dolomite crystals are ubiquitous. They generally constitute less than about 5-10% of the rock. More pervasively dolomitized lime mudstone contains disseminated dolomite crystals and fine networks of dolomite that surround individual calcite crystals (Plate 15a). Accessories such as peloids, ooids, and intraclasts occur rarely. The presence of poorly preserved peloids locally suggests that the precursor sediment was, in some cases, wackestone or packstone, rather than lime mudstone (Plate 15e). Other accessories, such as phosphatic brachiopods, trilobite fragments, and whole agnostids occur sporadically. Trace fossils are absent. Clay and organic matter are generally lacking, except in the Duchesnay and Oke units, where one or both line solution seams or microscopic cleavage planes (Plate 15d). Siliciclastic silt is also abundant only in these units. The fine laminae seen locally in outcrop are not always apparent in thin section, but may reflect, in part, subtle variations in crystal size.

⁸ The terminology follows that of Folk (1965). Microspar is 30 microns or less in size, but larger than micrite (<4 microns). Pseudospar is greater than 30 microns in size.

The transition from lime mudstone to argillaceous/dolomitic interbeds or interlaminae is usually sharp to rapidly gradational, and irregular on a microscopic scale (Plate 15a-d). Dolomite crystals increase in concentration as the boundary is approached, and ferroan microspar and/or pseudospar appear locally. Stylolites, microstylolite swarms, or accumulations of insolubles are uncommon at or close to the boundary. The boundary is commonly defined by the abrupt replacement of microspar and pseudospar by argillaceous sucrosic dolomite or variably dolomitic argillite. However, more gradational boundaries have also been observed (upper boundary in Plate 15a).

The interbedded and interlaminated argillite and dolomitic argillite are identical to those described earlier in the argillite lithofacies (Plate 15c). The more pervasively dolomitized varieties are composed of 60-70% ferroan dolomite crystals. Intercrystalline space is occupied by clay minerals and organic matter. The dolomite crystals do not have visible cores, and stain uniformly. This dolomite is most likely authigenic.

4.4.2.3 Sedimentary features indicative of syndimentary slope instability

The ribbon calcilutite lithofacies contains a number of sedimentary features indicative of slope instability. These provide information not only on mass movement processes, but also on the rheology of the sediments at the time of emplacement. There is strong evidence that the limestones were cemented at or just below the sea floor, whereas the argillaceous/dolomitic interbeds and interlaminae remained soft enough to deform plastically within a few metres of the sediment-water interface (cf. Cook, 1979; Cook and Mullins, 1983; Pfeil and Read, 1980; Coniglio, 1986). This has important implications for

interpreting the origin of the rhythmites, as it implies fundamental primary differences in the compositions of the alternating layers.

Rotated limestone blocks occur rarely, but are important indicators of extensional stresses on the sediment (Plate 13a). In these examples, small, decimetre-scale blocks of lime mudstone have broken away from the limestone bed and rotated slightly in a downslope direction. In the example shown (Plate 13a), the crack on the right side of the block was infilled by convex-downward, laminated sediment. This suggests that the infilling sediment was non-cohesive, and was not injected into the open space. The crack probably opened on the sea floor in response to downslope creep of the early-lithified limestone layer.

Pull-apart structures also illustrate the contrasting rheology of the rhythmite layers (Plate 13b). Gaps between the broken limestone layers were infilled by dolomitic material. The fine laminae in this material abruptly disappear at the gap margins, suggesting plastic injection. These structures probably formed in response to downslope creep, most likely in the shallow subsurface where the dolomitic material had compacted sufficiently to become moderately cohesive.

Slide masses are common features. The most obvious examples are small, internally deformed, laterally and vertically restricted bodies that can be seen in a single outcrop (Plate 13d). Tight, recumbent folds are common, and closely resemble examples illustrated by Cook (1979). Brittle breakage of the limestone interbeds and plastic flow of the intervening argillaceous/dolomitic material, particularly in the hinge zones of the folds, attest to their differing rheology in the shallow subsurface. In one particularly informative example, the degeneration of part of the folded zone into a clastic texture (Plate 13c, right) clearly illustrates the principle that coherent slide masses can undergo a progressive increase

in deformation until they are remolded into debris flows (Hampton, 1972; Cook and Mullins, 1983).

Undeformed slide masses provide evidence that ribbon calcilutite layers exhumed from the shallow subsurface can, in some cases, be transported without visible internal or margin deformation (Plate 13e). Small examples are easily identified in outcrop. It is sobering to note, however, that much larger slide masses of this type would be difficult to differentiate from autochthonous ribbon calcilutite sequences.

Irregular ribbon calcilutite is commonly interbedded and intercalated with planar ribbon calcilutite, and occurs in units ranging from a few decimetres to several tens of metres in thickness. They are analogous to the disrupted and irregular bedded argillite described previously (Section 4.3.2.5), and are characterized by irregular to rather chaotic bedding (Plate 12c, d, e). In many examples, variously shaped limestone lenses are surrounded by stringy masses of argillaceous/dolomitic material. All stages from irregular, but still recognizable bedding, to chaotic, clast-like textures have been observed in the field. The latter textures closely resemble the "anastomosing webs" of argillaceous partings described by Coniglio (1986) from slide masses and subsurficial shear zones. A similar origin is inferred for the Chancellor examples. Thinner examples not obviously associated with truncation surfaces (e.g. Plate 12d) were probably formed in subsurficial shear zones. Thick intervals of irregular ribbon calcilutite probably form part of internally deformed creep or slide masses that are too large to be easily recognized at outcrop scale.

Intraformational truncation surfaces of all scales are very common in the ribbon calcilutite lithofacies (Plate 14a-d). The truncated strata range in thickness from a few

decimetres to a few metres over the visible extent of the surface.⁹ Usually, the underlying ribbon calcilutites are undisturbed. The overlying fill forms a downslope-thickening wedge, in which the dip of the bedding progressively decreases stratigraphically upward until it becomes horizontal. In a few examples, this sedimentary package is internally deformed, probably reflecting post-depositional slippage and rotation along the underlying truncation surface (Plate 14d).

The intraformational truncation surfaces probably mark the detachment sites of the slide masses found elsewhere in this lithofacies. The smooth, listric geometry, lack of erosional irregularities and lags, and nature of the infilling sediments (ribbon calcilutite or argillite) serve to differentiate these slide scars from channels or current scours (see Davies, 1977).

4.4.3 Ribbon calcisiltite lithofacies

4.4.3.1 Introduction

The ribbon calcisiltite lithofacies is found mainly in the Oke unit, and to a lesser extent in the Duchesnay unit (Fig. 16). It also occurs in the Tokumm and Vermilion sub-units as interbeds or thin units associated with the ribbon calcilutite lithofacies.

The ribbon calcisiltite lithofacies is composed largely of interbedded and interlaminated calcisiltite and argillaceous/dolomitic material. Lime mudstone is commonly present in the upper parts of the limestone interbeds. It also occurs as discrete interbeds with silty laminated or crosslaminated horizons. In general, the limestone and

⁹ As will be documented in a subsequent chapter, the Chancellor sequence also contains megatruncation surfaces that cut out hundreds of metres of strata, implying similar processes on a much larger scale.

argillaceous/dolomitic components are roughly equal in proportion, or the former predominates over the latter. Exceptions to this general rule occur locally, especially in the upper Oke unit (Plate 16e).

Ribbon calcisiltite superficially resembles ribbon calcilutite (Plate 16c, d). However, the two are significantly different in terms of bedding style, sedimentary structures, dolomitization patterns, and composition. In contrast to the planar interbedding typical of ribbon calcilutite, ribbon calcisiltite tends to be nodular to irregular bedded, largely because the limestone contains abundant sedimentary structures. Dolomitization also tends to occur much more irregularly in this lithofacies, further contributing to its irregular appearance. Finally, as its name implies, ribbon calcisiltite is composed largely of silt- to very fine sand-sized carbonate and siliciclastic grains, as opposed to the overwhelming predominance of lime mudstone in ribbon calcilutite. Notably, however, the interbedded and interlaminated argillaceous/dolomitic material is identical in the two lithofacies.

4.4.3.2 General description

Rocks of the ribbon calcisiltite lithofacies are predominantly thin to medium-bedded. The interbedding of grey-weathering limestone and tan- to brown-weathering argillaceous/dolomitic material produces a characteristic striped or "ribbon" appearance (Plate 16a-d). The calcisiltite beds, especially where thin, tend to be wavy or irregular (Plates 18d; 19a). Where the argillaceous/dolomitic matrix is predominant, the rock locally loses its ribbon appearance.

The **argillaceous/dolomitic interbeds** are composed mainly of slightly to pervasively dolomitized argillite. The dolomite is almost exclusively ferroan and silt-sized.

Many dolomitic argillite interbeds are composed of millimetre-scale cycles (Plates 17a; 20d), identical to those in the argillite lithofacies. The cycles commonly have loaded bases, and their lower parts are strongly dolomitized. Grading is expressed by upward dilution of dolomite crystals and/or by upward disappearance of siliciclastic silt (Plate 20d). Less commonly, the argillite caps repeated, graded calcisiltite laminae (Plate 20c). These examples are analogous to the laminated silty argillite of the argillite lithofacies (Plates 8b, 10d).

The **limestone interbeds** are compositionally diverse. The thinner beds and nodules are typically composed of calcisiltite, which in the Oke and Duchesnay units contains a significant fraction of siliciclastic silt (commonly 10-20%). Laminae and very thin interbeds of lime mudstone are also quite common. Very fine-grained calcarenite, calcisiltite, and lime mudstone are commonly incorporated in one or more partial Bouma sequences in thicker beds. Predominantly lime mudstone beds containing thin, silty, parallel-laminated or crosslaminated layers are also included in this lithofacies, if they are intimately interbedded with more typical ribbon calcisiltite.

The simplest limestone beds in the ribbon calcisiltite lithofacies are predominantly composed of lime mudstone, but contain spaced, silty lenses and laminae (Plate 16a, b). Many beds contain a lower, parallel-laminated silty portion, and an upper, structureless lime mudstone portion (Plate 16b). Other sedimentary structures found in these beds are: (1) parallel-laminated or low amplitude, ripple crosslaminated layers; (2) isolated ripple forms (Plate 16b); and (3) spaced, graded dolomitic laminae 2-10 mm thick. Except for the presence of these silty layers, the limestones are identical to those in ribbon calcilutite units.

The limestone interbeds in the ribbon calcisiltite lithofacies are generally composed of one or more sharp-based Bouma sequences. These beds are generally less than 10-15 cm thick, and most contain bottom cut-out BCDE, CDE or DE sequences ranging from 1-10 cm in thickness (Plate 17b, c, d). The massive "A" division is rarely developed, but where present, usually consists of fine to coarse sand-sized grains (Plate 17b). Basal scour and load structures are typical of the more complete Bouma sequences (Plate 17b, d). Climbing ripples are commonly found in the "C" division (Plates 17d, 18a). Graded silt laminae (sensu Piper, 1972b) typically overlie the ripple crosslaminated division, or mark the bases of DE sequences (Plate 17c)¹⁰. Some transitions to the "E" division are marked by size or compositional grading. Most sequences are capped by structureless lime mudstone, although incomplete, amalgamated sequences are common (Plate 17b).

Many limestone interbeds contain starved ripple trains, in which deformed and oversteepened crosslaminae are common (Plate 18b, c). Some ripples appear to fade laterally into structureless lime mudstone (Plates 17c; 18b). The ripples have amplitudes of up to 5 cm, and wavelengths on the order of 10-15 cm. Their stoss-sides are sometimes preserved. The rippled horizons overlie and erosionally truncate various Bouma sequence structures (Plates 17c, 18c), or rest directly on structureless lime mudstone (Plate 18b). The ripples are usually draped by lime mudstone. Significantly, the ripple foresets are consistently oriented towards the southeast, perpendicular to the regional paleoslope.¹¹ These ripples are identical to the examples described earlier in the argillite lithofacies (Section 4.3.2.3).

¹⁰ Graded laminae are defined by Piper (1972b) as discontinuous and continuous layers of silt-sized material that decrease in frequency, thickness and grain size upward.

¹¹ Statistically significant paleocurrent measurements could not be obtained, as virtually all exposures are two dimensional.

The limestone beds are interbedded on a centimetre to decimetre scale with laminated dolomitic argillite (Plates 16a-d; 18d). As the limestones become thinner, the ribbons become much more irregular due to compaction of the laminated dolomitic argillite around the wavy interbeds and nodules (Plate 19a, b). Some crosslaminated nodules are simple, isolated ripple form sets, and others are large, bulbous features with multiple, deformed and oversteepened sets of crosslaminae. Irregular ribbon calcisiltites can be interbedded and intercalated in any proportion with more regularly bedded ribbon calcisiltite.

4.4.3.3 Thin section petrography

The parallel-laminated and ripple crosslaminated calcisiltites from the Oke and Duchesnay units typically contain 10-20% siliciclastic silt (quartz and feldspar), and 5-10% non-ferroan and ferroan dolomite. More pervasively dolomitized examples are also very common. The nature of the primary carbonate grains is masked by diagenesis, as illustrated by the following two examples from the Oke unit.

The first example is a parallel-laminated calcisiltite at the base of a thin Bouma CDE sequence. A vague, peloidal texture is visible in thin section (Plate 20a). The peloids are composed of silt-sized, spherical to oval, cloudy bodies of micrite or microspar surrounded by coarser grained microspar. Where the grain-to-matrix transition is vague, the result is a "clotted", or structure grumeleuse texture. These observations indicate that the original sediment contained a high proportion of primary carbonate grains in addition to siliciclastic silt.

The contribution of primary carbonate grains is much more subtle in the second example, a ripple crosslaminated calcisiltite containing abundant siliciclastic silt, together

with subhedral to euhedral dolomite crystals (Plate 20b). These grains are surrounded by what appears to be a patchwork of ferroan and non-ferroan calcite. Upon close examination, however, vague, silt- to very fine sand-sized, spherical to oval, cloudy patches of non-ferroan calcite can be discerned (Plate 20b). Some are encased in clear, non-ferroan calcite, and others by clear, ferroan calcite. The cores and surrounding clear rims are optically continuous. The cores were probably originally peloids that were subsequently replaced by non-ferroan calcite. Many of the dolomite crystals also have silt- to very fine sand-sized, round to oval, cloudy cores and clear rims, identical to the CCCR dolomite crystals described earlier in the argillite lithofacies. They also probably originated from diagenetic replacement and overgrowth of pre-existing carbonate peloids (*cf.* Coniglio and James, 1988).

Clearly, the precursor sediment in both of these examples contained a high proportion of carbonate peloids in addition to siliciclastic silt. The peloids are poorly preserved, and their origin is uncertain. Many may have been fecal pellets derived from the platform. However, well preserved grains of similar size and shape in calcisiltites from the Tokumm sub-unit suggest that many of the peloids were contributed by calcified algae (*cf.* Coniglio and James, 1985). The Tokumm sub-unit calcisiltite is composed of thin, normally graded layers, 0.7-2.5 mm thick (Plate 19c). The silt-sized particles in these layers consist mainly of fragmented Girvanella tubules (Plate 19d).¹² Other potential sources of coarse silt- to very fine sand-sized peloids would be fragmented Epiphyton branches, fecal pellets, and micritized intraclasts.

¹² Notably, the Girvanella tubules and fragments described by Coniglio and James (1985) had much smaller external diameters (10-15 microns) than those observed in the Chancellor. However, the internal diameters of the Chancellor examples generally fall within the range cited by Roux (1985).

4.4.4 Interpretation of ribbon limestones

4.4.4.1 Introduction

There is a growing consensus that most ribbon limestones are the product of both primary and diagenetic processes. Purely diagenetic models (e.g. the pressure solution models of Logan and Semeniuk, 1976 and Wanless, 1979) cannot explain all of the sedimentary features inherent in these sequences, and thus a number of combined depositional/diagenetic models have recently emerged (Einsele, 1982; Eder, 1982; Hallam, 1986; Coniglio and James, 1990). As the multidisciplinary approach advocated by Hallam (1986) has not been attempted in this study, the interpretation of the Chancellor ribbon limestones relies heavily on these models. The depositional/diagenetic model recently proposed by Coniglio and James (1990; see also Coniglio and James, 1988; Coniglio, 1989) is probably directly applicable to limestone rhythmites in the Chancellor, and will be used as a working hypothesis pending more intensive study of the diagenesis of these sediments.

4.4.4.2 Interpretation of ribbon calcisiltite lithofacies

The ribbon calcisiltite lithofacies is the most easily interpreted, as it contains abundant sedimentary structures. Although complete Bouma sequences occur rarely, careful observation has confirmed that a systematic, predictable succession of sedimentary structures is present (with the exception of the starved ripple trains; see below). These sediments are directly analogous to the laminated/crosslaminated argillaceous siltstones, and can similarly be interpreted in the context of Piper's (1978) silt turbidite model.

Most of the carbonate turbidites are bottom cut-out sequences starting with the parallel-laminated (Bouma B) or crosslaminated (Bouma C) divisions (Fig. 18). These pass upward into graded silt laminae of the Bouma D division. Most sequences are capped by structureless lime mudstone, which is inferred to be the Bouma E_{turbidite} and possibly E_{hemipelagite} divisions. However, the lime mudstone may also be partly diagenetic in origin (see below). The millimetre-scale cycles in the pervasively dolomitized argillite interbeds (Plates 17a; 20d) are identical to those in the argillite lithofacies (Plates 5e; 10a), and are accordingly interpreted as Bouma E_{turbidite} - E_{hemipelagite} cycles.

In summary, the Duchesnay and Oke units consist largely of centimetre- to decimetre-scale carbonate turbidites, which are interbedded and intercalated with millimetre-scale, terrigenous mud turbidites and hemipelagic sediments. Identical calciturbidites occur sporadically in the Tokumm and Vermilion sub-units and Takakkaw Tongue. This lithofacies closely resembles the calcisiltite/shale lithofacies described by Coniglio and James (1990), with the important exception that the Chancellor calciturbidites are capped, in many instances, by lime mudstone rather than by argillite or shale.

The starved ripple trains seen in many limestone beds appear to be the product of a sedimentary process superimposed on a general background of silt and mud turbidite deposition. This is emphasized by the fact that they overlie and erosionally truncate different levels within the Bouma sequence, and show no consistent relationship with other sedimentary structures. The ripples indicate a consistent, southeasterly paleoflow direction, and grew primarily by cannibalizing the substrate. They share all the attributes of their counterparts in the argillite lithofacies (Section 4.3.3.2), and were probably deposited by wind-driven, contour-following currents.

The recognition that turbidity currents were responsible for deposition of much of the middle, and probably part of the lower Chancellor (see below) has important implications for the origin of the sediments and patterns of sediment dispersal. The presence of both carbonate and terrigenous turbidites in the calcisiltite lithofacies implies that both sediment types were derived from the shelf.¹³ During periods of widespread shallow-water carbonate deposition (e.g. Oke time), both sand- and mud-sized carbonate sediments were supplied to the slope on a frequent basis. Many limestone beds contain multiple, incomplete Bouma sequences (typically 2-5), suggesting that the carbonate detritus was exported to the slope in closely spaced pulses, with little or no intervening terrigenous turbidite deposition. These periods of predominantly carbonate input were apparently separated by longer periods of terrigenous mud turbidite deposition, during which tens to hundreds of millimetre-scale cycles were laid down. The derivation of both carbonate and terrigenous sediment from the shelf, even during periods of predominantly shallow-water carbonate deposition, implies the operation of an effective bypassing mechanism for fine-grained terrigenous sediment originating from the inner detrital belt.

4.4.4.3 Interpretation of ribbon calcilutite lithofacies

The paucity of sedimentary structures in the lime mudstone portions of ribbon calcilutites makes their interpretation difficult. Some of these carbonate interbeds may be entirely diagenetic in origin. The protoliths for others were presumably sediments delivered to the slope by dilute turbidity currents, hemipelagic fallout, and/or contour currents (Cook and Mullins, 1983; McIlreath and James, 1984).

¹³ This contradicts the long held view by J.D. Aitken (Aitken, in press, a) that fine-grained terrigenous sediments in the slope succession were derived from other sources along slope.

The laminated argillite and dolomitic argillite in this lithofacies are identical to those in the ribbon calcisiltite lithofacies, and are accordingly inferred to be base cut-out muddy turbidites (Bouma $E_{\text{turbidite}}$ - $E_{\text{hemipelagite}}$ cycles). On this basis, it would be logical to infer that the intimately interbedded lime mudstone was also deposited by dilute turbidity currents. The currents would have been generated during periods of prolific carbonate production and/or reduced terrigenous input from the shelf. The close association between ribbon calcilutites and demonstrable calciturbidites (ribbon calcisiltites) in the Duchesnay and Oke units supports this suggestion.

The monotonous ribbon calcilutite sequences in the Tokumm sub-unit and Takakkaw Tongue are much more difficult to explain in this context. If turbidity currents were continually being shed from the carbonate margin, they should have entrained a variety of sediment sizes. However, a representative range of grain sizes has not been observed in these sequences. Basal scours and recognizable sedimentary structures are also lacking in the calcilutite beds. Thus, while dilute turbidity currents undoubtedly delivered lime mud to the slope, it is unlikely that they alone were responsible for deposition of the regularly bedded, thick sequences observed in the Chancellor.

Hemipelagic settling of periplatform muds during periods of prolific carbonate generation is a viable means of creating continuous carbonate beds devoid of basal scours and other sedimentary structures. The lime muds could have been swept off the platform during normal tidal exchange or storms (McIlreath and James, 1984), or they could have settled out from turbidity currents that spread laterally over pycnoclines in the water column (Coniglio and James, 1990). Hemipelagic settling is the most likely mechanism for producing a primary rhythm in slope sequences lacking obvious evidence for regular carbonate turbidite input.

The possible presence of muddy contourites cannot be meaningfully evaluated on the basis of present information. Although contour-following currents may have been active during Duchesnay and Oke unit deposition, there is no evidence for similar currents in the Tokumm and Vermilion sub-units and Takakkaw Tongue. As was noted by Coniglio and James (1990), lime mudstones laid down in this manner may be indistinguishable from lime mudstone turbidites, and thus the precise contribution of muddy contour currents, if any, remains unknown.

The obvious rheological differences between the carbonate and terrigenous mud layers early in the history of the sediment imply periodic, primary variations in sediment composition at the time of deposition. The reason for this can only be speculated upon. Climatic variation in response to Milankovitch orbital cycles is the most commonly cited cause (e.g. Einsele, 1982; Coniglio and James, 1990), but conclusive proof remains elusive for Early Paleozoic successions. Assuming that climatic variation was responsible, its effect could have been: (1) to periodically alter the rate of sediment supply (e.g. by increasing or decreasing carbonate productivity or the rate of terrigenous runoff from the craton); (2) to periodically change mechanisms of sediment delivery to the slope (e.g. by changing the direction or intensity of storms, or by changing the windward/leeward character of the margin); or (3) some combination of these processes.

As in many other carbonate slope successions, the Chancellor ribbon calcilutites probably originated partly by diagenetic enhancement of such primary depositional signals, and partly by purely diagenetic means. Available field and petrographic evidence is insufficient to determine the relative importance of these processes. According to Coniglio and James (1990), carbonate can be remobilized and precipitated during shallow burial in

response to pore-water pH changes associated with anaerobic oxidation of organic matter. Dispersed carbonate mud can be dissolved from the argillaceous layers and precipitated locally to: (1) lithify pre-existing, carbonate-rich turbidite or hemipelagite layers; (2) produce concretionary or diagenetic lime mudstones, if no primary signal was present; and (3) precipitate dolomite.¹⁴ This process clearly occurred either at or immediately below the sediment-water interface, as indicated by the common presence of tabular, slope-derived lime mudstone clasts in associated conglomerates (Plate 27a, c), and by the brittle behavior of lime mudstone interbeds in surficial slides (Plate 13c).

Diagenetic enhancement of areally extensive carbonate turbidite or hemipelagite beds would have resulted in the formation of continuously bedded ribbon limestones and ribbon argillites (Plates 5b; 11a, b, d; 12a, b). Uniform redistribution of diagenetic carbonate over a wide area would have had the same result. More localized carbonate redistribution would have resulted in irregular ribbon limestone or nodular argillite (Plates 5d, 8c). Authigenic dolomite crystals initiated during this stage would have continued to grow during deep burial diagenesis to produce the familiar, pervasively dolomitized argillite and dolostone interbeds and interlaminae typical of many Chancellor ribbon calcilutites (Plates 11b, d; 12a; see Coniglio and James, 1988).

4.5 CALCARENITE LITHOFACIES

4.5.1 Occurrence and terminology

The calcarenite lithofacies is a proportionately minor, but highly visible part of the Chancellor. It occurs in three main forms: (1) as sporadic, laterally continuous, medium to

¹⁴ Carbonate mud may also have been dissolved and redistributed from some calcisiltite turbidites in the manner described by Coniglio and James (1990), but the fact that the Bouma D division is gradationally succeeded by lime mud in these sediments suggests that this process was not as prevalent in the Chancellor.

thick, planar interbeds in the ribbon limestone sequences of the Tokumm and Vermilion sub-units and Takakkaw Tongue (Plates 22e, 23a); (2) as wavy to irregular beds and isolated, lens-shaped bodies in the Duchesnay and Oke units (Plates 23c, d; 24a); and (3) as megachannel fills in the Vermilion sub-unit, and to a lesser extent in the Tokumm sub-unit (Plates 21a-e, 22a-d). The last of these is the most spectacular and volumetrically significant occurrence of the calcarenite lithofacies in the Chancellor.

4.5.2 Calcarenite beds and lenses

4.5.2.1 General description

The planar, wavy, and irregular beds and lenses of calcarenite (types 1 and 2 above) are similar in terms of composition and sedimentary structures, despite obvious differences in external geometry. They are therefore described together below.

Bedding style is highly variable. Where planar bedding occurs, the calcarenite beds range from 30-100 cm in thickness, and are separated by thin (<5 cm) laminated argillites (Plate 23a, lower part of outcrop). More commonly, as typified by examples in the Duchesnay and Oke units, the calcarenite beds pinch and swell, or have highly irregular shapes (Plates 23c, d; 24a). These beds commonly range from about 10-60 cm in thickness. Calcarenite also occurs as discrete, irregular-shaped lenses, typically less than 30 cm thick and about 3 m long. The bases of the calcarenite beds and lenses are locally scoured, and load structures are ubiquitous (Plates 23c; 24a). Rarely, the calcarenite occupies broad, shallow scours several metres across. In both the Duchesnay and Oke units, individual beds and lenses are interbedded with finely laminated dolomitic argillite (Plate 23c).

The calcarenite beds are mostly massive and ungraded (Plate 23c, d). Where grading is present, it occurs either throughout the bed, or only in the uppermost few centimetres of the bed. Thicker beds commonly have scattered granule- to pebble-sized lithoclasts concentrated at their bases. Some beds are capped by horizontal laminae and, very rarely, by megaripples up to 15 cm in height.

In many beds, partial or complete Bouma sequences are developed. Both top cut-out and base cut-out sequences are present. The former are usually Bouma AB or ABC sequences, whereas the latter begin with either the B or C division. The most complete sequences grade upward into calcisiltite, and are compositionally gradational to ribbon calcisiltite (Plate 24b).

The Duchesnay and Oke calcarenite units are almost universally intraclast-peloid grainstone or packstone. Minor constituents include trilobite fragments, pelmatozoan grains, and oolites. Intraclast compositions are typically diverse (Plate 25d). The most common intraclasts are composed of dense micrite or microspar, which tend to be variably silicified and dolomitized. Peloidal grainstone intraclasts, some of which contain Girvanella tubules, are also very common. Fabric preservation is highly varied. A large number of observations confirms that a continuum of textures is present, ranging from sharply defined peloidal textures to structure grumeleuse (cf. Coniglio and James, 1985).

"Flakestones" are sporadic in the Takakkaw Tongue in the southern part of the study area (Plate 22e). They occur in sharp-based, normally graded beds, and consist mainly of tabular, variably dolomitized microspar intraclasts up to 20 mm long and 2 mm thick.

Very fine-grained calcarenite, composed of coarse silt- to very fine sand-sized grains, occurs in the Tokumm and Vermilion sub-units. The thicker beds exhibit both horizontal bedding and small-scale scours (Plate 23b). These rocks are composed of peloid packstone/grainstone, with common, scattered trilobite fragments (Plate 25b, c). The peloids range in diameter from about 40-150 microns, and are composed of micrite or microspar.

4.5.2.2 Interpretation of calcarenite beds and lenses

The calcarenite interbeds organized into partial or complete Bouma (1962) sequences are turbidites, analogous to the interbedded calcisiltite turbidites described earlier (Section 4.4.4.2). Like the calcisiltite turbidites, the calcarenite examples are interbedded with dolomitic argillite containing millimetre-scale cycles. They are inferred to be base cut-out mud turbidites (Bouma $E_{\text{turbidite}} - E_{\text{hemipelagite}}$). Very similar deposits have been documented in ancient and modern carbonate slope settings elsewhere (e.g. Cook, 1979; Cook and Mullins, 1983; Crevello and Schlager, 1980).

The massive calcarenite beds resemble, but are generally thinner than, the proximal turbidites described by many authors (Lowe, 1976a; Hiscott and Middleton, 1979; Hurst and Surlyk, 1983; Pickering *et al.*, 1986). The occurrence of ungraded sands in medium to thick, planar to irregular beds with sharp contacts is suggestive of rapid deposition following freezing of a dense, cohesionless suspension in a high-concentration turbidity current, or high fall-out rates without traction from a dense, turbulent suspension (Hiscott and Middleton, 1979; Pickering *et al.*, 1986).

Of the three sedimentary divisions described by Lowe (1982) for deposits of sandy, high-concentration turbidity currents, only the upper, or S_3 , division appears to be present in

the Chancellor. Basal traction features (S_1) and traction carpet deposits (S_2) have not been observed. The lack of water-escape features (dish and pillar structures) in the Chancellor examples may be attributed to the absence of fine-grained, interstitial sediment, or perhaps to a less forceful, upward escape of pore water during the final stage of deposition (Walker, 1978). Residual turbidity currents remaining after deposition of the coarser-grained suspended sediment load may well have been the primary source for the closely associated calcarenite and calcisiltite turbidites exhibiting partial or complete Bouma (1962) sequences (see Lowe, 1982). Reworking by residual flows probably also accounts for the occurrence of traction structures (primarily horizontal lamination and rarely megaripples) at the tops of some massive calcarenite beds (cf. Hiscott and Middleton, 1979).

4.5.3 Calcarenite megachannel fills

4.5.3.1 Megachannel anatomy

Calcarenite-filled megachannels are one of the most spectacular features in the Chancellor. They stand out on valley walls by virtue of their large size and light colour (Plate 44). Most "megachannel calcarenites" are in the Vermilion sub-unit, but probable dolomitized examples also occur in the Tokumm sub-unit.

The megachannels have various dimensions. The largest observed examples occur in the Vermilion sub-unit along Prospectors Valley (sections 11, 30; Fig. 2). The lowest megachannel traversed by section 11 is at least 23.5 m thick, and approximately 180 m wide (Plates 21a, 44). The composite body traversed by section 30 is at least 33.5 m thick, and has an exposed width of about 200 m. Assuming the feature is symmetrical, its total width is probably about 400 m. Elsewhere in these sections and other sections, there are smaller, channellized calcarenite bodies with thicknesses of 1-7 m and widths of a few tens of metres.

The megachannels have convex-downward bases and generally flat tops (Plate 21a). Their sides have a maximum inclination of about 20°, and are oriented approximately SSW-NNE (i.e. roughly parallel to regional paleoslope). As the megachannels have been observed only in two dimensional strike section, their geometry in the third dimension is uncertain.

The megachannel in section 11 has a pronounced keel (Plate 21a). Laterally, the megachannels wedge out rapidly into the surrounding argillaceous sediments (Plate 21b). The argillite beds beneath the megachannels are surprisingly undeformed, and were apparently rather cohesive at the time of channel emplacement. This is clearly shown by centimetre-scale, erosional irregularities in the megachannel base. These features cut up and down through the argillite without visibly disturbing the fine laminae. Locally, however, the argillite is squeezed upward into small irregularities in the megachannel underside, forming small flame structures. Minor deformation is also visible in the argillite beneath the lip of the channel margin (Plate 21b). Surprisingly, very few argillite intraclasts line the megachannel base.

Local sculpting has also been observed along the flat tops of megachannels. This suggests early lithification of the calcarenites, which were subsequently subjected to minor erosion prior to deposition of the succeeding argillite unit.

4.5.3.2 Internal channel anatomy

The megachannels contain a complex fill of broadly channellized calcarenite bodies, which are locally separated by laminated argillite. These bodies are typically amalgamated where the intervening argillites have been eroded. Individual calcarenite

bodies range from 0.25 to 9 m thick, and as many as 13 have been identified in a single megachannel. They are rarely associated with small periplatform talus blocks and thin (<1 m), channellized, clast-supported conglomerates. The intervening argillites are generally less than 5-10 cm thick.

The calcarenite bodies have broad, concave-upward bases, which truncate the underlying calcarenite bodies at low angles. These truncations are often subtle, but amalgamated bodies can usually be differentiated by grain size differences or other physical changes (Plates 21d, 22a). In detail, most erosion surfaces have centimetre-scale irregularities (Plate 22a).

Due to this progressive, low-angle truncation by broadly curved erosional surfaces, the calcarenite forms elongate, laterally tapering bodies up to several tens of metres wide (Plate 21c). Internal laminae generally parallel the bases and sides of these features.

Individual calcarenite bodies are usually composed of alternating, diffuse layers of coarser- and finer-grained calcarenite. The coarser layers are massive, and range from 2-50 cm thick. Most are less than 20 cm thick. Some are normally graded over their total thickness, but most appear to be ungraded (Plates 21e; 22b, c).¹⁵ Fluid escape features have not been observed. The calcarenite is poorly to moderately sorted, and commonly fine- to medium-grained. Subordinate coarse sand- to granule-sized grains are also typical. Steeply inclined intraclasts are present at the bases of some coarse layers.

¹⁵ Grain size trends are difficult to see on weathered surfaces in the field. If subtly expressed over a narrow range of grain sizes, they might be missed. Slabs are notoriously difficult to obtain due to the massiveness of these rocks. Hence, subtle inverse or normal grading may have been missed in the field descriptions.

The finer-grained layers are composed mainly of fine-grained carbonate sand, and tend to weather out slightly in relief (Plates 21d; 22b, c; frontispiece). They are typically 0.5-2 cm thick, and usually exhibit horizontal, sometimes rather crudely developed laminae (Plates 21e; 22a, b, c). Unlaminated or very vaguely laminated layers are also common. Rarely, ripple troughs are also preserved in these layers (Plate 22b).

Many of the contacts between the finer and coarser layers are obscured by selective dolomitization. Where visible, the contacts are usually rapidly gradational (Plate 22c). Obvious, sharp, scoured contacts are uncommon, except at amalgamation surfaces between calcarenite bodies.

In the thinner calcarenite bodies, there are no clear-cut thickness trends in the coarser and finer layers. In some of the thicker bodies, however, there is a definite thinning-upward trend from decimetre- to centimetre-scale alternations of the coarser and finer layers (Plate 21d).

4.5.3.3 Thin section petrography

The calcarenites are almost universally grainstones containing ooliths, peloids, intraclasts, and bioclasts (trilobite fragments, phosphatic brachiopod fragments, and pelmatozoan plates) in any proportion (Plate 24c, d). The grains typically have isopachous columnar calcite fringes, and the remaining pore space is filled with drusy mosaics of equant calcite spar. Well preserved cements are less common in the Duchesnay unit calcarenite.

The peloids are usually composed of dense micrite, and are spheroidal, ellipsoidal, or elongate.¹⁶ Some calcarenite beds are composed entirely of moderately to well sorted, coarse silt- to fine sand-sized peloids (Plate 25b, c). Fabric preservation varies, and transitions from obvious peloidal to structure grumeleuse textures can sometimes be seen in a single thin section.

The larger intraclasts exhibit a variety of textures (Plates 24d, 25d). Many of the tabular intraclasts are composed of uniform micrite or microspar. Oolitic or peloidal grainstone intraclasts are also common. Epiphyton boundstone intraclasts and intraclasts containing abundant Girvanella are locally recognizable. Commonly, however, original fabrics are obscured by poor preservation, dolomitization, and/or silicification. For example, selective replacement by ferroan dolomite is common (Plate 24c, d).

In the Duchesnay unit, dolomitic intraclasts containing siliclastic silt are quite common. Many are composed of cloudy core, clear rim (CCCR) dolomite with ferroan rims. If the spherical to oval, cloudy cores observed in most of the dolomite crystals were originally peloids (see Coniglio and James, 1988), these intraclasts may have originally been silty, peloidal grainstones.

Observations of a large number of intraclasts confirm the suggestion by Coniglio and James (1985) that many examples of structure grumeleuse can be attributed to variably preserved Girvanella fragments and tubules. Many of the silt-sized grains (<30-50 microns) in peloidal grainstone intraclasts can also probably be attributed to this source. However, structure grumeleuse can also result from poor preservation of coarse silt- to very fine sand-

¹⁶ This thesis uses the size classification of Coniglio and James (1985), who placed the size boundary between peloids and micritic intraclasts at 0.5 mm.

sized peloids. The origins of these larger peloids are uncertain. Many in the 40-80 micron range may have been contributed by fragmentation of Epiphyton branches (cf. Coniglio and James, 1985). Others may be fecal pellets. Alternative origins of this fabric have been discussed by Bathurst (1975).

Dolomitized zones are very common in the megachannel calcarenite (Plates 21e; 22c). Most are parallel to primary layering, although irregular or cross-cutting zones have also been observed (Plate 22d). Typically, the dolomitized zones are located along sedimentological discontinuities, especially the contact between the coarser and finer calcarenite layers. The dolomitic zones are composed mainly of CCCR dolomite with ferroan dolomite rims (Plate 25a). Some crystals contain oval- or rhomb-shaped cores, but most cores are irregular to diffuse. The dolomite crystals truncate both the grains and the pore-filling cement, indicating that dolomitization post-dated cementation. In the thicker dolomitic zones, scattered peloid ghosts and, rarely, incompletely dolomitized remnant peloids are visible.

4.5.3.4 Interpretation of megachannel calcarenites

Interpretation of the megachannel calcarenites must take into account the following features: (1) the stacked, broadly channellized calcarenite bodies, which are either amalgamated or locally separated by laminated argillite; (2) the alternating coarse, massive calcarenite layers and fine, horizontally laminated calcarenite layers within individual calcarenite bodies; (3) the common gradational contacts between the coarser and finer layers; and (4) the observed thinning-upward trends in layer thickness. On a broader scale, the interpretation must also take into account the sedimentological setting and possible origin(s) of the megachannels themselves.

The megachannels are features of the upper slope. Although the platform margin is not preserved near the principal exposures of these features on the southwest wall of Prospectors Valley (Plate 44), exposures of equivalent platform rocks on the opposite (northeast) side of the valley indicate that the margin was located at or just northeast of the present-day valley axis. The megachannels developed no further than 2.5 km basinward of this projected trend. Assuming a moderately steep slope like those flanking the present-day Bahamas (4° - 9° ; Schlager and Chermak, 1979; Mullins *et al.*, 1984), the channels were probably situated at water depths of about 175-400 m.

The currents that deposited most of the stacked calcarenite bodies were only capable of scouring out broad, shallow depressions several tens of metres across and a few metres deep. They clearly were not responsible for excavating the megachannels themselves. This situation is analogous to underfit streams in glacial valleys.

Gullies in the slopes bordering the Tongue of the Ocean are comparable in size to the megachannels, and have been attributed to erosion by turbidity currents (Schlager and Chermak, 1979; Hooke and Schlager, 1980). However, the absence of coarse lags and the overall, smooth morphology of the megachannels is not compatible with current erosion on the scale indicated.

A simpler explanation is that the megachannels originated from synsedimentary sliding, and were subsequently modified, and eventually infilled, by sediment-laden turbidity currents. This mechanism has also been proposed for the initiation of similar, though larger scale (1-3 km across, 50-150 m deep) gullies in the northern Little Bahamas slope (Mullins *et al.*, 1984). Although the Chancellor megachannels have not been observed in three

dimensions, their cross-sectional profiles and wall angles are compatible with known slide scar morphologies (Jacobi, 1984). Cohesiveness of the surrounding argillite would have been instrumental in maintaining the overall shape of the slide scar until it was infilled by calcarenite, thus explaining the lack of secondary failures along its margins.

The infill of a megachannel by shallow-water-derived oololiths, peloids, intraclasts and skeletal material is evidence that the slide scar not only cut back into the uppermost slope, but probably into the platform margin as well. It will be suggested later in this thesis that the margin was composed of two, parallel belts: an outer belt of Epiphyton buildups, and an inner belt of carbonate sand shoals. The lack of Epiphyton boundstone blocks in the megachannel fills, except very locally, suggests that the outer belt was carried away by the original slide, allowing carbonate sand to feed directly into the mouth of the slide scar (Fig. 19).

The megachannels were the main conduits for carbonate sand bypassing the upper slope. The situation may have been analogous to that prevailing today on the slope bordering northern Little Bahama Bank. There, sand-sized and larger particles are transported platformward, as the margin is situated in a windward setting. The adjacent slope receives predominantly bank-derived lime mud carried seaward by storm and tidal currents, together with minor pelagic sediment. Platform-derived sand bypasses the upper part of the slope via a series of gullies, and is deposited as turbidites on the lower slope apron (Mullins and Neumann, 1979; Mullins *et al.*, 1984).

The internal anatomy of the megachannels clearly indicates pulses of carbonate sand transport separated by quiescent periods of terrigenous mud turbidite deposition. The currents carrying each sediment pulse broadly scoured the substrate, and deposited a series of

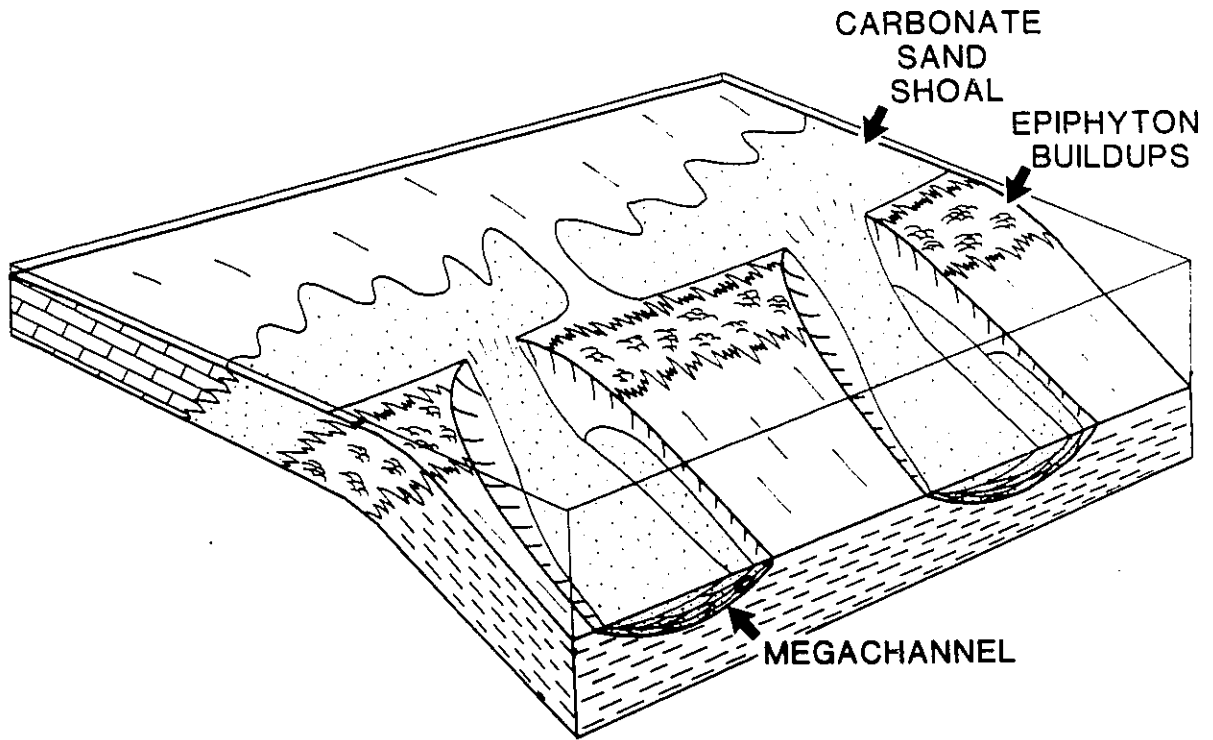


Figure 19. Origin of calcarenite-filled megachannels by deposition of broadly channellized calcarenite bodies in slide scars cut into the upper slope during Vermilion sub-unit time.

stacked carbonate sand bodies. The "keel" at the base of the lower megachannel in section 11 (Plate 21a) was probably excavated by the first current to enter the slide scar.

The calcarenite fill in the megachannels is inferred to have been deposited by high-concentration turbidity currents, like those that deposited the individual calcarenite beds and lenses in the Duchesnay unit (Section 4.5.2.2). However, the alternating massive and laminated calcarenite layers record additional processes not documented elsewhere in the Chancellor. Also, the thinning-upward trends seen in the thicker calcarenite bodies require an explanation.

The massive, generally ungraded coarser layers resemble the S₃ divisions of sandy, high-concentration turbidity flow deposits (Lowe, 1982). They are, however, much thinner than the massive sandstones found in many "proximal" turbidites (Walker, 1978; Hiscott and Middleton, 1979; Lowe, 1982). Deposition of each massive layer by rapid, suspended load fallout was followed by deposition of a laminated layer during a short-lived period of traction deposition. This may reflect the transition of the high-concentration turbidity current into a low(er)-concentration flow due to flow deceleration.

The reasons for the repeated interlayering of the massive and laminated layers and the observed thinning-upward trends are less clear. Two possible mechanisms will be discussed below: surging, decelerating flows, and retrogressive sliding.

Lowe (1982, p. 290) postulated that surging, high-concentration turbidity currents are likely to produce repetitions of grading and structure divisions. Surging flows show an oscillating decline in velocity, competence and capacity, with each surge being characterized by lower maximum and minimum velocities than its predecessor. This process could

account for the thinning-upward sequences observed in some calcarenite bodies. Thus, each body could represent the deposits of a single, large, high-concentration turbidity current. A progressive decline in velocity maxima and minima during oscillatory flow deceleration would result in the deposition of progressively thinner (and presumably finer-grained) S₃-T_b couplets.

According to Lowe (1982), each oscillation commences with an abrupt velocity increase, followed by a gradual deceleration. The fact that many upward transitions from laminated to massive bands appear to be rapidly gradational (*i.e.* they exhibit a rapid, upward coarsening; see Plate 22c) suggests that this abrupt velocity increase can enhance the competence of the flow without incurring scour.

An alternative explanation for the internal anatomy of the calcarenite bodies is retrogressive failure at the head of the slide scar. This mechanism has been invoked by Pickering (1979) to explain thinning-upward trends in certain turbidite packages in the Precambrian of Norway.

It was suggested earlier that the original slide scar cut back into the platform margin to tap an inner belt of carbonate sand shoals (Fig. 19). Unusual sand shoal migration, such as during infrequent, intense storms, may occasionally have heaped up large quantities of sand around the margin of the slide scar. Instability of the shoal margins due to oversteepening, or external factors such as storm current or wave attack, could initiate failure and a sudden release of carbonate grains downslope. Continued retrogradational failures of progressively declining size could conceivably continue until the shoal margin regained a stable profile.

Retrogradational failure of this type would generate a series of sand pulses that would evolve downslope into high-concentration turbidity flows of progressively declining capacity and competence. During initial steady flow, the first (and presumably largest) high-concentration turbidity current would scour out a broad, erosional trough prior to depositing a massive S_3 sand. During the subsequent, short-term traction stage, finer-grained sediments would be deposited. Deposition of other traction structures would be prevented by the arrival of the next sand pulse, and the sequence of events just described would be repeated. As in the case of surging flows, the successive, abrupt increases in current velocity would not necessarily be accompanied by scour. A progressive decrease in competence and carrying capacity of the turbidity currents would result in a series of thinning- and fining-upward S_3 - T_b couplets.

In summary, the megachannels are probably slide scars that removed a portion of the upper slope and outer platform margin. Once formed, they acted as conduits for the transport of carbonate sand from the inner platform margin to the lower slope. Periodic influxes of carbonate sand at the mouth of the slide scar evolved into high-concentration turbidity flows downslope. Initially, each flow scoured out a broad, shallow channel. A series of S_3 - T_b couplets was subsequently deposited, reflecting surging of a very large, declining flow, or perhaps a series of small flows generated by retrogressive failure of the sand shoal at the mouth of the scar. Siliciclastic mud turbidites were subsequently deposited under relatively quiescent conditions until the next influx of carbonate grains. Successive calcarenite bodies were stacked in this manner, until the megachannel was eventually filled.

4.6 CONGLOMERATE LITHOFACIES

4.6.1 Occurrence and terminology

Limestone conglomerates stand out as massive, resistant, light grey-weathering bodies against a background of thin-bedded, darker grey carbonate rocks or massive, brown-weathering, argillaceous rocks (Plates 11a; 26a, b; 27d; 28b, d; 30d; 52-54). They are most abundant in the Vermilion sub-unit, Duchesnay unit, and Takakkaw Tongue (Fig. 16).

The limestone **conglomerates** contain granule-, pebble-, cobble- and boulder-sized clasts in a muddy or grainy, usually dolomitic matrix. **Megaconglomerates** contain a conspicuous proportion of platform-derived clasts larger than 1 m in diameter, but are similar in other respects to the limestone conglomerates.

The Chancellor megaconglomerates closely resemble the megabreccias and megaconglomerates described in similar sedimentological settings elsewhere in the Cordillera by Cook *et al.*, (1972), in the southern and northern Appalachians by Read and Pfeil (1983), Hiscott and James (1985), and James and Stevens (1986), and in the southwestern United States by Kepper (1981). In all of these areas, these spectacular sedimentary deposits have provided valuable clues for reconstruction of the ancient platform margins from which they were derived.

4.6.2 Clast types

Conglomerate clasts are either slope-derived or platform-derived ("exotic"). The slope-derived clasts were eroded from ribbon limestone or argillite sequences, and thus are generally thin and platy. Exotic blocks, on the other hand, commonly stand out as light grey-

weathering, massive bodies consisting of algal boundstone or calcarenite. The major clast types are described below, following the nomenclature used by James and Stevens (1986).

Limestone plates are slope-derived, tabular clasts of dark grey lime mudstone. The clasts have lengths up to 25 cm, and thicknesses in the range of 1-3 cm. They are petrographically identical to the lime mudstone interbeds in the ribbon calcilutite lithofacies. The same is true of the dark grey, lime mudstone chips (see below). Both were undoubtedly eroded from precursor ribbon calcilutite sequences.

Rafts are metre-scale clasts of ribbon limestone or argillite that were transported downslope as coherent blocks. Some are internally deformed, whereas others show no evidence of soft sediment deformation. Rafts occur rarely in Chancellor conglomerates, but where observed, range up to 3 m long and 1 m thick.

Limestone chips are pebble-sized clasts ranging from about 1-6 cm long, and 1-3 cm thick (Plate 27b, c). Rock-types include light or dark grey lime mudstone, wackestone, calcisiltite, calcarenite, and occasionally algal boundstone. With the exception of the last rock-type, the chips were derived from a variety of thin-bedded limestones, and may have been slope- or platform-derived. The grainy varieties contain any proportion of peloids, intraclasts, bioclasts and ooliths. The intraclasts range in composition from lime mudstone, through peloidal packstone and grainstone, to oolitic grainstone (Plate 32c, d, e). Intraclast fabric is variable due to the effects of dolomitization and/or silicification (the latter being very common in the Duchesnay unit). Otherwise, the intraclasts are petrographically identical to those described earlier in the calcarenite lithofacies (Section 4.5.3.3).

Other slope-derived clasts include argillite and argillaceous limestone, which generally show evidence of synsedimentary deformation. Silty argillite and argillaceous siltstone clasts are also common in the Duchesnay unit.

Exotic (platform-derived) boulders are sub-equant to elongate, rounded to sub-angular bodies of light to medium grey-weathering limestone. Most of these boulders measure 1-5 m in maximum dimension. Examples up to 30x50 m have been observed in the Vermilion sub-unit (Plates 27e, 53).

In the field, most exotic megaclasts appear to be composed of light grey-weathering, structureless lime mudstone. Many are characterized by numerous, small (<1 cm), irregular-shaped, orange-weathering splotches. These are primary growth cavities that were partially or wholly infilled by ferroan calcite or dolomite. Rarely, the cavities contain micrite or calcarenite intraclasts, peloids and ooliths. Some megaconglomerates also contain medium grey-weathering megaclasts, which invariably turn out to be calcarenite.

The exotic megaclasts are composed of algal boundstone or calcarenite. The calcarenite megaclasts are usually grainstones and packstones identical to the limestone chips. The boundstone megaclasts are composed predominantly of Epiphyton, and some contain minor Girvanella and/or Renalcis. The taxonomic affinities of these forms are uncertain, and they are now conveniently referred to as "calcified microbial microfossils", or "calcimicrobes" (James and Gravestock, 1990).

The Epiphyton boundstones contain variously preserved Epiphyton, ranging from well-defined, bush-like features (Plate 31a) to a series of long branches with a strong, preferential alignment (Plate 31c). The former growth habit is comparable to that in the Cow

Head Group of western Newfoundland and Shady Dolomite of Virginia (James, 1981; Read and Pfeil, 1983). The latter growth habit resembles the "flat-lying growth form" described by Read and Pfeil (1983), although no geopetal sediments are available to determine original growth orientation.

The Epiphyton thalli are composed of dense micrite, and are typically 40-60 microns in diameter. No chambers or segmentation have been observed. In well preserved examples, the "interbush" space is partially to completely filled with cloudy, fibrous, non-ferroan calcite (Plate 31d). The interbranch space is occupied by similar fibrous cement, or by microspar. Large, primary growth cavities usually contain a second generation of non-ferroan, equant calcite. Coarsely crystalline, equant ferroan calcite commonly completes the cavity fill (Plate 31a), and is commonly replaced in whole or in part by ferroan dolomite.

Geopetal sediment has not been observed in any of the well preserved Epiphyton boundstone. Due to commonly poor fabric preservation, it may well have gone unrecognized in the other megaclasts studied. Thus, the original growth orientation of the Epiphyton is uncertain.

Renalcis occurs as variously preserved clumps of micrite-walled lunules in a small number of megaclasts (Plates 31e; 32a). Typically, it is found in growth cavities in Epiphyton boundstone, and is surrounded by fibrous cements.

Girvanella occurs rarely in the megaclasts, but its relative importance is probably underestimated due to poor preservation. Only one megaclast could be demonstrated to contain arcuate Girvanella sheets with attached Epiphyton clumps like those described by James (1981) in the Cow Head Group. In that example, the sheets are widely separated by

arcuate to irregular, primary growth cavities with arcuate to irregular shapes. The cavities are as much as 3 mm across and 10 mm wide, and almost completely infilled by non-ferroan, fibrous calcite cement.

4.6.3 Conglomerate matrix

Matrix dolomitization is generally so pervasive that it is difficult or impossible to decipher primary matrix compositions. Pervasively dolomitized examples are usually replaced by silt-sized rhombs of ferroan dolomite, but matrices composed mainly of non-ferroan dolomite with ferroan rims also occur (Plate 32b). Where the composition of the original matrix can be observed or inferred, it is one of three types: (1) terrigenous mud (argillite); (2) lime mud; and (3) calcarenite. The cutoff for differentiating clasts from matrix is arbitrarily set at 1 mm.

Terrigenous mud matrices are probably the most prevalent, especially in the megaconglomerates. Field observations suggest that, as in the case of the dolomitic interbeds in ribbon calcilutites, a complete compositional spectrum is present from essentially pure argillite, to variously dolomitized argillite, to argillaceous dolostone, to essentially pure dolostone. At least part of the argillaceous matrix was derived from underlying argillites and ribbon limestones, as indicated by injection structures at the bases of many megaconglomerates (Plates 26c, 29c). All stages of incorporation of limestone clasts and interbedded argillaceous material have also been observed where ribbon calcilutites have been injected into the base of a flow.

Primary lime mud matrices are generally preserved as microspar or pseudospar mosaics. This type of original matrix can often be inferred in heavily dolomitized examples

by the presence of relict microspar or pseudospar patches (Plate 32b). The argillaceous coatings on the dolomite crystals in these examples suggest that the lime mud was originally argillaceous.

Grainstone matrices are common in many of the thinner conglomerate units (Plate 30b). Grain types include ooliths, bioclasts (mostly trilobite debris), and a variety of intraclasts. The interparticle cement is commonly partly or wholly replaced by ferroan dolomite (Plate 32c).

4.6.4 Conglomerate fabric

The limestone conglomerates are typically massive and ungraded (Plates 26c; 27a-c; 30a, b, e). Clasts are either chaotically oriented, or lie subparallel to bedding. Local domains of imbricated clasts can sometimes be identified. Several examples are clast-supported near the base, and become matrix-rich upward (Plate 27c). The proportion of matrix varies greatly, both between and within flows. In some clast-supported conglomerates, the matrix is only visible as a rind around the clasts, and constitutes no more than 10-15% of the rock (Plates 27a, b; 29d). In extreme cases, the matrix is barely discernable, particularly if it has been selectively removed by pressure solution. Matrix-supported conglomerates are less common. Their matrix is always muddy, and constitutes more than 30% of some examples.

4.6.5 Conglomerate classification

Four types of conglomerate can be differentiated on the basis of clast type, matrix composition, fabric, and unit thickness. Three of these resemble the conglomerate types

described by Hiscott and James (1985) and James and Stevens (1986) in the Cow Head Group.

Grainy matrix conglomerate generally occurs in beds less than 1 m thick. It contains various types of limestone chips and occasionally limestone plates (Plate 30b). The matrix is a mixture of grainy and muddy intraclasts, together with ooliths, peloids, and bioclasts. Interparticle space is filled by a drusy mosaic of equant calcite spar. No sedimentary structures have been observed, and the deposits are ungraded. Calcarenite caps have only been observed locally.

Limestone plate conglomerate is oligomictic, and typically occurs in units less than 2 m thick. It is composed of poorly sorted lime mudstone plates, set in a dolomitic argillite or argillaceous dolostone matrix. The conglomerate has a chaotic fabric, and is mostly clast-supported. Pure limestone plate conglomerate is relatively uncommon. Most units contain at least some limestone chips and blocks of other compositions (Plate 27a), reflecting contamination by periplatform debris from the nearby platform margin. These are termed "**mixed clast conglomerates**" (Plate 27a, c).

Limestone chip conglomerate is usually polymictic and clast-supported, and units range from 10 cm to about 2 m in thickness. The limestone chips are set in a dolomitic argillite or argillaceous dolostone matrix. The clasts are either chaotically arranged, or lie subparallel to bedding. Some units contain a few periplatform blocks up to 2 m in size. Exceptionally, these flows were capable of freighting outsized megablocks up to 10-20 m in diameter (Plates 26a, b; 28a).

Megaconglomerate occurs in units 2-15 m thick. Amalgamated examples up to 34 m thick occur at the top of the Vermilion sub-unit (section 9; Appendix 2). The megaconglomerate units are always polymictic, and contain, in addition to the periplatform megaclasts, a variety of slope- and platform-derived limestone chips, plates, and blocks (Plate 29d, e). Most examples are clast-supported, and have matrices of variously dolomitized argillite.

4.6.6 Bed geometry and lateral extent

Most conglomerate units (excluding megaconglomerate) are less than 2 m thick. Thicker examples are usually composed of two or more amalgamated flows. Individual conglomerate units can commonly be traced at least a few tens of metres along depositional strike. Some form a series of discontinuous, decimetre-scale lenses at the same stratigraphic horizon.¹⁷ These are inferred to be fingers of debris projecting out of a single flow (cf. Hiscott and James, 1985).

The conglomerate bodies are generally parallel-sided, and have flat to somewhat irregular tops and relatively flat bases (Plates 11a; 30e). The underlying sediments commonly show evidence of soft-sediment shearing (Plate 30c) or brecciation. Some conglomerate occupies broad, shallow channels several tens of metres wide. Where seen, the lateral margins of all these flows are abrupt and tapered (Plate 30a).

The megaconglomerate occupies broad channels up to 150 m wide (Plate 28d). These channels are similar in scale and cross-sectional profile to the calcarenite-filled megachannels described earlier, and probably have the same origin. In longitudinal profile,

¹⁷ Good examples of these are exposed in the Tokumm sub-unit in the cliffs overlooking Marble Canyon (Fig. 5).

the megaconglomerate units are downslope-tapering wedges measuring hundreds to perhaps thousands of metres in extent (Plates 52, 53). They have abrupt, lateral margins. The tops of these features tend to be highly irregular due to upward-projecting megaclasts (Plates 28c; 53). Clearly, the megaconglomerate bodies had considerable relief on the sea floor.

Amalgamated conglomerates can usually be recognized by abrupt, internal changes in clast and matrix composition or clast size. Thin, relict argillites or ribbon limestones are preserved locally along these discontinuities.

4.6.7 Interpretation of conglomerate lithofacies

With the exception of the grainy matrix conglomerate, the Chancellor conglomerates were deposited by debris flows. High matrix strength is indicated by: (1) the abrupt, tapered margins; (2) the presence of blocks projecting from the top of some flows; and (3) the ability of the flows to transport oversized clasts, often with diameters many times the thickness of the units in which they are embedded. Other evidence compatible with a debris flow origin includes: (1) the lack of an organized clast fabric, as indicated by poor sorting and a lack of grading and stratification; (2) the incorporation of penecontemporaneously-deformed material; and (3) the essentially planar bases exhibited by most of the thinner (<2 m) examples (cf. Cook *et al.*, 1972; Middleton and Hampton, 1976; Ineson, 1980; Kepper, 1981; Hurst and Surlyk, 1983; Hiscott and James, 1985). The lack of matrix support in most of the conglomerates is attributed to the fact that very little clay-water matrix (1-5%) is required to provide buoyant lift and lubricate the grains in poorly sorted debris flows (Rodine and Johnson, 1976; Lowe, 1982 and references therein).

The grainy matrix conglomerates share many of the attributes of limestone chip conglomerates, but there is no evidence of a primary muddy matrix. The grainy matrix in these conglomerates indicates deposition by cohesionless flows. The clasts may have been supported by the buoyant lift of a dense, but cohesionless silt-sand suspension in a density-modified grain flow. The lack of normal or inverse grading suggests that the flow had little size-sorting capability, and that dispersive pressures were low (Lowe, 1976b). Alternatively, these conglomerates could have been deposited by gravelly, high-concentration turbidity flows, similar to those responsible for deposition of the massive calcarenite beds.

4.7 PERIPLATFORM TALUS AND OTHER SLIDE BLOCKS

Isolated periplatform talus blocks occur sporadically in the Tokumm and Vermilion sub-units and Takakkaw Tongue. Wedges of periplatform debris also occur in the Takakkaw Tongue (Cathedral megabreccia; Plates 40, 41) and Vermilion sub-unit (Plate 54). These are thought to have accumulated by rockfall at the bases of slide scar headwalls, and will be described further in sections 5.3.3 and 6.2.3.

The periplatform blocks are identical in size, shape and petrography to the megaconglomerate megaclasts described earlier (Plate 33). Measured examples range up to 14.5 m in diameter. Some of the megablocks seen in mountain wall exposures of the Vermilion sub-unit have maximum dimensions of about 50-120 m (Plates 33d; 44; 45)

Commonly, there is surprisingly little deformation of the sediments underlying these blocks (Plate 33a). However, some of the periplatform blocks appear to have plowed up their substrates, which became chaotically deformed and sometimes disaggregated to

produce debris flow-like textures. Some periplatform blocks are incorporated in chaotically deformed units that appear to be slide masses.

Most isolated periplatform blocks were probably deposited by rockfall from the platform margin. It is conceivable, however, that some are stranded blocks left by passing debris flows, which were unable to maintain sufficient matrix strength due to dilution or other factors (see Middleton and Hampton, 1976).

Slope-derived slide blocks are comparatively rare. Argillite slide blocks tend to be internally deformed. Ribbon calcilutite slide blocks exhibit little deformation, indicating early lithification in the shallow subsurface (Plate 13e). These blocks were derived from small sediment failures higher on the slope.

4.8 SHALLOW-WATER LITHOFACIES

4.8.1 Introduction

Rocks of shallow-water origin are exposed along the northeastern margin of the study area, and have been traversed by many of the stratigraphic sections measured for this thesis. The Cathedral, Stephen and Eldon formations were encountered in Prospectors Valley and other valleys along strike (sections 20, 21, 18, 17, 10, 9, 34, 28; Fig. 2), as well as near Field (sections 31, 25), Mount Assiniboine (sections 14, 15) and Miller Pass (section 12). Succinct descriptions of the various shallow-water lithofacies on the platform have been provided by Aitken (1966 and in press, a). The brief descriptions that follow are based partly on Aitken's work, and are supplemented by the writer's observations.

4.8.2 Burrow-mottled and burrow-stratified limestone lithofacies

4.8.2.1 General description

Burrow-mottled limestone forms thick-bedded to massive units, in which resistant, orange-brown to dark grey-brown dolomite mottles and burrow tubes stand out in relief against a smooth, grey-weathering limestone background (Plate 34a, b). **Burrow-stratified limestone** resembles burrow-mottled limestone, but the mottles are distinctly bedded (Plate 34c). These two rock-types are prominently exposed in the lower Eldon Formation along Misko and Prospectors valleys (sections 9, 10, 17, 18, 20, and 21; Appendix 2).

All burrow-mottled and burrow-stratified limestones contain a significant proportion of lime mud, now aggraded to microspar. Disseminated dolomite crystals are always present, and some examples are pervasively dolomitized. Rock types range from lime mudstone and wackestone to peloidal packstone. The peloidal packstone has variously preserved fabrics (Plate 35a). The major allochems in these rocks are scattered trilobite fragments, rare pelmatozoan fragments, Girvanella tubules, and silt-sized peloids (Plate 34e). The peloids were assumed by Aitken (in press, a) to be fecal pellets, but they almost certainly include, or may even be predominantly calcimicrobe fragments (poorly preserved Girvanella and Epiphyton).

The dolomite mottles consist of sucrosic ferroan dolomite. Non-ferroan dolomite is less common. Much of the dolomite occurs in irregularly shaped blobs and clusters of blobs several centimetres across (Plate 34b). Closer inspection sometimes reveals irregular dolomitic networks. Some well defined, locally branching tubes less than a centimetre in diameter are visible (Plate 34a). They lie sub-parallel to bedding, and are dwelling and feeding burrows (Aitken, in press, a). The sub-horizontal, irregular networks are probably

Thalassinoides, whereas the sub-horizontal, cylindrical burrows are probably Planolites. The spectrum of ichnofabrics in these rocks strongly resembles that described by Droser and Bottjer (1988) in Cambrian platform strata of the Great Basin.

In the burrow-stratified limestones, the ichnofossils are confined to particular stratigraphic units (Plate 34c). As the burrowing intensity increases, the ichnofabric approaches that of burrow-mottled limestones. The burrow-stratified limestones observed in the study area are probably transitional to the parted lime mudstone lithofacies described by Aitken (1966, in press, a).

Small-scale cycles containing burrow-stratified and burrow-mottled limestones are exposed in the upper Duchesnay unit near Hamilton Lake (Plate 34d; Fig. 4). The cycles range in thickness from about 1 to 14 m, with most in the 3-6 m range. They are analogous, in scale and composition, to the "clearing upward" cycles described by Aitken (in press, a) in the Pika Formation. At Hamilton Lake, complete cycles are characterized by: (1) a sharp, planar base, overlain by nodular argillite (usually dolomitic) with bedding planes exhibiting horizontal and vertical burrows; (2) burrow-stratified limestone; and (3) burrow-mottled limestone. Thin (<10 cm), intraclast-oolith grainstones can occur at any level within a given cycle.

4.8.2.2 Interpretation

In the Cathedral, Eldon and Waterfowl formations, burrow-mottled limestones form thick, non-cyclical sequences, and are inferred to have been deposited below fair-weather wave base in a subtidal environment (Aitken, 1978, 1989, in press, a; Waters, 1986). They are commonly associated with flat-pebble conglomerates and skeletal calcarenite lenses,

which were probably introduced by storms. Burrow-mottled limestone sequences containing interbedded cryptalgal laminite probably accumulated in shallower environments (Aitken, oral communication, 1991). The detailed sedimentology of this lithofacies remains to be documented.

Aitken (in press, a) suggested that the small-scale cycles in the Pika Formation were shallowing-upward cycles, based on their similarity to complete shallowing-upward cycles in the Stephen Formation. The same interpretation is applied here to the small-scale cycles exposed at Hamilton Lake.¹⁸ The ichnofabric of the burrow-stratified limestones suggests an impoverished ichnofauna, which may reflect lower oxygen levels. With progressive shallowing, bottom conditions ameliorated, and a more abundant ichnofauna became active. Thus, a burrow-mottled texture was produced in the upper part of the cycle. A subsequent, abrupt return to deep-water conditions temporarily shut down the carbonate factory, leading to renewed terrigenous mud deposition and the start of a new cycle.

4.8.3 Fenestral lime mudstone

Fenestral fabrics are common in Kicking Horse Rim exposures of the Cathedral, Eldon and Pika formations at The Monarch (section 28) and Verdant Headwaters (vicinity of sections 33, 34). These rocks have been fully dolomitized, and are accordingly termed "fenestral dolostone".

Limestone with identical fenestral textures has been documented elsewhere on the platform by Aitken (in press, a), who noted a common association with cryptalgal laminite

¹⁸ It must be emphasized, however, that unequivocal evidence of upward shallowing is lacking, and purely environmental controls (e.g. degree of terrigenous input controlled by climatic changes) may have played a role.

and "pale-pellet" grainstone.¹⁹ According to McIlreath (1977a), the protoliths for fenestral dolostone behind the Cathedral margin on Mt. Field (section MJA-722, Fig. 3) ranged from lime mudstone to peloidal packstone. Some of the examples in the study area may originally have been grainstone, but textures are too poorly preserved for positive identification.

The fenestral dolostone contains white dolomite blebs (the fenestrae) in a dark grey-weathering matrix (Plate 35b). The fenestrae range from 1-5 mm in length. Longer examples appear to be composites of two or more fenestrae.

The fenestral dolostone presumably formed in the upper intertidal and/or supratidal zone. This is supported by an association with thin, cryptalgal laminite (Aitken, 1967) and occasional stromatolitic units. Some of the thicker, ex-grainstone units with irregular fenestral textures possibly had a subtidal origin (see Shinn, 1983).²⁰

4.8.4 "Yoholaminites" and associated sediments

The name "Yoholaminites" refers to what was originally thought to be a cryptic, organosedimentary structure characterized by light grey to white dolomite with fine, chevron-kinked laminae (McIlreath and Aitken, 1976; McIlreath, 1977a; Aitken, in press, a). It is reported to occur immediately platformward of the Cathedral Escarpment on Mt. Field and Mt. Stephen (McIlreath, 1977a; Aitken, in press, a), in the Cathedral Formation at Wedgewood Peak (section AC-103; Fig. 2), and in the Eldon Formation on Mt. Eon (section AC-102; Aitken, in press, a). "Yoholaminites" has also been observed by the writer in

¹⁹ According to Aitken (in press, a), pale-pellet grainstone contains pale-coloured pellets, 30-50 microns in diameter and 60-100 microns in length. The grainstone units are associated with cryptalgal laminite (which is commonly made up of pale pellets) and burrow-mottled limestone.

²⁰ The "ex-" prefix refers to completely dolomitized rocks in which the original fabric is still visible. This terminology conforms with that used by Aitken (in press, a).

Stephen cirque, near Verdant Headwaters, and in Monarch cirque (in and near sections 25, 33 and 28 respectively).

"Yoholaminites" typically occurs as tabular layers 2-8 cm thick (Plate 35b, c), although digitate, bifurcating, and irregular structures have also been reported (Aitken, in press, a). Commonly, small Epiphyton bushes line the floors and/or tops of these structures (Plate 35b). McIlreath and Aitken (1976) speculated that "Yoholaminites" might be a form of coralline alga or an ancestral stromatoporoid.

"Yoholaminites" is closely associated with ex-fenestral limestone and ex-oid and pisolitic grainstones (Plate 35b, c). Both McIlreath (1977a) and Aitken (in press, a) reported that these rock-types are arranged in a series of distinctive, decimetre-scale cycles. No consistent vertical sequence could be discerned by the author in the well exposed examples in Monarch cirque.

"Yoholaminites" has recently been re-examined on Mt. Stephen by Aitken, McIlreath and others, who now agree that it is a cement-filled cavity rather than an organic structure. According to B. Pratt (oral communication, 1991), "Yoholaminites" is a type of teepee structure formed under conditions of groundwater discharge in the upper intertidal to supratidal zone of a tidal flat (cf. peritidal teepees of Kendall and Warren, 1987). The delicately layered cements in these structures are inferred to have been precipitated incrementally in extensive sheet crack systems beneath supratidal tufa crusts.

4.8.5 Fine-grained siliciclastic sequences of shallow-water aspect

Fine-grained siliciclastic sediments, inferred to have been deposited under relatively shallow-water conditions, are present in the upper Naiset Formation (sections 2, 3, 14, 15), the "platformal" Stephen Formation (sections 10, 12, 17, 20; Plates 35d, e; 36a, b), and the upper "basinal" Stephen Formation near Field (sections MJA-725, 733, Fig. 3). These sequences will be described under the appropriate formational headings in Chapter 5. They are inferred to have been deposited under relatively shallow-water conditions on the basis of the following indicators: (1) the occurrence of horizontal and vertical burrows (chiefly Palaeophycus and Skolithos), which are unknown in all other exposures of the argillite lithofacies; (2) the appearance, in the uppermost Naiset Formation and upper "basinal" Stephen Formation, of thin, calcarenite interbeds containing various proportions of oolites, oncoids, and bioclasts (chiefly trilobite skeletal debris); (3) the increasing incidence of thin, bioturbated sandstone interbeds in the upper Naiset Formation; and (4) the paucity of features indicative of slope instability, such as intraformational truncation surfaces, slide masses and intrafolial folds.

4.9 **SUMMARY: LITHOFACIES DESCRIPTIONS AND INTERPRETATIONS**

1. The **argillite lithofacies** contains a wide spectrum of rock-types, with protoliths ranging in composition from essentially pure claystone to siltstone. Diagenetic and structural factors have further contributed to the heterogeneity of this lithofacies. It contains abundant evidence for synsedimentary deformation in the form of intrafolial recumbent folds, disrupted and irregular bedding, and intraformational truncation surfaces, and was deposited below maximum storm wave base in an upper slope environment.

2. **Argillaceous argillite and laminated silty argillite** are characterized by millimetre-scale, light and dark laminae inferred to be Bouma E_{turbidite} - E_{hemipelagite} cycles. They were deposited by dilute, muddy turbidity currents.
Laminated/crosslaminated argillaceous siltstone is composed of partial or complete Bouma sequences, and was deposited by silty turbidity currents. It contains sets of starved, southeasterly-directed, asymmetric ripples, which were probably deposited by superimposed, contour-following currents associated with wind-driven surface circulation.
3. Two types of **ribbon limestone** occur in the Chancellor: ribbon calcilutite, which occurs mainly in the Tokumm and Vermilion sub-units and Takakkaw Tongue, and ribbon calcisiltite, which is confined mainly to the Duchesnay and Oke units.
4. **Ribbon calcilutite** consists of lime mudstone with interbedded and interlaminated argillaceous/dolomitic material. The latter ranges from argillite to essentially pure dolostone, and is composed of millimetre-scale, siliciclastic mud turbidites. Ribbon calcilutite sequences are the product of both primary and diagenetic processes. They contain abundant evidence of synsedimentary slope instability, including rotated limestone blocks, pull-apart structures, slide masses, and intraformational truncation surfaces.
5. **Ribbon calcisiltite** is more irregularly bedded. The limestone interbeds are characterized by partial or complete Bouma sequences and spaced sets of asymmetric, southwesterly-directed, starved ripples. These beds are calciturbidites, which have been reworked to a minor degree by contour-following currents

associated with wind-driven surface circulation. The intervening argillaceous material is identical to that in the ribbon calcilutite.

6. The **calcarenite lithofacies** occurs as sporadic, planar interbeds in ribbon limestone sequences of the Tokumm and Vermilion sub-units and Takakkaw Tongue; as wavy to irregular, lens-shaped bodies in the Duchesnay and Oke units; and as megachannel fills chiefly in the Vermilion sub-unit.
7. The planar, wavy and irregular-shaped **calcarenite beds and lenses** are usually massive and ungraded, and consist mainly of intraclastic-peloidal grainstone and packstone. They are inferred to have been rapidly deposited by high-concentration turbidity flows. Beds containing partial or complete Bouma sequences may have been deposited by less concentrated, residual flows.
8. The **megachannel calcarenite** was deposited as a series of stacked, overlapping channel fills inside much larger megachannels, which probably originated as slide scars cutting back into the upper slope and platform margin. Each calcarenite body is organized into alternating coarser, massive layers and laminated, finer layers, and some are characterized by thinning-upward trends. The grainstones units were deposited by surging, high-concentration turbidity currents, or by a series of smaller, high-concentration flows triggered by retrogressive failure at the head of the slide scar.
9. The **conglomerate lithofacies** consists of two main rock types. **Conglomerates** contain granule- to cobble-sized clasts set in a muddy or grainy matrix, and occur in units generally less than 2 m thick. **Megaconglomerate** contains a significant

proportion of platform-derived clasts larger than 1 m in diameter, and occurs as channellized bodies up to 150 m wide. These deposits contain a variety of slope- and platform-derived clasts. Most conglomerates contain abundant evidence of original matrix strength, and were thus deposited by debris flows. Grainy-matrix conglomerate, on the other hand, may be the product of density-modified grain flows or high-concentration turbidity currents.

10. **Periplatform talus** occurs as isolated blocks, and as thick talus wedges. These deposits contain abundant Epiphyton boundstone blocks derived by rockfall from the platform margin. Argillite and ribbon limestone slide blocks originated from failures on the upper slope.

11. **Shallow-water lithofacies** encountered in and near the study area include: (a) burrow-mottled and burrow-stratified limestone, deposited below fair-weather wave base in a subtidal environment; (b) rock-types indicative of peritidal deposition near the platform margin in the vicinity of the Kicking Horse Rim, including fenestral dolostone, oolitic and pisolitic grainstone, and "Yoholaminites"; and (c) fine-grained siliciclastic sediments containing burrows and other features suggestive of relatively shallow-water deposition in the upper Naiset Formation, "platformal" Stephen Formation, and upper "basinal" Stephen Formation.

CHAPTER 5

STRATIGRAPHIC SYNTHESIS: BASIN MARGIN SEDIMENTS

5.1 INTRODUCTION

In the zone of facies change, the Chancellor is composed of eight major lithostratigraphic units (Fig. 16). Three of these, the Naiset Formation, Takakkaw Tongue, and "basinal" Stephen Formation (Fig. 20) have been studied and described in varying detail by previous workers (Deiss, 1941; McIlreath, 1977a, b; Aitken, in press, a). A fourth unit, the upper Chancellor, has been studied on a regional reconnaissance basis by Cook (1975). Its detailed stratigraphy remains unknown, and only one complete section has ever been measured through it (section AC-150/154, Fig. 2; Aitken, unpublished data). The four intervening stratigraphic units, the Tokumm and Vermilion sub-units of the lower Chancellor, and the Duchesnay and Oke units of the middle Chancellor (Fig. 20), are described herein for the first time.¹ In this chapter, new stratigraphic information has been integrated with all pre-existing data to produce comprehensive stratigraphic summaries for every unit in the Chancellor.

5.2 NAISSET FORMATION

5.2.1 Definition

The Naiset Formation is a predominantly siliciclastic Middle Cambrian unit that unconformably overlies the Gog Group, and is conformably overlain by the Cathedral

¹ These stratigraphic units were briefly described by Stewart (1989).

KEY TO TEXT FIGURE STRATIGRAPHIC SECTIONS

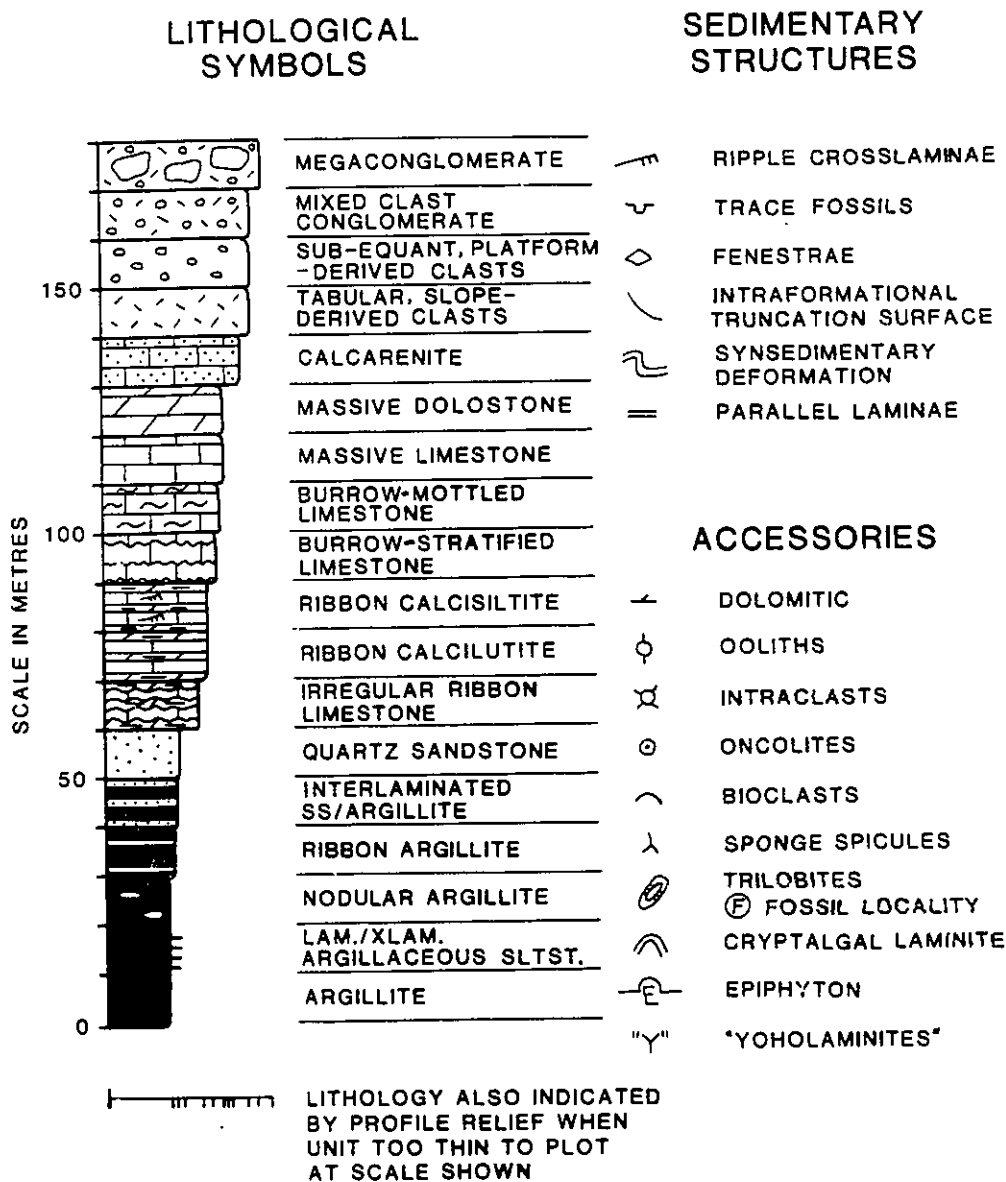
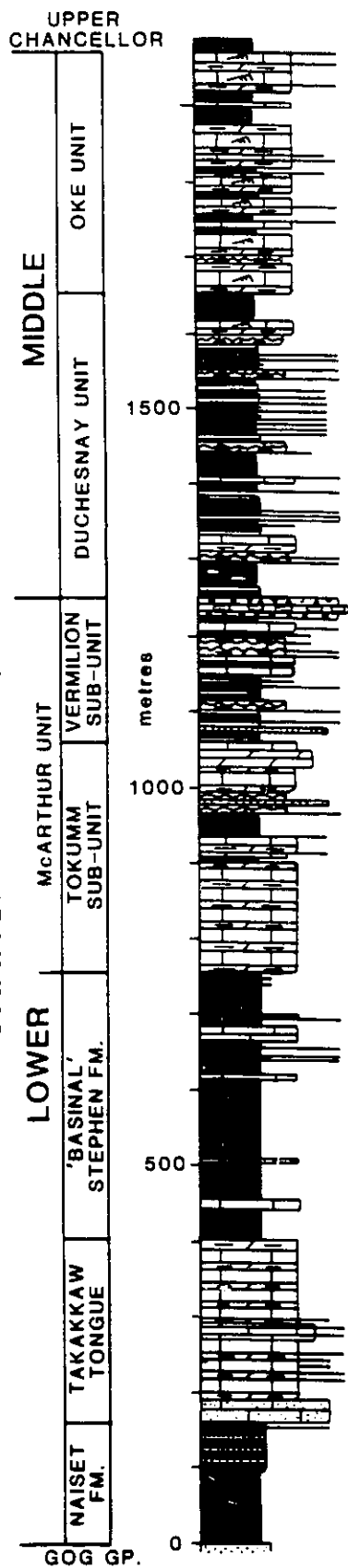


Figure 20. Opposite page: composite stratigraphic section of the lower and middle Chancellor. Above: legend for this and all subsequent stratigraphic columns.

CHANCELLOR SEQUENCE



COMPOSITE LOWER AND MIDDLE CHANCELLOR

Formation or its basinal equivalent. The name was originally proposed by Deiss (1940), and has since been used by Aitken (in press, a) to denote all basal Middle Cambrian siliciclastic units of "outer detrital" aspect west of the Kicking Horse Rim. The Naiset Formation is the basal unit of the Chancellor succession.

5.2.2 Section localities

Stratigraphic sections have been measured through the Naiset Formation in Mount Assiniboine Provincial Park and near Field.² The former area contains two principal sections: the type section on the east side of Naiset Point (Deiss, 1940)³, and a reference section near Wedgewood Peak (section AC-103; Aitken, in press, a; Plate 37a).⁴ The Naiset is also exposed a short distance north at Ferro Pass (section AC-129, Figs. 2, 5; Aitken, in press, a). Near Field, stratigraphic sections have been measured in North Gully on Mt. Stephen (section 2)⁵, and in Wedge Gully on Mt. Field (section 3; Figs. 2, 3)⁶. A third section has also been measured farther west on Mt. Field by I.A. McIlreath (section MJA-723; McIlreath, 1977a).

5.2.3 Lithology

5.2.3.1 Type area

In the type section (section 14, Appendix 2), the base of the Naiset Formation is marked by the abrupt appearance of argillite over medium- to thick-bedded, fine- to medium-

² The unit referred to as the Naiset Formation in the Monarch and Nataoko Lake areas (Stewart, 1989) is, in fact, the lithologically similar "basinal" Stephen Formation (see Section 5.4).

³ This section has also been remeasured by the author as section 14 (Appendix 2; Fig. 2), and by J.D. Aitken as section AC-105 (Aitken, in press, a).

⁴ Remeasured during this study as section 15.

⁵ Measured parallel to, and about 100 m west of section AC-112 (Aitken, in press, a).

⁶ Corresponds to the lower part of section MJA-725 (McIlreath, 1977a).

grained quartzites of the Gog Group (Fig. 21). In contrast, the basal 6.2 m of the Naiset in the Wedgewood Peak reference section (section 15) contains finely laminated, burrowed sandstone, silty shale, and granular to pebbly sandstone containing small-scale channels.

In both sections, the lower half of the formation is predominantly composed of variously dolomitic, argillaceous and silty laminated argillites of the argillite lithofacies (Plate 1a-c). These rocks also contain millimetre-scale laminae, lenses, stringers, and interbeds of brown-weathering, very fine- to coarse-grained sandstone. The millimetre-scale laminae commonly contain very low amplitude, ripple crosslaminae (Plate 1c). Some thicker lenses and interbeds contain normal grading or small-scale crosslaminae, but most are simply structureless. Load structures and small sandstone load balls a few centimetres across are also locally present. Syndimentary deformation features are common, including centimetre- to decimetre-scale recumbent-folded layers and intraformational truncation surfaces.

About the upper half of the Naiset Formation is composed of the bioturbated argillite sub-facies in the type area (Fig. 21). This sub-facies is represented by green-, brown-, grey-brown- and tan-weathering argillite, which is interbedded and interlaminated on a centimetre-scale with very fine- to fine-grained, poorly sorted quartz sand (Plates 1d; 2a). The sand occurs as burrowed laminae (containing burrows up to 0.5 cm in diameter), isolated lenses (which may originally have been starved ripples), discontinuous, irregular, burrowed layers, and scattered, isolate sand-filled burrows (Plate 9c).⁷ Small load structures occur at the bases of some of the sand layers. Thin, silt laminae and normally graded, sandy laminae also occur sporadically. Small-scale, intrafolial recumbent folds and

⁷ The degree of bioturbation is not always apparent on weathered surfaces perpendicular to bedding, but is readily visible in slabbed specimens.

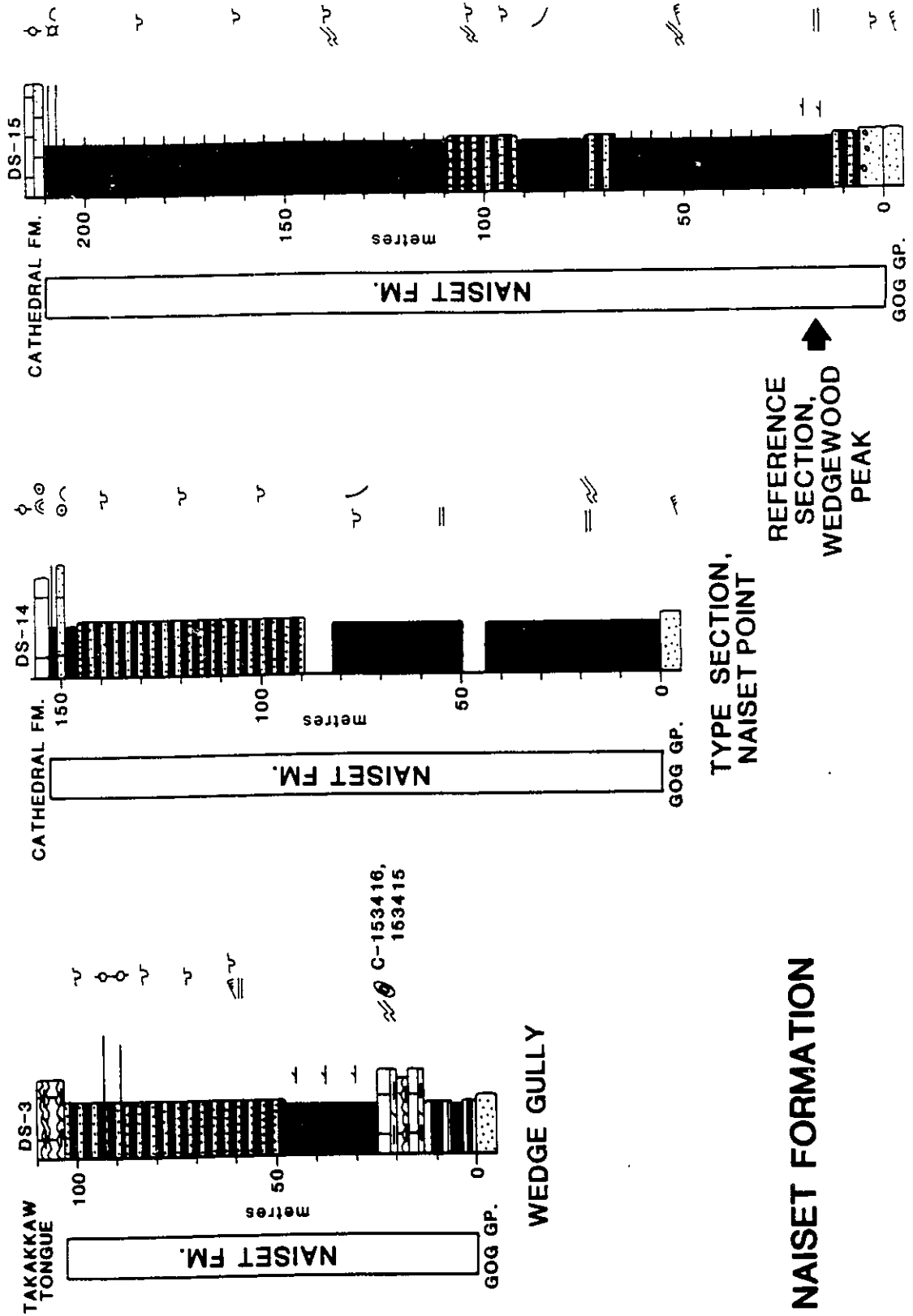


Figure 21. Stratigraphic sections of the Naiset Formation in the type area and near Field. See Fig. 20 for legend.

intraformational truncation surfaces occur near the base of the bioturbated sequence, but decrease in frequency and disappear upwards (Plate 2d). Less sand is present in equivalent strata in the more distal reference section. There, the upper part of the section is composed of nearly 50 m of monotonous argillite, which contains only minor burrowed, sandy lenses.

Minor interbeds of oncolite packstone with a skeletal matrix appear in the uppermost 5 metres of the type section. The Naiset is succeeded sharply by stromatolitic limestone and oolitic grainstone of the basal Cathedral Formation. Thin grainstone interbeds appear in the uppermost 2 m of the Wedgewood Peak reference section, where the Naiset is succeeded sharply by crossbedded oolite of the Cathedral Formation. Where primary sedimentary structures have not been significantly disturbed by bioturbation, base cut-out Bouma sequences can be discerned in the upper Naiset. Bouma CDE and DE sequences less than about 2 cm thick appear to be the most common. Thus the interbedded and interlaminated argillite and sand beds were probably deposited by dilute, sandy and silty turbidity currents. However, most primary sedimentary structures have been partially or wholly obliterated by a resident ichnofauna.

At Ferro Pass, 7 km along depositional strike to the northwest, the basal Naiset contact is clearly eroded, and is overlain by a prominent quartz pebble conglomerate. The section also contains prominent units of black lime mudstone, in addition to argillite (Aitken, in press, a).

5.2.3.2 Field area

In the Field area, the Naiset Formation shows considerable lithological variability on either side of the Kicking Horse Valley (Sections 2, 3; Figs. 2, 3). Both sections are situated close to the eastward pinchout of the Naiset against the Kicking Horse Rim.

The Wedge Gully section (Fig. 21) most resembles the type section. The lower third of the section is predominantly argillite, but also contains a unit of ribbon limestone and irregular ribbon limestone (11.7 m thick) with scattered trilobites and laminae of trilobite "hash".⁸ Above is a sequence of thinly interbedded and interlaminated argillite, siltstone and sandstone, very similar to the bioturbated argillite sub-facies in the type section.

Paleophycus-like and Skolithos-like horizontal and vertical burrows are moderately abundant on bedding surfaces (Plate 2b). The degree of bioturbation is sufficiently intense in the uppermost part of the formation to produce a burrow-mottled texture in some beds. Thin interbeds of oolitic grainstone first appear 15 m below the top of the formation, and the transition to the overlying Takakkaw Tongue (basinal Cathedral equivalent) is rapid.

Across the valley in North Gully (section 2; Appendix 2), the lower 30 m of the Naiset are characterized by argillite with thin interbeds and lenses of siltstone and sandstone.⁹ Soft-sediment deformation and intraformational truncation surfaces are common (Plate 2c). Overlying this is a quartz sandstone unit containing a few intraformational truncation surfaces, and a sequence of irregular to nodular skeletal grainstone/packstone, calcisiltite and shale. The remainder of the formation is composed mainly of dolomitic

⁸ A similar sequence is present about 660 m to the west at McIlreath's (1977a) Avalanche Section (Section MJA-723; Fig. 3).

⁹ The base of the Naiset, as defined in section 2, is placed about 43 m lower than that recorded by Aitken (in press, a) in his nearby section AC-112.

argillite and shale, except for a single, prominent unit of ooid packstone containing scattered oncoids (Aitken, in press, a).

5.2.4 Contacts

In the type area, the sub-Naiset contact is sharp, planar, and not noticeably eroded. At nearby Sunburst Peak and Ferro Pass, however, local erosional relief and a paleoregolith have been reported at the contact by Aitken (in press, a). Regional stratigraphic relationships indicate deep erosion of the underlying Gog Group at these localities (Palonen, 1976). Erosional truncation of the upper Gog Group has also been documented in the Field area by Aitken (in press, a).

The upper contact of the Naiset Formation is conformable and rapidly gradational. In the type area, the Naiset is overlain by platform strata of the Cathedral Formation, and the approach of the contact is heralded by thin calcarenite interbeds containing grains of shallow-water origin (ooliths, skeletal debris). Near Field, where the Naiset is overlain by the deep-water equivalent of the Cathedral Formation (Takakkaw Tongue), thin calcarenite and lime mudstone interbeds appear in the upper 15 m of the section.

5.2.5 Distribution and thickness

The Naiset Formation is exposed only in Mount Assiniboine Provincial Park and near Field (Plates 37a; 39).¹⁰ According to Aitken (in press, a), the formation onlaps and wedges out against the Kicking Horse Rim. This is supported by two lines of evidence:

¹⁰ The basal Middle Cambrian siliciclastic rocks near Field were erroneously assigned to the Mount Whyte Formation by McIlreath (1977a) and Price *et al.* (1980).

1. Limited stratigraphic control indicates that the formation thickens westward from the Kicking Horse Rim. Near Mt. Assiniboine, the sequence thickens from 153.2 m at Naiset Point (section 14), to about 210.2 m near Wedgewood Peak (section 15), 2 km to the west. On Mt. Field, the Naiset thickens from 102.2 m at Wedge Gully (section 3), to 143 m in section MJA-723, about 670 m farther west (McIlreath 1977a).
2. At several localities along the Kicking Horse Rim, the Cathedral Formation rests unconformably on the Gog Group, and the Mount Whyte and Naiset formations are missing. These localities include Wenkchemna Pass (Cook, 1975, p. 35), Vermilion Pass (Aitken, in press, a), The Monarch (section 27; Plate 37b, c), and the Egypt Lakes area (Plate 37d).

5.2.6 Age and correlation

All trilobites recovered from the Naiset Formation (Deiss, 1940; Aitken, in press), including those collected by the author (Appendix 1), have been referred to the Plagiura - "Poliella" Zone. The formation is therefore largely correlative with the Mount Whyte Formation on the platform (Rasetti, 1951; Aitken, in press, a; Fig. 16).

5.2.7 Basic interpretation of the Naiset Formation

The Naiset Formation was deposited in a deep-water slope and outer shelf setting on the western flank of the Kicking Horse Rim. Water depths gradually decreased with time,

until the formation was buried by prograding, peritidal oolite and other carbonate sediments of the Cathedral Formation and its deep-water equivalent, the Takakkaw Tongue.

The lower, argillite-dominated Naiset Formation was deposited on a slope in a quiescent, probably oxygen-deficient environment below maximum storm wave base. This is collectively indicated by the preservation of fine laminae, the lack of biogenic structures, the moderately dark colour of the sediment, and abundant evidence for gravitational instability (intraformational truncation surfaces, slide units, synsedimentary deformation).

Gradual shallowing-upward and more oxygenated conditions are suggested in the upper Naiset by the increasing proportion of sand in the sequence, and by the appearance of individual burrows and bioturbated layers. The upward disappearance of sedimentary features characteristic of gradational instability probably reflects slope aggradation and the establishment of a moderately deep, outer shelf. The preservation of muddy, silty, and sandy turbidite deposits, and the absence of sedimentary structures suggestive of storm activity, imply continued deposition below maximum storm wave base. With continued aggradation, the outer shelf became the foundation for prograding carbonate sand shoals of the basal Cathedral Formation.

5.3 TAKAKKAW TONGUE

5.3.1 Definition

The term "Takakkaw Tongue" was applied by Aitken (in press, a) to a prominent wedge of deep-water limestones projecting westward from about the lower two thirds of the Cathedral platform on Mount Stephen and Mount Field (Plates 38b; 39). This unit

corresponds to the "thin" Cathedral Formation of Fritz (1971) and McIlreath (1977a), and is assigned herein to the lower Chancellor (Fig. 16).

5.3.2 Section localities

The type section of the Takakkaw Tongue is the lower part of the classical Fossil Gully section on Mount Stephen (section AC-114, Fig. 3; Aitken, in press, a).¹¹ This unit is also spectacularly exposed on Mt. Field (Plate 39), where it has been traversed by the Wedge Gully (MJA-725), Dry Gully (MJA-726), Big Fly Gully (MJA-727), and Avalanche Gully (MJA-723) sections (McIlreath, 1977a; Fig. 3). Of these, parts of the Fossil Gully, Wedge Gully and Big Fly Gully sections have been examined by the writer.

During this study, three new sections were measured through the Takakkaw Tongue in the Nataoko Lake/Monarch area, about 55 km southeast of Field (sections 22, 23, 27; Fig. 2; Plates 41-42; 43a, b). A spectacular, unmeasured exposure also overlooks Nataoko Lake (Plates 38d, 40).

5.3.3 Lithology

According to Aitken (in press, a), the lower 23 m of the Takakkaw Tongue type section are composed of oolith grainstone with dolomite partings, and minor pelmatozoan - trilobite grainstone/packstone with abundant cryptalgal clasts (Fig. 22). In the remainder of the type section and all other sections in the area, the ribbon calcilutite lithofacies predominates (Plate 11a). The sequence is punctuated by thin, allochthonous calcarenite. Other important constituents include megaconglomerate, with megaclasts up to 30 m in

¹¹ This section also corresponds to McIlreath's (1977a) section MJA-732.

TAKAKKAW TONGUE

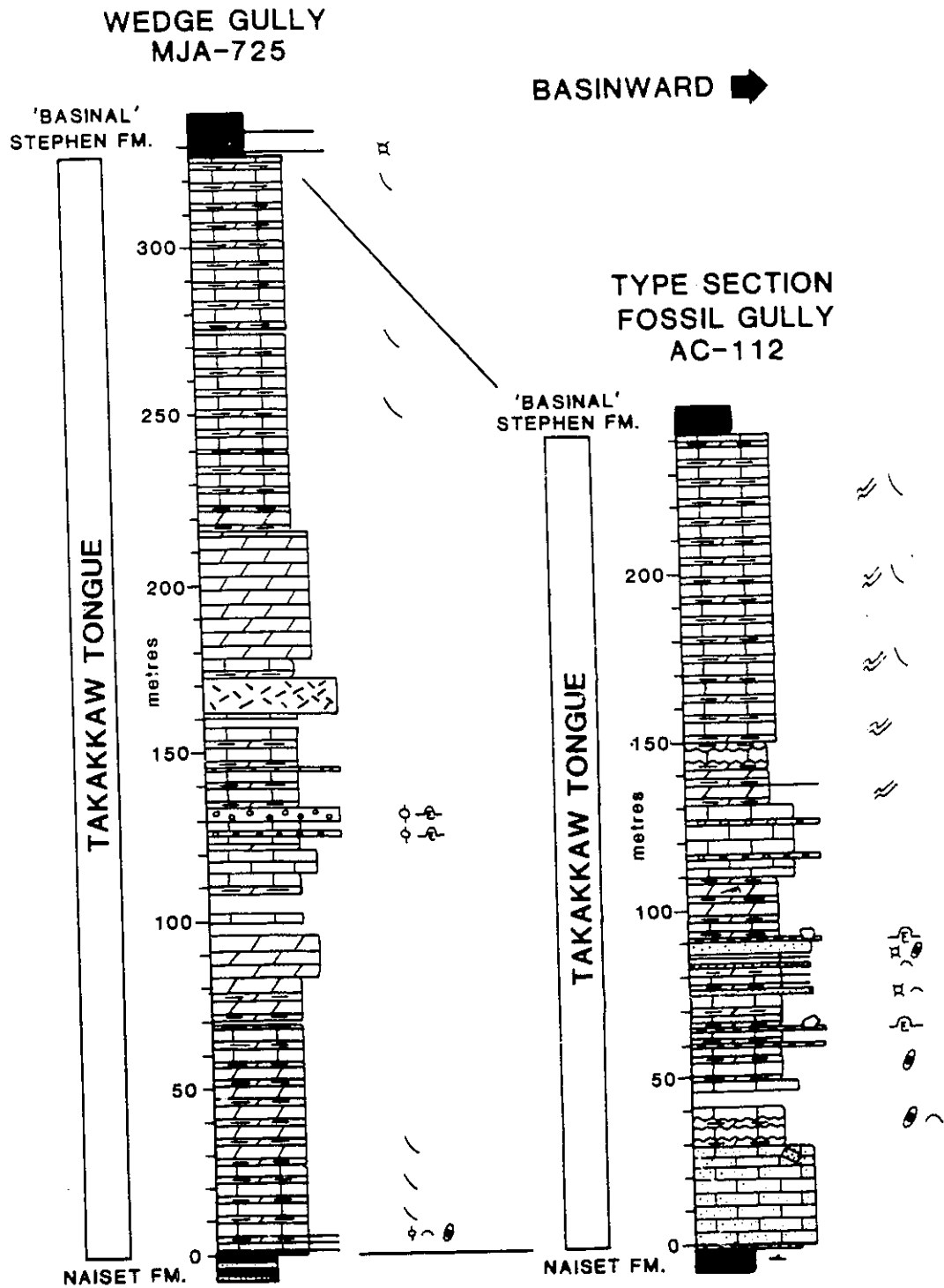


Figure 22. Stratigraphic sections of the Takakkaw Tongue in the type area near Field (based on section descriptions by McIlreath, 1977a, his Appendix I; and Aitken, in press, a). See Fig. 20 for legend.

maximum dimension (Plates 26a, b; 39), and limestone plate conglomerate, which tends to be more common in distal sections. The periplatform talus blocks in the Takakkaw Tongue (Plate 33a) decrease in size and number basinward, and are reported to increase in size stratigraphically upward (McIlreath, 1977a, p. 97). Intraformational truncation surfaces and internally deformed slide masses of various scales are also common throughout this unit.

The Takakkaw Tongue has similar characteristics in the Nataalko Lake/Monarch area, but is much thinner. There, the sequence is composed mainly of the ribbon calcilitite lithofacies (Plate 11b), and contains numerous intraformational truncation surfaces, slide masses, and conglomerate, including megaconglomerate (sections 22, 23, 27, Appendix 2; Plate 26c). Thin interbeds of graded, intraclast-peloidal grainstone occur in the upper part of the unit near Nataalko Lake (section 23, Appendix 2). Periplatform talus blocks of various scales are spectacularly, though locally exposed (Plate 41).

One of the most spectacular sedimentary features recognized in the Nataalko Lake/Monarch area is the **Cathedral megabreccia**, which overlies and abuts the Cathedral Escarpment (Plates 40, 41). This unit has been assigned to the lower Takakkaw Tongue (sections 22, 27, 28; Appendix 2), and is thought to have accumulated primarily by rockfall at the base of a submarine cliff during late Cathedral time (Chapter 7).

The Cathedral megabreccia is about 40 m thick at Nataalko Lake, and more than 50 m thick in Monarch cirque. From a distance, huge, variously oriented "ghost" blocks are recognizable within it (Plates 40, 41). The most impressive of these is a megaclast, 90 m tall and 70 - 90 m wide, exposed on the south wall of Monarch cirque (Plates 26d; 41). The megaclast projects upward more than 50 m into the ribbon limestones of the upper Takakkaw Tongue. Steeply-dipping internal bedding indicates that it is standing nearly on end. Other

blocks in the megabreccia range from a few metres to more than 50 m across. Abundant fracturing and veining, extensive recrystallization, and local mineralization (pyrite and hematite) combine to obscure much of the original depositional fabric in the megabreccia. As a result, most blocks are barely discernable from the surrounding matrix.

Local preservation of original depositional fabrics demonstrates that most, if not all of the megaclasts are composed of interbedded fenestral dolostone, ex-oolitic and pisolitic grainstone, and planar to somewhat irregular layers of "Yoholaminites". The associated pebble- to cobble-sized clasts have the same composition (Plate 26e), with the addition of minor quartz sandstone. Identical fabrics occur in the adjoining, autochthonous strata of the Cathedral Formation (Sections 4.8.3; 4.8.4; Plate 35b, c).

The top of the megabreccia is very irregular in places due to the presence of these large, projecting blocks (Plates 40, 41)¹² Laterally, the contact can appear quite smooth where irregularities were filled in by other sediments prior to deposition of the upper Takakkaw Tongue ribbon limestones. In section 28 (Appendix 2), one such irregularity is occupied by about 15 m of intraclast, oolitic and skeletal grainstone, limestone conglomerate, dolomitized breccia, and minor ribbon limestone.

5.3.4 Contacts

In the Mt. Stephen type section, the upper contact of the Takakkaw Tongue is abrupt, as it corresponds to an intraformational truncation surface (Aitken, in press, a). Across the valley on Mt. Field, the upper contact is sharp, but appears to be concordant.

¹² The thin, shaly layers in the overlying ribbon limestones appear to have acted as effective permeability barriers to the late-stage, dolomitizing fluids that so pervasively altered the underlying carbonate sequence.

Eastward, the Takakkaw Tongue passes into a narrow, massive dolostone zone at the Cathedral platform margin (Plate 39a, c).¹³

In the Nataoko Lake/Monarch area, the base of the Takakkaw Tongue is defined as the base of the Cathedral megabreccia (section 28, Appendix 2; Plates 40, 41). This contact is abrupt, and is inferred to be a megatruncation surface associated with platform margin collapse (Chapter 7). The top of the Takakkaw Tongue is an intraformational truncation surface of unknown scale immediately south of Nataoko Lake (section 23, Appendix 2). On the north face of The Monarch and in Monarch cirque, this contact is sharp, but appears to be concordant (Plates 41-42).

5.3.5 Distribution and thickness

The Takakkaw Tongue can be mapped only in the Field and Nataoko Lake/Monarch areas. It is presumably present along strike between these two localities, but is simply not exposed.

At the type section on Mt. Stephen, the Takakkaw Tongue is 242.2 m thick (Aitken, in press, a; Fig. 22). On Mt. Field, it progressively thins from about 328 m at Wedge Gully (MJA-725; Figs. 3, 22) to about 192 m at Avalanche Gully (MJA-723; McIlreath, 1977a), and presumably wedges out farther west. Thus, in more distal Chancellor exposures, the lithologically similar Naiset and "basinal" Stephen formations would not be separated by this distinctive carbonate marker.

¹³ The configuration of the Cathedral margin will be discussed in more detail in Chapter 7.

In the Nataalko Lake/Monarch area, the Takakkaw Tongue, like the Cathedral Formation, is substantially thinner than near Field. In Monarch cirque, the Takakkaw Tongue (including the basal Cathedral megabreccia) is 98.4 m thick (section 28; Appendix 2). At Nataalko Lake, this unit is estimated from photographs to have a maximum thickness of about 100 m.

5.3.6 Age and correlation

Trilobites collected from the Takakkaw Tongue by Rasetti (1951, p. 49-50) have been referred to the Plagiura-"Poliella" and Albertella(?) zones (Fritz, 1971, p. 1163). The top of this unit cannot be younger than the Glossopleura Zone, as trilobites belonging to that zone have been recovered from the overlying "basinal" Stephen Formation (Fritz, 1971, p. 1164; see also McIlreath, 1977a, his Appendix I). Glossopleura Zone trilobites have also been collected from talus securely tied to the upper Takakkaw Tongue in Monarch cirque (C-167278, section 27; Appendix 1).

Sedimentological and biostratigraphic evidence indicate that the Takakkaw Tongue and platformal Cathedral Formation accumulated contemporaneously. However, low faunal recoveries, poor biostratigraphic resolution, and destructive dolomitization of the outer platform sequence make it impossible to trace specific stratigraphic horizons between the slope and platform successions. This has two important implications. First, the top of the Takakkaw Tongue cannot be correlated with any specific horizon in the Cathedral platform. Second, in the absence of obvious physical evidence, unconformities or condensed zones would probably go unrecognized in the Takakkaw Tongue. Thus, precise correlations between the platform and slope successions are impossible. The correlations of the

Takakkaw Tongue and "basinal" Stephen Formation will be considered together in Section 5.4.6.

5.3.7 Basic interpretation of the Takakkaw Tongue

In the type area, most of the Takakkaw Tongue accumulated as a major carbonate apron downslope from an active, prograding, rimmed carbonate platform (the lower two thirds of the Cathedral Formation). This relationship is clear in the superb exposures on Mt. Field (Plate 39). A deep-water slope setting is also indicated by the presence of abundant intraformational truncation surfaces, slide masses, debris flow conglomerate and megaconglomerate, allochthonous calcarenite, and numerous, isolated blocks of periplatform talus. The relationship between the upper Takakkaw Tongue and the part of the Cathedral platform bounded by the Cathedral Escarpment is controversial, and will be discussed in Chapter 7.

In the Nataoko Lake/Monarch area, the Takakkaw Tongue abuts another example of the Cathedral Escarpment, and contains a prominent megabreccia in its lower half. There, the Takakkaw Tongue is inferred to have accumulated at the foot of a submarine escarpment formed by platform margin collapse in late Cathedral time. A detailed interpretation of these stratigraphic relationships will be presented in Chapter 7.

5.4 "BASINAL" STEPHEN FORMATION

5.4.1 Definition

The term "basinal" Stephen Formation was applied by Aitken (in press, a) to a predominantly fine-grained siliciclastic succession exposed west of the Cathedral

Escarpment on Mt. Stephen and Mt. Field (Plates 38b, 39). This unit corresponds to the "thick" Stephen Formation described by Fritz (1971) and McIlreath (1977a, b).

Aitken (in press, a) subdivided the "basinal" Stephen Formation into the Amiskwi and Wapta members (Fig. 16). The Wapta Member is physically continuous with at least part of the Waputik Member in the "platformal" Stephen Formation (Section 3.3.4). The Amiskwi Member contains the world famous Burgess Shale, which is exposed on the west slope of Fossil Ridge (Plate 38c).

5.4.2 Section localities

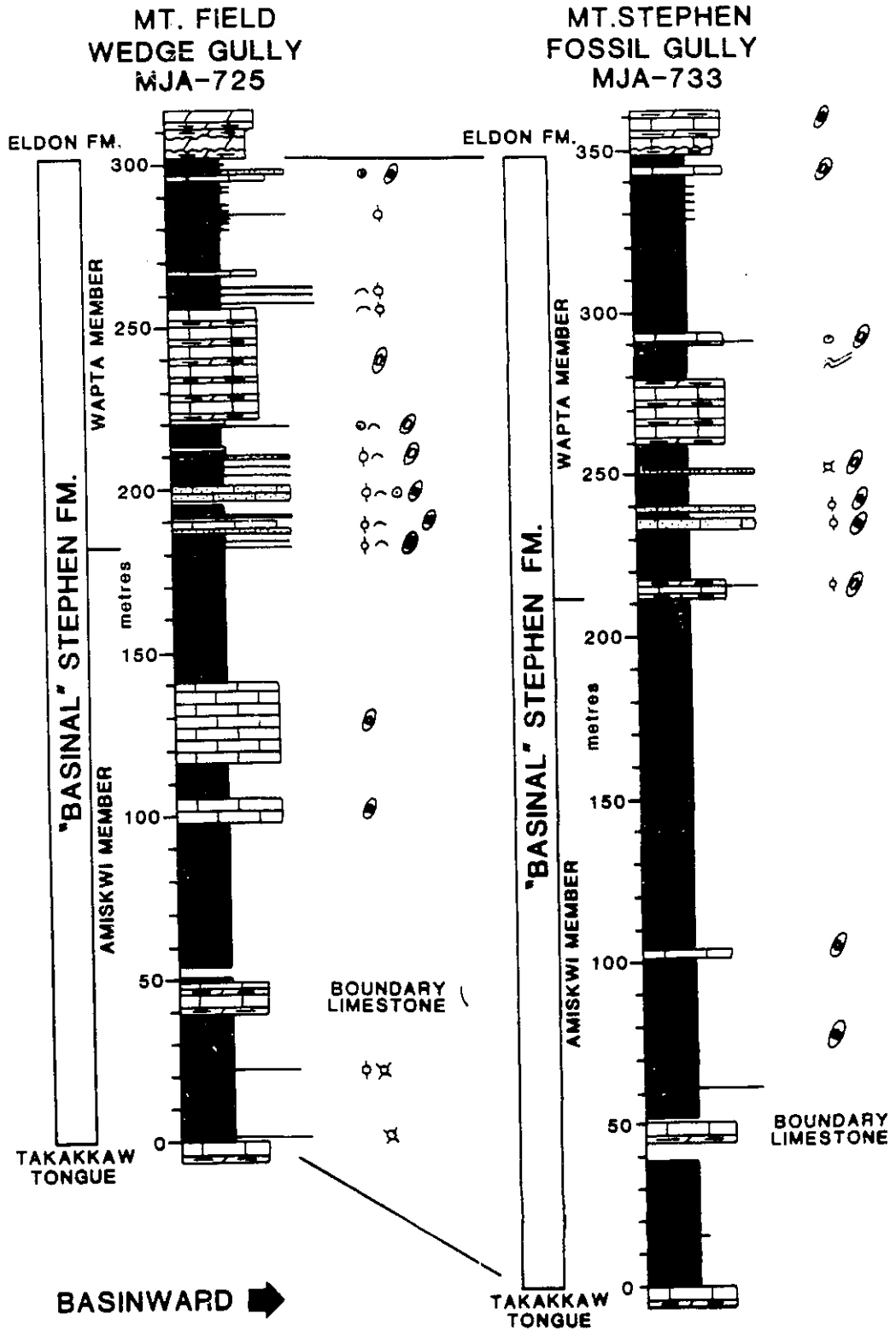
Due to Walcott's rather confusing designation of a type section on Mt. Stephen (see discussion by Rasetti, 1951, p. 70-72), Aitken (in press, a) designated a reference section representative of the "platformal" Stephen Formation on the south slope of Mt. Bosworth (AC-3, Fig. 3; see also Deiss, 1940; Rasetti, 1951).¹⁴ He also designated a second reference section representative of the "basinal" Stephen Formation on the south face of Mt. Field. The latter section contains the type sections for the Amiskwi and Wapta members (section AC-161/162; Fig. 3). Aitken's Fossil Gully section on Mt. Stephen (section AC-114) serves as a third reference section, although access is more difficult. All three sections have been examined by the writer.

Numerous sections have also been measured by McIlreath (1977a) on Mt. Stephen and Mt. Field at various distances from the Cathedral Escarpment (sections MJA-723, 724b, 725, 727, 731, 732/733, and 734; Figs 3, 23). Additional, unmeasured sections of the

¹⁴ In his original manuscript, Aitken stated his intention to change the type section of the Stephen Formation from Mt. Stephen to Mt. Bosworth. As of the time of writing, it was not clear whether this would be allowed, and thus the Mt. Bosworth section has been described herein as a reference section.

Figure 23. Stratigraphic sections of the "basinal" Stephen Formation in the type area near Field (based on section descriptions by McIlreath, 1977a, his Appendix I). See Fig. 20 for legend.

"BASINAL" STEPHEN FORMATION



"basinal" Stephen are also present on Odaray Mountain and Park Mountain (McIlreath, 1977a; Collins *et al.*, 1983; Fig. 3, Plate 38e).

Three previously unknown sections of the "basinal" Stephen Formation were measured during this study in the Nataoko Lake/Monarch area. The sections are situated immediately south of Nataoko Lake (section 23; Plate 43b), on the north face of The Monarch (section 22; Plates 42, 43a), and in Monarch cirque (section 27; Plate 41).

5.4.3 Lithology

5.4.3.1 Lithology in the type area

According to Aitken (in press, a), the **Amiskwi Member** is composed mainly of grey-, grey brown-, and brown-weathering shale that is commonly calcareous and silty. These rocks are generally very thin, platy bedded or fissile (Plate 3a). Dolomitic argillite (Plate 3b) and argillite exhibiting splintery to conchoidal fracture also occur. Massive, dolomitic argillite predominates in the upper part of the member, at least near Fossil Gully Fault. The shales and argillites are composed mainly of illite and minor calcareous mud, as determined by X-ray diffraction (McIlreath, 1977a, p. 196).

McIlreath (1977a, p. 196) emphasized the importance of graded laminae in the lowermost Amiskwi Member, but subtly graded laminae and silty laminae are common in most parts of the unit (Plate 3c). Adjacent to the Cathedral Escarpment on Mt. Field, for example, variably dolomitized and vaguely laminated argillite units contain local silty layers, parallel laminae, and possible, very low amplitude ripple crosslaminae. Many of the more massive and indistinctly laminated beds in the "basinal" Stephen Formation appear to have been partially homogenized, most probably as a result of syndimentary deformation.

Intraformational truncation surfaces and other features indicative of synsedimentary deformation are present, though not abundant. Some beds are extremely fossiliferous, and yield large numbers of trilobites, phosphatic brachiopods, gastropods, hyolithids, and some soft-bodied organisms (Aitken, in press, a).

The Amiskwi Member also contains the "Boundary Limestone" (Fritz, 1971; McIlreath, 1977a, b), a minor carbonate apron that accumulated at the foot of the Cathedral Escarpment in the Field area.¹⁵ The Boundary Limestone is documented best on Mt. Stephen, where it consists of a proximal **bench** that is 100 m thick and projects 180 m outward from the escarpment wall, and a basinward-tapering **wedge** that thins to 12 m within 1.2 km of the escarpment (McIlreath, 1977b; Fig. 24).

According to McIlreath (1977b), the bench consists of about 40 m of platform-derived debris and 60 m of in-situ lime mudstone. However, his stratigraphic log indicates that peloidal, oolitic and bioclastic grainstone predominates in only the basal 11 m of the Boundary Limestone adjacent to the escarpment. The rest of the section is composed mainly of thin-bedded lime mudstone with widely spaced, medium beds of peloidal and/or bioclastic packstone (MJA-731a; McIlreath, 1977a, his Appendix I). This suggests that the input of platform-derived sands was less prevalent in the later stages of Boundary Limestone deposition than had previously been emphasized. Periplatform talus up to small boulder size and debris flows less than 1 m thick are also reported to occur in this sequence (McIlreath, 1977b, p. 119).

¹⁵ The Boundary Limestone derives its name from the fact that the boundary between the Glossopleura and Bathyriscus - Elrathina trilobite zones occurs within it (Fritz, 1971).

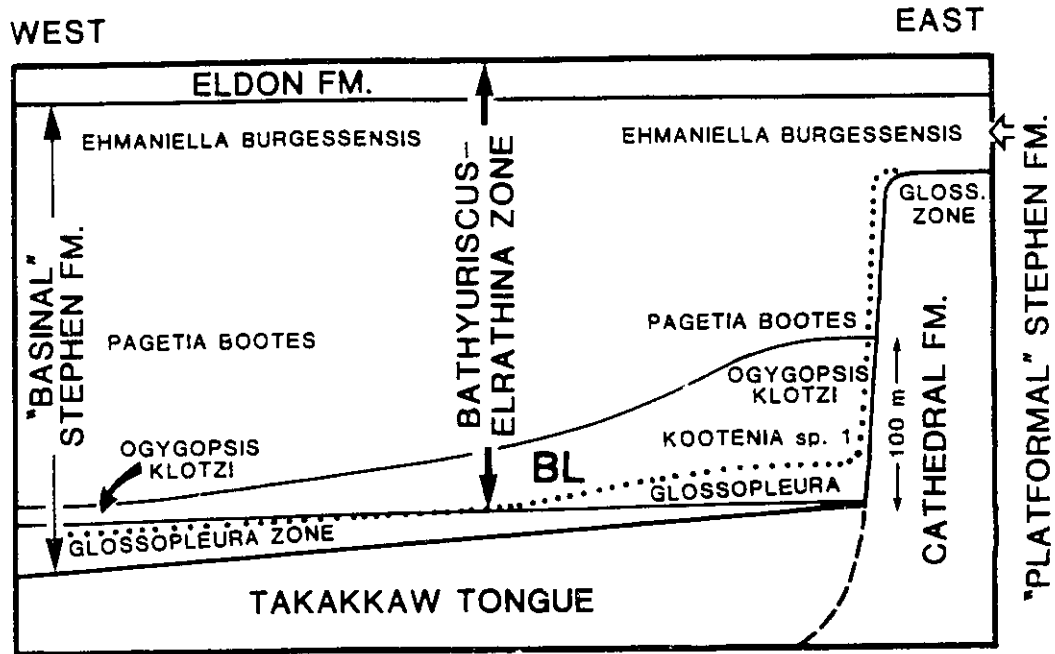


Figure 24. Distribution of the *Glossopleura* Zone and faunules of the *Bathyriscus-Elrathina* Zone in the Cathedral and Stephen formations near Field (modified from McIlreath, 1977b).

AGE	LOCHMAN-BALK AND WILSON (1958)	GREAT BASIN (ROBISON, 1976)		
		"RESTRICTED SHELF" POLYMEROIDS	"OPEN SHELF"	
			POLYMEROIDS	AGNOSTOIDS
MIDDLE CAMBRIAN	BOLASPIDELLA	ELDORADIA	BOLASPIDELLA	LEJOPYGE CALVA
		BARREN INTERZONE		UNNAMED
				PTYCH. PUNCTUOSUS
	BATHYRISCUS-ELRATHINA	EHMANIELLA		PTYCH. ATAVUS
				PTYCH. GIBBUS
		GLOSSOPLEURA		GLOSSOPLEURA
ALBERTELLA	ALBERTELLA	ORYCTO-CEPHALUS	P. PRAECURRENS	
PLAGIURA - 'POLIELLA'	PLAGIURA - 'POLIELLA'		BARREN INTERZONE	
			PERONOPSIS BONNERENSIS	

Figure 25. Inferred chronocorrelation of Middle Cambrian trilobite zones proposed by Lochman-Balk and Wilson (1958) and Robison (1976). Redrawn from Robison (1976).

The flanking wedge is composed mainly of ribbon calcilutite. Intraformational truncation surfaces and slide masses are common. Complete trilobite exoskeletons are also rarely present in these rocks (McIlreath, 1977b, p. 119-120).

Across the valley on Mt. Field, the Boundary Limestone is reportedly missing due to non-deposition on a paleobathymetric high adjacent to the Cathedral Escarpment (McIlreath, 1977a, p. 220).¹⁶ Farther west near Fossil Gully Fault (Plate 39), this unit is composed of 15 m of ribbon limestone, mixed-clast conglomerate, and a clast-supported megaconglomerate containing megaclasts up to 10 m in maximum dimension. The megaclasts are grainstones composed of micritic peloids (including possible *Girvanella* remnants), intraclasts, oolites, and skeletal debris (trilobites, molluscs and calcareous algae).

The Boundary Limestone should be regarded as a scaled-down version of the Takakkaw Tongue. It is a carbonate apron that accumulated in response to carbonate generation on and export from the shelf. At the same time, its limited areal extent suggests that the "carbonate factory" was much reduced in size and/or capability, and was thus unable to export carbonate sediment as abundantly as during Takakkaw Tongue deposition.

The **Wapta Member** has been described in summary form by Aitken (in press, a). The most detailed descriptions available are those by McIlreath (1977a). Evidence for progressively shallowing depositional conditions is clearly expressed in the type section of this member on Mt. Field, and less clearly so on Mt. Stephen (Aitken, in press, a).

¹⁶ Alternative correlations are also possible. The Boundary Limestone may well be represented by destructively dolomitized strata adjacent to the middle part of the Cathedral Escarpment, as depicted in the line drawing accompanying Plate 39. This outcrop occurs immediately east of McIlreath's (1977a) Dry Gully section (MJA-726). Thus, the uppermost thin-bedded lime mudstones in this section probably belong to the Boundary Limestone, and can be traced westward to the Fossil Gully Fault.

According to Aitken (in press, a), the Wapta Member consists largely of grey-, greenish grey-, and brown-weathering shale with carbonate interbeds and units (Fig. 23). The carbonate rocks are wackestone, packstone and grainstone containing various skeletal elements (trilobites, pelmatozoans, hyolithids), in addition to oncoids, oolites, peloids and pellets. Some of the grainstones are ripple crosslaminated. Calcisiltite is also reported to be prominent. Feeding burrows appear in the upper half of the member, and very thin interbeds of quartz siltstone occur in about the upper 15 m. Synsedimentary deformation is rare, and is lacking in the upper part of the member.

5.4.3.2 Lithology in the Nataalko Lake/Monarch area

In the Nataalko Lake/Monarch area, the "basinal" Stephen is overlain by the deep-water equivalent of the Eldon Formation, the Tokumm sub-unit (Plates 41, 42). Hence, no shallowing-upward trend is detectable, and the sequence cannot be subdivided into the two members identified in the Field area. The rocks in the Nataalko Lake/Monarch area are reminiscent of the Amiskwi Member, although they are generally better indurated and significantly less fossiliferous.

In the Nataalko Lake/Monarch area, the "basinal" Stephen Formation is composed mainly of variously dolomitic, massive, cleaved argillite (Plates 3d; 4a; 43a, b). Zones of convolute laminae and small-scale synsedimentary overfolds are fairly common, as are discrete slide masses and homogenized zones (Plate 4b). A few, thin grainstone interbeds containing abundant trilobite, pelmatozoan and phosphatic brachiopod debris occur in Monarch cirque section (section 27; Appendix 2). Lenses of trilobite grainstone also appear just beneath the top of the formation. Fossils of soft-bodied organisms have also been

recovered rarely from talus, and appear to be mostly of priapulid-like worms (e.g. C-167291; Appendix 1).

In Monarch cirque (section 27), the basal part of the formation contains a few, large periplatform talus blocks (up to 11 m in maximum dimension) composed of Epiphyton boundstone (Plate 41). Minor Renalcis and ?Girvanella also occur in these blocks. A limestone conglomerate (2.2 m thick) containing both platform- and slope-derived clasts occurs about 6 m above the base of the formation on the north face of The Monarch (section 22; Appendix 2).

5.4.4 Contacts

In more proximal areas, the "basinal" Stephen Formation is overlain by the Eldon Formation (e.g. Mt. Field; Mt. Stephen; Prospectors Valley). Due to westward facies change in the lower Eldon Formation, the "basinal" Stephen Formation is succeeded by the Tokumm sub-unit in more distal areas (e.g. the Nataalko Lake/Monarch area; western Stephen cirque).

The upper contact of the Stephen Formation (whether "platformal" or "basinal") is gradational by interbedding, and is defined as the top of the highest shale (Aitken, in press, a). This transition is usually very rapid. In the Nataalko Lake/Monarch area, lenses of trilobite grainstone occur rarely immediately below the contact, which is quite abrupt. Limestone conglomerate and minor slide masses occur locally along the contact near Nataalko Lake (section 23) and in Monarch cirque (section 27).

5.4.5 Distribution and thickness

Like the Takakkaw Tongue, the "basinal" Stephen Formation is a distinct entity only in the Field and Nataalko Lake/Monarch areas. In both areas, it is recognized by its stratigraphic position above the Takakkaw Tongue, and by its relationship with the Cathedral Escarpment.

On Mt. Field, the "basinal" Stephen Formation thickens from 164.6 m immediately west of the Cathedral Escarpment to 301.8 m in Wedge Gully, about 400 m to the west (Fig. 23; McIlreath, 1977a).¹⁷ No complete sections are available farther west on that mountain.

¹⁷ Aitken (in press, a) measured 277.8 m in nearby section AC-161/162, slightly farther west.

On Mt. Stephen, the "basinal" Stephen Formation thickens to 349 m in the Fossil Gully section, about 1200 m from the escarpment (MJA-733; McIlreath, 1977a).¹⁸

The exposures in the Nataoko Lake/Monarch area are thinner than those near Field, and also thicken westward. The "basinal" Stephen Formation has a thickness of 149.3 m near Nataoko Lake (section 23; Appendix 2), and 177.8 m on the north face of The Monarch (section 27). The closest section to the Cathedral Escarpment is in Monarch Cirque (section 27), where the formation is only 84.1 m thick.

5.4.6 Age and Correlation

5.4.6.1 Introduction

The "basinal" Stephen Formation is Middle Cambrian in age. According to the trilobite zonation scheme proposed by Lochman-Balk and Wilson (1958), the formation ranges from the uppermost Glossopleura Zone to the lower Bathyriscus-Elrathina Zone (Fritz, 1971, 1981; Fig. 16).

The validity of this trilobite zonation scheme has recently been questioned. Taxonomic problems with both Bathyriscus and Elrathina caused Robison (1976) to replace the Bathyriscus-Elrathina Zone with the much longer-ranging Oryctocephalus Zone in the Great Basin (Fig. 25). In addition, he proposed a new, biofacies-dependent zonation scheme, in order to "more realistically reflect the major faunal patterns and their relationships" (Robison, 1976, p. 93).

¹⁸ Aitken (in press, a) reported a thickness of 268.7 m in his Fossil Gully section (AC-114). For reasons of accessibility, the upper part of the section was offset to a point closer to the Cathedral Escarpment, where the "basinal" Stephen Formation is thinner. This may explain the thickness discrepancy between sections AC-114 and MJA-733.

These revisions to Great Basin biostratigraphy have led to concern about the trilobite zonation scheme utilized by Fritz (1971) to correlate strata in the vicinity of the Cathedral Escarpment (Briggs and Robison, 1984; Ludvigsen, 1989, 1990). The questions raised about the relative ages of the Cathedral and Stephen formations have largely been answered by Fritz (1990), and will be addressed further in the sections that follow (see also Section 7.4 and Appendix 3).

Of concern here is the establishment of accurate correlations between the shelf and slope successions. These correlations are crucial to the choice of a suitable depositional model for late Cathedral and Stephen time.

5.4.6.2 Correlations by Fritz (1971)

The basal "basinal" Stephen Formation contains fauna referable to the upper Glossopleura Zone. The boundary between this zone and the overlying Bathyriscus - Elrathina Zone occurs within the Boundary Limestone (Fritz, 1971, 1990; McIlreath, 1977a, b). Six local faunules have been recognized in the latter zone by Fritz (1971), who modified an earlier zonation scheme by Rasetti (1951). Four of these faunules reside in the "basinal" Stephen Formation. In ascending stratigraphic order, they are the Kootenia sp. 1, Ogygopsis klotzi, Pagetia bootes, and Ehmaniella burgessensis faunules (Fig. 24).

Of the four faunules, only the last occurs in the Waputik Member of the "platformal" Stephen Formation. The underlying Cathedral Formation and coeval strata of the Narao Member in the platform interior contain fauna referable to the Glossopleura Zone. The missing faunules are cited by Fritz (1971, p. 1169) as evidence for a disconformity at the base of the Waputik Member along the Kicking Horse Rim. This implies a disconformable

relationship between the Waputik and Narao members throughout the remainder of the platform region as well. An intra-Stephen Formation disconformity was also inferred to be present at the same level by Rasetti (1951, p. 108), on the basis of missing fauna "believed to occupy this time interval in Montana, Wyoming and Utah . . .".

According to the sedimentological model proposed by Fritz (1990), siliciclastic mud deposition commenced simultaneously on the platform and adjoining slope during latest Glossopleura time. A brief respite in this siliciclastic influx permitted the local re-establishment of shallow-water carbonate sedimentation, which contributed carbonate mud, sand and other debris to the Boundary Limestone carbonate apron at the foot of the escarpment. This was followed by deposition of the terrigenous muds containing the Ogygopsis klotzi and Pagetia bootes faunules. Erosion is then thought to have removed all accumulated sediments down to the top of the former carbonate platform, while sedimentation continued unabated on the slope (early Ehmaniella burgessensis faunule time). After siliciclastic sedimentation resumed on the shelf, the rapidly aggrading slope entombed the Cathedral Escarpment (late Ehmaniella burgessensis faunule time).

5.4.6.3 An alternative view of the biostratigraphy

One persistent problem with the correlations advocated by Fritz (1971, 1990) is the need for a disconformity at the base of the Waputik Member throughout the shelf region. No physical evidence of erosion has ever been observed at the base of that member, and the great areal extent of the two sedimentary cycles in the underlying Narao Member would seem to preclude any significant erosional break (Aitken, in press, a).¹⁹ In addition, there is

¹⁹ Similarly, no obvious evidence of erosion has been seen by the writer at the base of the Waputik Member along the Kicking Horse Rim (sections 9, 10, 12, 17, 20).

no evidence in the slope succession for the significant erosional event postulated by Fritz (1990).

The Kootenia sp. 1, Ogygopsis klotzi, and Pagetia bootes faunules appear to have strictly local distributions. Aitken (in press, a) observed that all three faunules are largely characterized by taxa that were probably confined to deep-water environments. Fritz (in McIlreath, 1977a, p. 206) also considered many of these species to be indigenous to the basin. Thus, these faunules are probably unrepresented in the shelf succession for environmental, rather than temporal reasons. If so, the "platformal" Stephen Formation may not only be equivalent to the Ehmaniella burgessensis-bearing strata on the slope, but to at least part of the underlying succession as well. Notably, Ehmaniella burgessensis has been found in strata as low as those bearing the Pagetia bootes faunule (Fritz, 1971, his Fig. 5). This suggests that the entire "basinal" Stephen Formation above the top of the Boundary Limestone is coeval with the "platformal" Stephen Formation.

In the Boundary Limestone, about 66 m of predominantly lime mudstone overlie Glossopleura-bearing strata immediately adjacent to the Cathedral Escarpment (McIlreath, 1977a; his Appendix I). This implies that the adjoining platform continued to generate and export lime mud following the demise of Glossopleura. Thus, on sedimentological grounds, the top of the Boundary Limestone is most reasonably correlated with the top of the Cathedral Formation, as presently mapped over the Kicking Horse Rim.²⁰ This scenario is attractive, as it solves the long-standing problem of a source for the Boundary Limestone.

²⁰ In this area, the uppermost Cathedral Formation contains the lateral, carbonate equivalent of the Narao Member in the "platformal" Stephen Formation.

If the above correlations are correct, it must be assumed that a minor hiatus is present at the top of Narao-equivalent strata along the outer edge of the Cathedral platform (Fig. 16). As evidence for physical erosion is lacking at the Cathedral-Stephen contact along the Kicking Horse Rim, this disconformity is more likely to reflect non-deposition than subaerial exposure. The depositional history of the Cathedral margin will be discussed further in Section 7.5.

The above correlation is not without its problems. For example, the missing faunas reported by Rasetti (1951, p. 108) remain to be explained. It would have to be assumed that these faunas were locally, rather than regionally distributed, so that their absence does not necessarily imply a hiatus in the study area.

5.4.7 Basic interpretation of the "basinal" Stephen Formation

Most of the "basinal" Stephen succession accumulated on a deep-water slope flanking the Cathedral Escarpment. The finely laminated argillites that make up the bulk of the Amiskwi Member were deposited by dilute, muddy and silty turbidity currents below maximum storm wave base (Section 4.3.3.1). All indicators suggest a progressive shallowing of depositional conditions during deposition of the Wapta Member (McIlreath, 1977a; Aitken, in press, a).

If the alternative correlations proposed above are correct, the lower part of this succession (Boundary Limestone and underlying shale) accumulated during the terminal stages of carbonate accretion on the Cathedral platform. The platform was subsequently smothered by predominantly siliciclastic sediments of the Waputik Member, most of which bypassed the shelf to be deposited on the slope. The bypassing can probably be attributed to

the limited accommodation space available on the shelf for the obviously large volumes of fine-grained siliciclastic sediment that were being supplied. Rapid slope aggradation subsequently entombed the Cathedral Escarpment, leading to the eventual establishment of a relatively shallow, siliciclastic ramp. This interpretation will be developed more fully in Chapter 7.

5.5 UNDIVIDED NAISSET - TAKAKKAW TONGUE - "BASINAL" STEPHEN EQUIVALENT

5.5.1 Description

The obvious, basinward wedging of the Takakkaw Tongue at all localities indicates that it must disappear by facies change into siliciclastic sediments at some point farther west. Without this distinctive carbonate marker, the predominantly siliciclastic Naiset and "basinal" Stephen formations would become lithologically indistinguishable in distal sections of the lower Chancellor.

This undivided unit crops out along the Vermilion River Valley (Fig. 4). Although the base of the unit is not exposed, its top is readily identifiable where capped by relatively resistant limestones of the Tokumm sub-unit. The undivided unit was mapped as part of the undivided lower Chancellor by Price and Mountjoy (1972) and Price *et al.* (1978b), but was separated as a distinct, recessive map-unit by Leech (1979). It has been examined on the southwest side of Hawk Ridge, in the lower reaches of Floe Creek, and in a series of roadside exposures immediately northwest of Vermilion Crossing (Figs. 4, 5). The unit is also intermittently exposed on the lower slopes of Numa Mountain, below sections 5 and 36 (Fig. 2). Section measurement is precluded by a lack of continuous exposure, and thus the total stratigraphic thickness of this sedimentary package is unknown.

The undivided unit is composed of grey slate that weathers light grey to slightly reddish-grey. These rocks are characterized by light and dark grey laminae that alternate on a millimetre-scale (Plate 4d). Favorably oriented cleavage faces near Vermilion Crossing exhibit abundant evidence of synsedimentary deformation, including recumbent folded or partially homogenized zones, chaotically folded zones, and debris flows (Plate 4c, e). Ribbon argillite occurs very rarely as small, exotic blocks up to 50x18 cm in size.

5.5.2 Basic interpretation

Abundant features indicative of sediment instability indicate that this unit accumulated on a slope. The millimetre-scale cycles in the slate are inferred to be base cut-out turbidites ($E_{\text{turbidite}} - E_{\text{hemipelagite}}$), which were deposited in a deep-water environment below maximum storm wave base.

5.6 **McARTHUR UNIT: TOKUMM SUB-UNIT**

5.6.1 Definition

The McArthur unit (new name) is a deep-water limestone and argillite sequence of Middle Cambrian age. It was named after Lake McArthur, which is situated beneath a major exposure of the unit on Park Mountain (Figs. 4, 5).²¹

The McArthur unit corresponds to the upper part of the lower Chancellor division, as defined by Cook (1975). It is divisible into two, distinctive sub-units: the **Tokumm sub-unit** (new name), named after Tokumm Creek in Prospectors Valley (Fig. 4), and the

²¹ Stewart (1989) used the term "Park unit" to designate this sequence.

Vermilion sub-unit (new name), named after Vermilion Peak (Fig. 5; described in Section 5.7).

The **Tokumm sub-unit** is a Middle Cambrian slope sequence that is composed of predominantly thin-bedded limestones and subordinate, intercalated argillites. It conformably and gradationally overlies the Stephen Formation (and locally the lower Eldon Formation), and is unconformably overlain by the Vermilion sub-unit.

The following description of the Tokumm sub-unit is complicated by the fact that it is traversed by two major unconformities attributed to large-scale outer platform and upper slope collapse. As similar unconformities occur in other stratigraphic units as well, they will be described and interpreted together in Chapter 6.

5.6.2 Section localities

The Tokumm sub-unit is exposed throughout the study area. The most widely exposed, and hence most "typical" Tokumm sections are situated immediately southwest of the facies change in Prospectors Valley (Plate 44, 48a) and along Haffner Creek. These sections are incomplete, as they overlie a westward-projecting tongue of the lower Eldon Formation (Fig. 26).

Two readily correlatable sections in Prospectors Valley are proposed as a composite type section (Fig. 26). Section 10 contains the lower Eldon tongue (99.2 m), which is overlain by the lower 107.6 m of the Tokumm sub-unit. The upper of two, conspicuous argillite markers can be used to correlate this sequence with section 11, about 500 m southeast along depositional strike (Plate 44). This section contains the remainder of the

Tokumm sub-unit, as well as its upper contact. Excellent exposures are also found in nearby section 9 (Appendix 2), although the top of the sub-unit is covered. Incomplete sections of the Tokumm sub-unit are also present above Haffner Creek, 8 km to the southeast (sections 4, 29; Fig. 2). The Tokumm sub-unit is also well exposed on the southwest side of Marble Canyon (Plate 48b).

Stratigraphic sections of the Tokumm sub-unit have also been measured at Stephen Cirque (sections 24, 25), Mt. Biddle (section 20), Curtis cirque (section 21), Tokumm headwaters (section 17), The Monarch (section 22) and Monarch cirque (section 27). All lie within about 1-2 km of the facies change. The most distal section measured through the Tokumm sub-unit is at Numa Mountain (section 36), about 4-5 km southwest of the facies change.

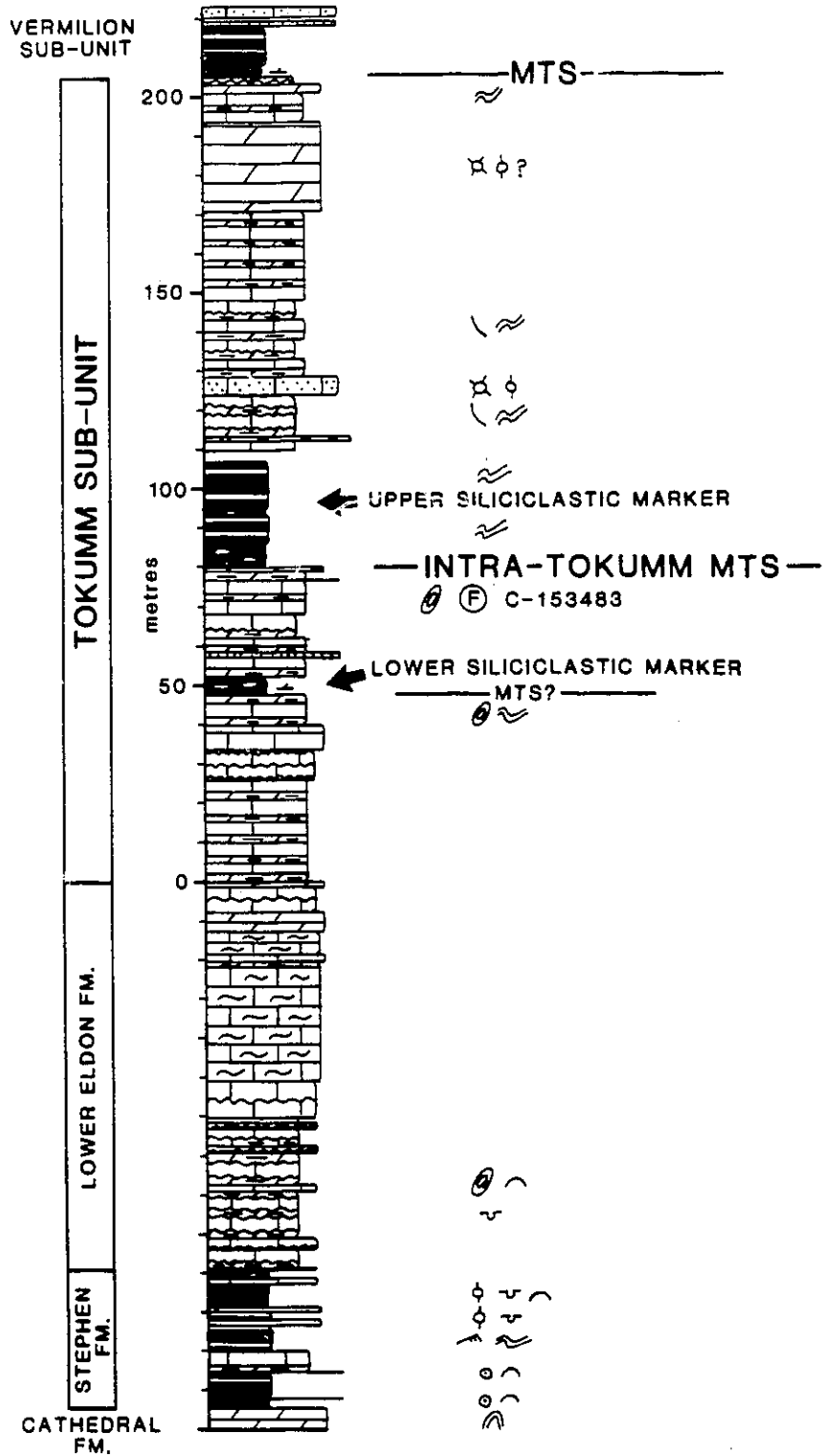
5.6.3 Lithology

The Tokumm sub-unit is composed primarily of planar to irregular ribbon limestones of the ribbon calcilutite lithofacies (Plates 11c-e; 48b, e). Rotated blocks, pull-apart structures, intrafolial folds, slide masses and intraformational truncation surfaces of all scales provide abundant evidence of sediment instability during deposition of this sub-unit (Plates 13, 14). Excellent examples of these features can be viewed in the cliffs overlooking Marble Canyon.

Two fine-grained siliciclastic marker units occur in sections along Prospectors Valley. Both have abrupt contacts. The lower marker is 5-10 m thick, and has not been recognized outside of Prospectors Valley. The upper marker is 27-33 m thick, and has also

Figure 26. Composite type section of the Tokumm sub-unit, based on sections 10 and 11 in Prospectors Valley. The section conformably overlies platformal strata of the Cathedral, Stephen and lower Eldon formations. The intra-Tokumm megatruncation surface is inferred to pass through the section at the base of the upper siliciclastic marker. MTS: megatruncation surface. See Fig. 20 for legend.

TOKUMM SUB-UNIT: COMPOSITE TYPE SECTION



been identified above Haffner Creek (sections 4, 29; Appendix 2).²² Major siliciclastic markers are present at comparable stratigraphic levels at The Monarch (section 22), Numa Mountain (section 36), and the western part of Stephen cirque (section 24; Plate 47). All of these markers are composed of finely laminated argillite and ribbon argillite (Plate 5a, b), and contain recumbent folds, chaotic structures, and other features indicative of synsedimentary deformation.²³

Minor rock-types in the Tokumm sub-unit include calcarenite and limestone conglomerate. The calcarenite beds and lenses are generally less than 1 m thick (Plate 23a, b). Massive dolostone units up to 30 m thick (sections 9 and 11; Appendix 2) may originally have been calcarenite-filled megachannels like those documented in the overlying Vermilion sub-unit (Section 4.5.3). Their overall geometry could not be determined. The limestone conglomerate beds are generally less than 1 m thick, and contain both platform- and slope-derived clasts. Stacked conglomerates are locally present at the top of the Tokumm sub-unit in Prospectors Valley (section 30), and are also found in the headwaters of Tokumm Creek, at Mt. Biddle, and in Curtis cirque (sections 17, 20 and 21 respectively; Appendix 2). The section at Mt. Biddle also contains a 4.5 m thick megaconglomerate with megaclasts up to 9x5.3 m in size.

Periplatform talus blocks occur rarely in the Tokumm sub-unit. The most prominent example is about 6x20 m, and occurs at the top of the upper siliciclastic marker in Section 10 (Plate 33c). A more accessible example is present at the same stratigraphic level near Marble Canyon (Plate 48b).

²² The lower marker, if present, is not exposed.

²³ The origin of these markers will be discussed in Chapter 6, where it will be suggested that they overlie internal megatruncation surfaces.

Small-scale hummocky cross-stratification is uniquely present in a basal Tokumm sub-unit dolosiltite at The Monarch (Plate 5c). The hummocky forms have amplitudes of only a few centimetres (as opposed to the tens of centimetres typical in siliciclastic settings), and occur in a sequence otherwise dominated by horizontally laminated dolosiltite. They are very similar in scale and geometry to the small-scale hummocky cross-stratification documented in calciclastic turbidites by Prave and Duke (1990), who suggested that these structures are a form of antidune cross-stratification deposited during the waning-flow stage of a turbidity current.

In more distal sections, argillite becomes more important. The Tokumm sub-unit at Mt. Biddle (section 20, Appendix 2; Plate 46) contains substantially more argillite than coeval strata in the Tokumm Creek headwaters area (section 17; see Fig. 32). In the most distal section measured during this study (Numa Mountain, section 36; Appendix 2), the ribbon limestones are quite argillaceous, and tend to be indistinctly to wavy bedded. Normally graded laminae and small-scale crosslaminae occur sporadically in the lower part of the sub-unit, and nodules containing deformed laminae and southeasterly-oriented, starved ripple sets up to 4 cm thick occur in its upper part.

5.6.4 Contacts

The contact relationships of the Tokumm sub-unit are complicated by facies changes in the lower part of the sub-unit, and by the significant unconformity at its top. As a result, contact relationships differ markedly from area to area.

In the type area, the Tokumm sub-unit overlies the lower Eldon tongue (Fig. 26). The contact is characterized by a gradual, upward change from massive, burrow-mottled

limestone to ribbon calcilutite. Westward, the lower Eldon tongue changes facies into the lower Tokumm sub-unit. Thus, in the Nataoko Lake/Monarch area (sections 22, 23, 27) and in western Stephen cirque (section 24), the Tokumm sub-unit rests sharply on either the "platformal" or the "basinal" Stephen Formation (Section 5.4.4). At Numa Mountain (section 36), the Tokumm sub-unit presumably overlies the undivided Naiset - Takakkaw Tongue - "basinal" Stephen Formation equivalent, but the actual contact is not exposed.

Near Mt. Biddle and in eastern Stephen cirque, the Tokumm sub-unit overlies megatruncation surfaces that progressively cut out the Eldon Formation stratigraphy laterally (Plates 46, 48c; 49). These localities will be described more fully in Section 6.2.1.

The upper contact of the Tokumm sub-unit is generally recognizable as the point where grey-weathering, resistant carbonate strata are abruptly succeeded by brown-weathering, slightly recessive argillaceous rocks of the Vermilion sub-unit. This contact is marked by a subtle topographic break throughout Prospectors Valley (Plates 44; 45; 48a; 48d; 55b), and in the Nataoko Lake/Monarch area (Plates 42; 43b). Aside from the abruptness of the contact, there is no hint that it is, in fact, a large-scale erosional surface. The regional evidence for this interpretation will be discussed in Chapter 6.

5.6.5 Distribution and thickness

The Tokumm sub-unit is distributed throughout the study area, except for the cross-strike exposures in Verdant cirque (Plates 52-54). There, the Vermilion sub-unit directly overlies truncated Eldon-Pika platform strata, which presumably change facies downslope (and out of view) into the Tokumm sub-unit. This locality will be described in detail in Chapter 6.

The thickness of the Tokumm sub-unit varies considerably as a result of facies changes in its lower part, and large-scale erosional truncation from above. The basinward transition from the lower Eldon tongue into the lower Tokumm sub-unit causes the sub-unit to thicken westward. At the same time, however, large-scale erosional truncation by the sub-Vermilion megatruncation surface thins the Tokumm sub-unit in the same direction. Thus, the thickness of the sub-unit at any one locality depends on the interplay of these two factors.

In the type area (Prospectors Valley and Haffner Creek; sections 4, 9, 10, 11, 29, 30; Fig. 2), the Tokumm sub-unit is about 200 m thick (204.2 m in the type section; Fig. 26). These rocks overlie about 100 m of platform strata belonging to the lower Eldon tongue. Eleven kilometres to the northwest in the Tokumm headwaters area (section 17), the Tokumm sub-unit is thinner (144.8 m), and the lower Eldon tongue is correspondingly thicker (216.7 m). On the opposite (southwestern) side of the same ridge in Misko Valley, the Tokumm sub-unit is sandwiched between two megatruncation surfaces, and thus its thickness changes rapidly both along and across depositional strike. This is reflected in the 130.1 m thickness at Mt. Biddle (section 20), compared to 95.9 m at Curtis cirque (section 21), only 1.2 km away.

The lower Eldon tongue is absent from the Nataoko Lake/Monarch area. On the north face of The Monarch (section 22), the Tokumm sub-unit rests directly on the "basinal" Stephen Formation (Plate 42), and is 239.4 m thick.

In western Stephen cirque (section 24), the Tokumm sub-unit also rests directly on the Stephen Formation, and is 179.9 m thick. At the most distal locality examined (Numa

Mountain; section 36), the Tokumm sub-unit is at least 144.4 m thick, but its base is not exposed.

5.6.6 Age and correlation

All fossils collected from the Tokumm sub-unit have been referred to the Bathyriscus-Elrathina Zone. Only three collections, recovered immediately above and below the upper siliciclastic marker in the type area, permit a more specific age assignment within this zone. Collections C-153438, 153483 and 166530 (Appendix 1) have all been referred to the Ptychagnostis gibbus Zone by W.H. Fritz (Appendix 1).²⁴ The only other fossil collection of possible significance comes from a bed 11 m below the top of the Tokumm sub-unit in section 18 (C-166635; Appendix 1). The collection is characterized by "Rowia-like cranidia [resembling] those in the Pika Formation, which is lower Bolaspidella Zone in age, whereas the remainder of the collection is most suggestive of the Bathyriscus - Elrathina Zone". Collectively, the fossil evidence suggests that the Tokumm sub-unit is correlative with the upper Eldon Formation and possibly the basal Pika Formation.

Physical correlation indicates that the Tokumm sub-unit is equivalent to the entire Eldon Formation, and about the lower half of the Pika Formation. This is based mainly on lateral facies relationships observed in the exceptional, cross-strike exposure of the facies change in Stephen cirque (Plate 49). The stratigraphy at this locality is inextricably linked to at least three megatruncation surfaces, and will therefore be discussed in Chapter 6 (Section 6.2.2).

²⁴ A fauna from the same zone has also been reported from the Field Member of the Eldon Formation (Robison, 1982, p. 133).

5.6.7 Basic interpretation of the Tokumm sub-unit

The Tokumm sub-unit accumulated in an upper slope environment. Deposition on a slope is amply indicated by a variety of features indicative of sediment instability (Plates 13, 14). Evidence for wave or current activity is lacking, suggesting that sedimentation took place below maximum storm wave base.

Although the Tokumm sub-unit lithologically resembles the Takakkaw Tongue, it contains fewer intraformational truncation surfaces, slide masses, periplatform talus blocks, and debris flows. This may reflect a lower sedimentation rate, a gentler slope, or perhaps lesser seismic activity during Tokumm sub-unit time.

5.7 McARTHUR UNIT: VERMILION SUB-UNIT

5.7.1 Definition

The Vermilion sub-unit is a Middle Cambrian sequence of brown-weathering argillite and thin-bedded limestone containing prominent, grey-weathering, allochthonous carbonate masses (megaconglomerate, periplatform talus blocks, and calcarenite-filled megachannels). It unconformably overlies the Tokumm sub-unit or platformal strata of the Eldon Formation, and is conformably overlain by the Duchesnay unit (Arctomys equivalent).

5.7.2 Section localities

The type section of the Vermilion sub-unit is exposed on the lower east slope of Vermilion Peak (upper section 4, Figs. 2, 27). Unfortunately, the lower contact of the sub-unit is covered at that locality. A reference section exposing this contact has therefore been

VERMILION SUB-UNIT

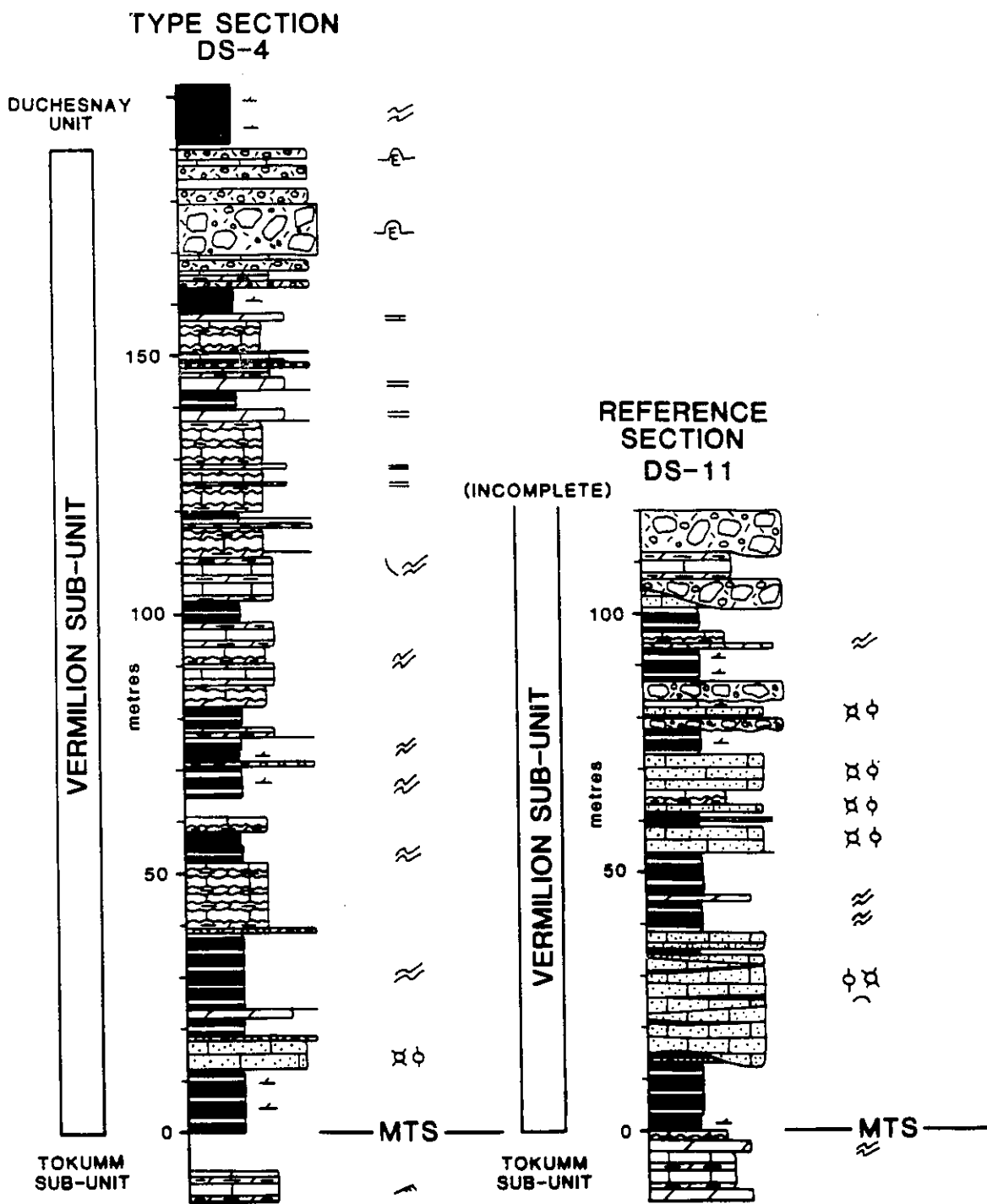


Figure 27. Type and reference sections of the Vermilion sub-unit, based on sections 4 and 11 in the Haffner Creek - Prospectors Valley area. MTS: megatruncation surface. See Fig. 20 for legend.

designated in Prospectors Valley (section 11, Fig. 27; Plate 44). Other aspects of the Vermilion sub-unit can also be studied in nearby canyons (sections 9, 30; Fig. 2).

The physical relationships between the platform and slope sequences are spectacularly displayed by the cross-strike exposures in Stephen cirque (Plates 49, 50; sections 25, 26, 35), Duchesnay basin (Plate 51), and Verdant cirque (Plates 52-54; sections 33, 34). At each of these localities, the Vermilion sub-unit unconformably overlies the truncated upper Eldon-Pika margin. A fourth, cross-strike exposure near Mt. Biddle (sections 20, 21) displays the relationship between the Vermilion and Tokumm sub-units in a slightly more distal setting (Plates 46, 48d). The most distal sections studied are exposed on Numa Mountain (sections 5, 36; Fig. 2), about 4.5 km west of the facies change.

5.7.3 Lithology

The Vermilion sub-unit is laterally and vertically heterogeneous. It has two distinctive attributes: (1) it can usually be differentiated from the underlying Tokumm sub-unit by its brown-weathering colour, imparted mainly by an abundance of dolomitic argillite and dolostone; and (2) it contains prominent, allochthonous, grey-weathering carbonate bodies, particularly in its upper part (e.g. Plates 33d; 44; 45; 48a; 55a).

Argillite occurs throughout the Vermilion sub-unit (Plate 5d, e), but is most common in about the lower half of the sequence (Fig. 27). Laminated argillaceous siltstone beds occur sporadically in the upper part of the sub-unit (Plate 6a, b). Convolute laminae, intrafolial folds, intraformational truncation surfaces, slide masses, chaotically deformed zones, and homogenized units are common in these rocks (Plate 6c-e).

Ribbon calcilutite is commonly volumetrically significant in the upper half of the Vermilion sub-unit (section 4, Fig. 27; Plate 12a, b). The distinction between ribbon calcilutite and ribbon argillite is often arbitrary in this sequence, as the two typically intergrade vertically and laterally. The ribbon calcilutite is also characterized by numerous features indicative of sediment instability.

Volumetrically minor rock types in the Vermilion sub-unit include calcarenite beds and lenses and limestone conglomerates. The calcarenite is identical in all respects to that in the Tokumm sub-unit. Limestone conglomerate beds less than 2 m thick are common in all sections. Most are mixed clast conglomerate containing both slope- and platform-derived clasts (Plate 27a-c).

Allochthonous carbonate masses are volumetrically less important than argillite and ribbon limestone, but are nevertheless the most visible component of the Vermilion sub-unit. At least four types of "grey bodies" are present: megaconglomerate, periplatform talus blocks, calcarenite-filled megachannels, and large-scale slide masses.

Megaconglomerate dominates the upper Vermilion sub-unit along Prospectors Valley (sections 9, 11, 29) and Haffner Creek (sections 4, 29). In these valleys, complexes of channellized megaconglomerate are largely confined to the upper part of the sub-unit (Plates 28b-d; 48a; 55e). In more proximal sections, megaconglomerate occurs at other stratigraphic levels as well. By far the most impressive examples occur in the cross-strike exposures in Verdant cirque (sections 33, 34; Plates 27d, e; 52-54). Five megaconglomerates are visible on the northwest wall of the cirque (Plates 52, 53). In similar cross-strike exposures in Stephen cirque, the megaconglomerates are more local (Plates 50, 51).

Periplatform talus blocks are very common in the upper Vermilion sub-unit. Spectacular examples are visible at and immediately upstream of Marble Canyon (Plates 33d; 48b). Numerous other examples are exposed along the southwest wall of Prospectors Valley (Plates 44, 45).

Megachannel calcarenite is best developed in the vicinity of section 11 in Prospectors Valley (Figs. 2, 27; Plates 21a; 44). Thinner examples occur along Haffner Creek (section 29; Appendix 2), in Verdant cirque (section 33), and in the cliffs overlooking Marble Canyon.

Large-scale slide masses composed of ribbon limestone occur in and near section 9 in Prospectors Valley (Plate 28c), above section 33 in the Verdant headwaters area (Plate 54), and in Stephen cirque (Plate 50). All are elongate, laterally pinching bodies of planar to irregular ribbon calcilutite. The examples in Stephen cirque are estimated to be up to 35 m thick and at least 600 m long. Notably, had sufficient lateral exposure not been available, these features would have been mistaken for autochthonous ribbon limestone sequences.

5.7.4 Contacts

The upper contact of the Vermilion sub-unit is generally marked by an abrupt lithological change from relatively resistant carbonate rocks to monotonous, cleaved, brown-weathering argillite or slate of the Duchesnay unit (Plates 44; 45; 52-54; 55c, e). The prominent, grey-weathering carbonate band in the upper Vermilion sub-unit is typically composed of channellized megaconglomerate and subordinate ribbon limestone slide masses. As these bodies are laterally discontinuous and have local relief, the contact is somewhat

irregular. The contact is readily recognizable over a distance of at least 35 km from Misko Valley in the northwest to Verdant Creek in the southeast.

On the west side of Dennis Pass near Field (Fig. 3), the upper contact of the Vermilion sub-unit is similarly represented by an abrupt change from massive, grey-weathering carbonate rocks to reddish brown-weathering slate (Plate 55c). The carbonate unit has not been studied in detail, but is composed at least partly of massive limestone conglomerate with megaclasts or massive interbeds of oolitic grainstone. At lower elevations on the north and south sides of Mt. Dennis, the contact is underlain by up to 120 m of ribbon calcilutite (Plate 56a). The ribbon calcilutite unit on the north side of Mt. Dennis terminates abruptly uphill, and may be a single, gigantic slide block.

East of Dennis Pass in Stephen cirque (Fig. 3), the upper contact of the Vermilion sub-unit is less distinct. In the central part of the cirque, two major stratigraphic packages can be discerned (Plate 50).²⁵ The lower package is composed largely of bedded argillite and ribbon argillite (both commonly dolomitized), and contains elongate, intercalated slide masses of ribbon limestone. A thick, laterally discontinuous megaconglomerate also occurs in this sequence. The ribbon limestone slide masses and the megaconglomerate resemble the "grey bodies" so typical of the Vermilion sub-unit on the southwest wall of Prospectors Valley. Above is a second stratigraphic package of massive, cleaved, monotonous, brown-weathering argillite. This package strongly resembles the lower Duchesnay unit in Prospectors Valley and Verdant Creek. Thus, the contact between these two stratigraphic packages is thought to correspond to the contact between the Vermilion sub-unit and Duchesnay unit elsewhere. This contact is not easily mapped, as it is not marked by a

²⁵ This locality will be described in greater detail in Chapter 6 (Section 6.2.2).

widespread, massive carbonate unit. Nevertheless, it appears to make the most sense for the purposes of mapping and correlation.

5.7.5 Distribution and thickness

The Vermilion sub-unit is exposed throughout the study area, and available evidence indicates that it thickens basinward. In Verdant cirque, where the Vermilion sub-unit overlies the truncated Eldon/Pika margin, it is 158.3 m thick (section 34). The type section along Haffner Creek, which is slightly more distal, is 190.1 m thick. The only complete section of the Vermilion sub-unit in Prospectors Valley (section 9) has a very similar thickness (194.3 m). However, the level of the upper contact varies as much as 20-40 m, due to lateral thickness variations and irregularities in the top of the carbonate marker. In sections 30 and 11 (Plate 44), for example, the Vermilion sub-unit is estimated to have complete thicknesses of 150 and 170 m respectively.²⁶ In Stephen cirque, the sub-unit is anomalously thick at 340 m. No complete sections have been measured farther basinward, but the section at Numa Mountain (section 36; Appendix 2) exceeds 200 m in thickness.

5.7.6 Age and correlation

Fossils are extremely rare in the Vermilion sub-unit. In-situ trilobites referable to the Bolaspidella Zone have been recovered in Stephen cirque (C-167264, Appendix 1; section 26). Trilobites found in talus at the foot of the south wall of Verdant cirque (Plate 54) have also been referred to this zone (C-179299 and C-179300; Appendix 1). Both the Vermilion sub-unit and Duchesnay unit crop out in the cliffs above, but the lithology of the

²⁶ These thicknesses were estimated from an oblique aerial photograph. Complete sections could not be measured directly, as the upper, cliff-forming carbonate marker was inaccessible.

fossil-bearing samples indicates that they most likely came from the former stratigraphic unit.

In the absence of substantive paleontological data, the age and correlation of the Vermilion sub-unit are best inferred from the lateral stratigraphic relationships visible in Stephen and Verdant cirques (Plates 49, 50; 52-54). These exposures suggest that the Vermilion sub-unit is correlative with about the upper half of the Pika Formation (Fig. 16). The stratigraphy in both cirques is complicated by a series of megatruncation surfaces, and will be described in detail in Chapter 6 (Sections 6.2.2 and 6.2.3).

5.7.7 Basic interpretation of the Vermilion sub-unit

The abundance of intraformational truncation surfaces, slide masses, and gravity flow deposits, including impressive megaconglomerate, provides confirmatory evidence of deposition on a slope. Local gullying of the slope by slide scars is indicated by the presence of calcarenite-filled megachannels (Section 4.5.3.4). Biogenic structures are absent, and no substantive evidence exists for surface wave or current activity. Deposition below maximum storm wave base is indicated.

5.8 DUCHESNAY UNIT

5.8.1 Definition

The Duchesnay unit (new name) is a late Middle Cambrian succession of argillite, slate, and various types of deep-water carbonate sediment. Regionally, it conformably overlies the Vermilion sub-unit, and appears to be conformably overlain by the Oke unit (Fig. 16).

The Duchesnay unit corresponds to the recessive, lower middle Chancellor division mapped by Cook (1975) in the southern part of his study area. Its name was derived from Mt. Duchesnay (Fig. 3), where a highly deformed section of the Duchesnay unit is exposed (see photograph in Cook, 1975, p. 45).

5.8.2 Section localities

Stratigraphic sections have been measured at five localities. Only two complete, undeformed sections of the Duchesnay unit were found in the study area. Due to lateral variability and structural complexity, this unit is probably one of the least understood stratigraphic units in the Chancellor.

The type section of the Duchesnay unit is designated as the exposure on the north side of Mt. Dennis (section 1, Figs. 3, 28; Plate 56a). The main disadvantage of this section is that it contains a long offset along a major conglomerate marker in its lower part. The exposure on the opposite (south) side of Mt. Dennis serves as a convenient reference section (section 8; Figs. 3, 28; Plate 56d). It is less readily accessible, but has the advantage that original depositional textures are better preserved. Although the base of the formation is tightly folded on the eastern ridge of Mt. Dennis (Plate 55c), the lower contact can be picked with reasonable certainty at lower elevations where the deformed zone passes into a westward-dipping monocline. This occurs in a wooded area with poor exposure on the south side of Mt. Dennis, and thus the reference section contains significant stratigraphic gaps near its base.

DUCHESNAY UNIT

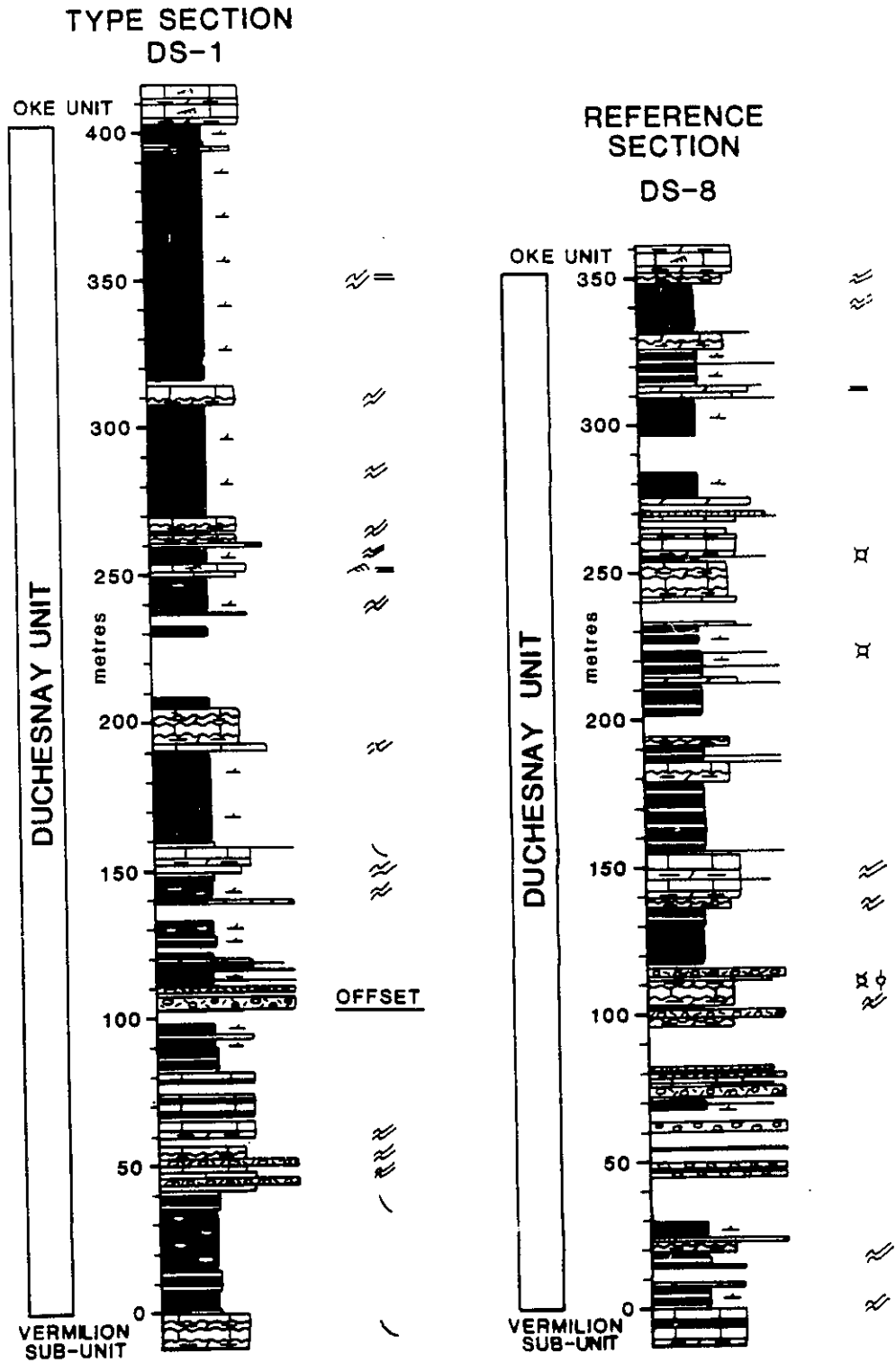


Figure 28. Type and reference sections of the Duchesnay unit, based on sections 1 and 8 on Mt. Dennis. See Fig. 20 for legend.

Additional, nearly complete sections of the Duchesnay unit have been measured farther southeast in the vicinity of Mt. Oke (sections 7, 19; Fig. 2). The succession at Mt. Oke, though incomplete, is different in many respects from the type section, and is therefore designated as a second reference section (Fig. 29; Plate 58a). Short sections have also been measured through the upper part of the Duchesnay unit near Misko Mountain (sections 16, 16a; Fig. 2; Appendix 2).

Along the remainder of Prospectors Valley and above Haffner Creek, the Duchesnay unit is complexly deformed and usually poorly exposed. Prominent, structurally complex exposures are also visible along Hawk Ridge (Fig. 5).

The Duchesnay unit has also been examined in the southeasternmost extremity of the study area near Miller Pass (Fig. 5). There, the unit sharply overlies platform carbonate rocks of the undivided Eldon and Pika formations (Plate 56b, c; section 12, Appendix 2). Due to structural complexity, only the uppermost 113 m of the unit (section 13) could be measured. The Duchesnay unit also overlies the undivided Eldon and Pika formations near Hamilton Lake (Fig. 3), where two additional sections were measured (sections 31, 32; Plate 57).

5.8.3 Lithology

The Duchesnay unit is lithologically heterogeneous, and is difficult to describe concisely. The dramatic appearance of abundant laminated/crosslaminated siltstone and ribbon calcisiltite in this succession indicates a fundamental change in the style of slope sedimentation.

DUCHESNAY UNIT: REFERENCE SECTION DS-7

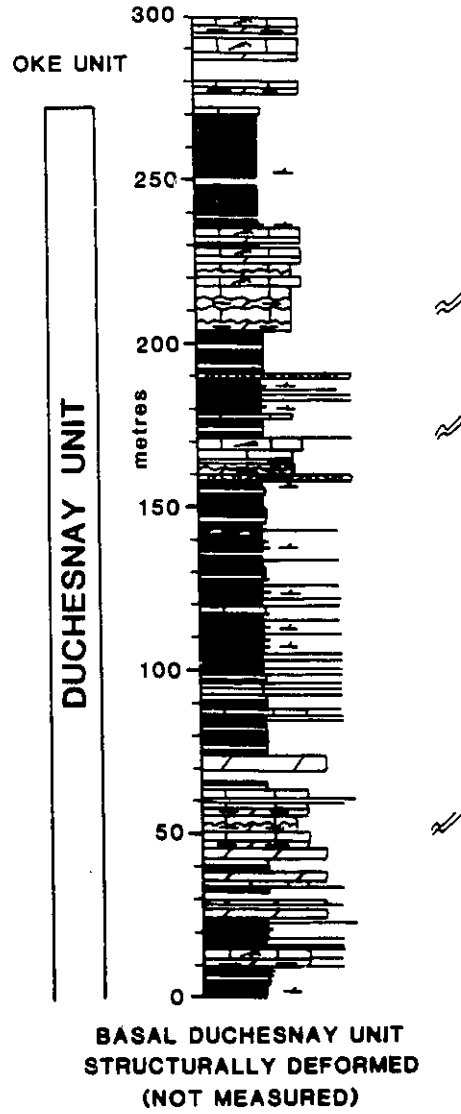


Figure 29. Reference section of the Duchesnay unit on Mt. Oke. See Fig. 20 for legend.

The **type section** (section 1) is predominantly composed of the argillite lithofacies, but also contains intercalated ribbon limestone and limestone conglomerate (Fig. 28). The predominantly siliciclastic intervals in the Duchesnay unit are composed of massive, nodular to ribbon argillite and slate. These rocks are strongly dolomitic on both sides of Mt. Dennis (Plate 7a, b), which accounts for the conspicuous, brown- to reddish-brown-weathering colour of the Duchesnay unit on that mountain (Plates 55c, 56d). The sequence also contains proportionately minor ribbon limestone, thin beds and lenses of intraclastic grainstone, and limestone conglomerate. The ribbon calcisiltite contains graded laminae, crosslaminae and starved ripple horizons. Sedimentary features indicative of slope instability (e.g. intraformational truncation surfaces, synsedimentary deformation, slide masses) are less common than in the underlying Vermilion sub-unit.

In both the type and reference sections, prominent limestone conglomerate units are intercalated with argillite and slate in the lower Duchesnay unit (Fig. 28). The distinctive marker conglomerate used to offset the type section contains poorly preserved, probable Epiphyton boundstone and peloidal-intraclastic grainstone clasts. Other clast types include limestone plates and chips, deformed argillite, and ribbon limestone rafts up to 3.5 m long. The other conglomerate units are mainly clast-supported limestone chip and mixed clast conglomerates (Plate 30a-c).

The stratigraphic succession in the **Mt. Oke and Misko Mountain areas** (sections 6, 7, 16, 16a, 19; Fig. 2) is broadly similar to that in the type area. However, conglomerates are much less common, and ribbon calcisiltite and laminated/crosslaminated argillaceous siltstone are much more prominently developed (Fig. 29; Plates 7c, d; 17b, d). These rock types were described in detail in Sections 4.3 and 4.4.

Near **Miller Pass** (sections 12, 13; Appendix 2), the basal Duchesnay unit rests abruptly on dolomitic, peritidal platform strata of the undivided Eldon and Pika formations. The contact is inaccessible, but appears to be planar and parallel to underlying bedding (Plates 56b, c). The basal Duchesnay unit is composed of ribbon argillite (Plate 8d), which is overlain by 11 m of ribbon limestone. The ribbon argillite contains abundant intraformational truncation surfaces and internal slide masses, and, rarely, cobble-sized, Epiphyton-Renalcis boundstone clasts (Plate 31e). The ribbon limestone passes upward into a structurally complex zone composed mainly of slate.

The basal Duchesnay unit is anomalously fossiliferous at this locality. Large numbers of trilobites, hyolithids and a soft-bodied fauna (including previously undescribed forms) have been recovered from talus and outcrop (Plate 8e).²⁷ The soft-bodied fauna is highly significant in that it is considerably younger (Bolaspidella Zone; Appendix 1) than the Burgess fauna near Field.

The uppermost 113 m of the Duchesnay unit at Miller Pass is characterized by nodular slate and ribbon limestone (section 13; Appendix 2). The sequence also contains several limestone plate and mixed clast conglomerate units up to 3.7 m in thickness (Plate 30b).

5.8.4 Stratigraphic succession at Hamilton Lake

The stratigraphic succession exposed at **Hamilton Lake** is unique, as it is the only known locality where the shelf-to-slope relationships are largely preserved at the level of the

²⁷ This fossil locality was originally discovered by a mineral explorationist, D.L. Pighin, and was kindly shown to the writer by C. Schultze. Some of the fossils recovered are listed in entries 24 and 25 in Appendix 1. A large number of other fossils were collected by the Royal Ontario Museum in 1988, but have not yet been reported on.

middle Chancellor. The more proximal character of the Duchesnay unit at this locality is also reflected by the lithology of the succession, which differs substantially from that of other areas. The Hamilton Lake locality is critical to the regional interpretation of the Duchesnay unit, and is accordingly described in detail below.

Previous geological maps of the Hamilton Lake area (Cook, 1975; Balkwill *et al.*, 1980) show a platform sequence (Eldon, Pika, Arctomys and Waterfowl formations) in the northern part of the cirque, juxtaposed with lower and middle Chancellor strata across a thrust fault to the south and west (Plate 57). The major rock units in the northern part of Hamilton cirque (informal name) are described below in ascending stratigraphic order:

1. **Platform carbonate sequence (Pika Formation):** burrow-mottled limestone, burrow-stratified limestone, and their dolomitized equivalents. Crossbedded ex-calcarenite and a few, thin layers of cryptalgal laminite are also present. The upper contact is covered in northern Hamilton cirque, and thus the stratigraphic relationship with the overlying ribbon limestone sequence there is uncertain. On the south ridge of Mt. Carnarvon, the burrow-mottled limestones grade upward into irregular, non-burrowed ribbon limestone (Plate 56e).
2. **Ribbon limestone sequence** (uppermost Pika Formation; 15-20m below section 31): dark grey ribbon limestone, with abundant agnostid and larger trilobites, trilobite debris, and phosphatic brachiopods (C-179248; C-179249; Appendix 1). The ribbon limestone on the south ridge of Mt. Carnarvon is thinner (5-8 m) and more irregular in appearance. Its contact with the overlying argillite is abrupt (Plate 56e).

3. **Argillite** (lower Duchesnay unit; 97 m): monotonous, finely laminated argillite and nodular argillite (Plate 8b), with subordinate, thin interbeds of oolitic-intraclastic grainstone and minor burrows near its top. Intraformational truncation surfaces, thin slide masses and limestone conglomerate are conspicuously rare.

4. **Argillite-dominated cyclical sequence** (upper Duchesnay unit; 91 m in section 32): sharp-based, small-scale shallowing-upward cycles (1-13 m thick), in which bioturbated argillite grades upward into burrow-stratified and burrow-mottled limestone (Section 4.8.2.1; Plate 34d). Thin, intraclastic-oolitic-skeletal grainstone interbeds occur sporadically.

The nature of the overlying sequence depends on location within the cirque. On Mount Carnarvon proper, the argillite-dominated cycles grade upward into a sequence of carbonate-dominated cycles estimated to be about 180 m thick (Plate 57). The carbonate sequence is largely dolomitized, and consists mainly of ex-burrow-stratified and ex-burrow-mottled limestone, together with minor nodular argillite. This sequence has been positively identified as the Waterfowl Formation, on the basis of lithology and stratigraphic position beneath the Sullivan Formation.²⁸

On the south ridge of Mt. Carnarvon, the carbonate sequence is eroded, and the argillite-dominated sequence abruptly kinks downward across a dog-legged thrust fault (Fig. 57).²⁹ South of this fault, the argillite-dominated cyclical sequence is overlain by 41.8 m of nodular and ribbon argillite containing minor intraclast grainstone lenses. This sequence,

²⁸ This relationship was accurately mapped by Balkwill *et al.* (1980). However, the upper Pika contact was mapped too high in Hamilton cirque, and the Duchesnay unit was mapped as Arctomys Formation.

²⁹ The writer is grateful to Dr. D.G. Cook, who assisted in sorting out the structural relationships at this locality during a brief, but memorable visit.

which also contains a single megaconglomerate, has been assigned to the basal Oke unit (section 32, 72.1-113.9 m; Appendix 2).

The argillite passes upward into a ribbon limestone sequence more typical of the Oke unit. This succession is severely deformed, and resembles the strongly deformed exposures of the Oke unit above Marble Canyon, 42 km to the southeast.

5.8.5 Contacts

Through most of its area of exposure, the Duchesnay unit conformably overlies the Vermilion sub-unit (Section 5.7.4). The sequences at Miller Pass and Hamilton Lake are the only known exceptions. At both localities, the Duchesnay unit overlies the undivided Eldon-Pika sequence with an abrupt, but structurally concordant, contact (Plates 56b, c, e).

Outside of the Hamilton Lake area, the contact between the Duchesnay and Oke units is readily mapped as the topographic break separating a recessive, brown-weathering, predominantly argillite/slate sequence from a resistant, grey-weathering, carbonate-dominated sequence. The contact is conformable, and is placed at the top of the highest major argillite/slate unit (on the order of ten or more metres thick). This contact is readily visible at Mt. Dennis (sections 1, 8; Plate 56d), Misko Mountain (section 16; Plate 58b), Mt. Oke (section 7; Plate 58a), and Miller Pass (section 13; Plate 58c).

In northern Hamilton cirque, the upper Duchesnay unit contact is easily recognized as a distinct break between brown-weathering, predominantly siliciclastic strata and grey-weathering, carbonate strata (Plate 57). On the south ridge of Mt. Carnarvon, the contact

between the Duchesnay and Oke units is inferred to be a megatruncation surface (section 32; Appendix 2). This interpretation will be discussed in detail in Section 6.5.

5.8.6 Distribution and thickness

The Duchesnay unit is exposed throughout the study area. The unit is 402.9 m thick in the type section on Mt. Dennis (section 1; Fig. 28), and 347.8 m in the reference section on the opposite side of that mountain (section 8). The only other complete section is the composite section at Hamilton Lake (sections 31, 32), where the unit is estimated to be about 230 m thick.

Complete sections could not be measured at any other locality due to strong structural deformation affecting part or all of the unit. However, thicknesses southeast of the type locality are likely to be similar to those in the type area. In the Mount Oke area, correlations between sections 8 and 19 (Fig. 2; Appendix 2) suggest that the Duchesnay unit there has a minimum thickness of about 395 m.

5.8.7 Age and correlation

No fossils were found in the type or reference sections of the Duchesnay unit. However, Bolaspidella Zone trilobites have been recovered from the remarkable fossil locality at the base of the unit near Miller Pass (section 12; C-153361 through C-153368; also entries 24, 25; Appendix 1). At Hamilton Lake, Bolaspidella Zone trilobites have also been recovered a few tens of metres below the lower contact of the unit from ribbon limestone assigned herein to the Pika Formation (section 31; C-179248, 179249; Appendix 1).

As the Boiaspidella Zone spans a significant lithostratigraphic interval (Fig. 16), physical evidence must be used to secure a more precise correlation between the shelf and slope strata. The exposure at Hamilton Lake is crucial in this regard, as it is the only known locality where the platform-to-basin relationships are largely preserved.

Above Hamilton Lake on Mt. Carnarvon, the Duchesnay unit is sandwiched between the Fika and Waterfowl formations (Plate 57), a stratigraphic interval occupied by reddish-weathering siliciclastic sediments of the Arctomys Formation in the President Range, only 7.5 km to the northeast (Fig. 5). On the south ridge of Mt. Carnarvon, the Duchesnay unit underlies rocks easily recognized as the Oke unit, despite intense structural deformation. Thus, the Duchesnay and Oke units can be unequivocally correlated with the Arctomys and Waterfowl formations, respectively (Fig. 16).

5.8.8 Basic interpretation of the Duchesnay unit

Outside the Hamilton Lake area, the Duchesnay unit was deposited in a relatively deep-water slope environment. Slope deposition is suggested by the abundance of gravity flow deposits in this sequence (siliciclastic silt and carbonate turbidites, debris flows; Plates 17b, d; 23c, d; 24a, b; 30a-c). These sediments were modified slightly by southeast-directed contour currents (Section 4.3.3.2; Plate 7d). Slope instability is indicated by intraformational truncation surfaces, slide units, and synsedimentary deformation in this unit. Notably, these features are less common than in the underlying Vermilion sub-unit, possibly due to a lower slope angle.

The succession exposed at Hamilton Lake is more proximal in nature. In essence, it is a large-scale, shoaling-upward sequence. A detailed interpretation of these rocks will be presented in Section 6.5.

Duchesnay-Oke (Arctomys-Waterfowl) time was marked by an abrupt, regressive shift in the position of the cratonal shoreline some 600 km to the southwest (Fig. 12; section 3.3.6). The resultant reduction in shelf width had important implications for sedimentation on the adjoining slope. First, large quantities of siliciclastic silt and fine-grained sand were exported from the narrow shelf to be deposited as siliciclastic silt turbidites. Second, silt- and sand-sized carbonate particles were supplied in abundance to the slope from a narrow carbonate barrier rimming the margin (Section 3.3.6), giving rise to carbonate turbidites (ribbon calcisiltite and calcarenite lithofacies). The abundance of shelf-derived siliciclastic and carbonate turbidites in the Duchesnay and Oke units implies that off-shelf sediment transport processes were far more effective than during deposition of the Vermilion sub-unit and older strata.

5.9 OKE UNIT

5.9.1 Definition

The Oke unit (new name) is a predominantly carbonate unit of late Middle Cambrian to early Late Cambrian age. It corresponds to the upper middle Chancellor division mapped by Cook (1975). This unit is the most distinctive and easily mapped marker in the Chancellor, because it is sandwiched between recessive, argillaceous strata (Plate 58b). The Oke unit derives its name from Mt. Oke in northwestern Kootenay National Park (Fig. 5).

5.9.2 Section localities

The type section for the Oke unit is situated on the east flank of Mt. Oke (Figs. 5, 30; Plate 58a). A second, complete reference section is situated 5 km to the northwest on Misko Mountain (Fig. 30; Plate 58b).

Due to strong structural deformation, no other complete sections of the Oke unit could be obtained. A partial section covering about the lower two thirds of the unit was measured on the south side of Mount Dennis (section 8; Appendix 2). The only other stratigraphic section of note was measured by J.D. Aitken through the upper 196.9 m of the Oke unit, immediately northeast of Mt. Duchesnay (section AC-130; Aitken, unpubl. data).³⁰

5.9.3 Lithology

The type and reference sections of the Oke unit are composed of a series of carbonate and slate sub-units, each ranging from a few metres to a few tens of metres thick. The sections are divisible into four parts (Fig. 30): (1) a lower carbonate sequence (about 78 m thick); (2) a middle carbonate and slate sequence (about 145 m); (3) an upper slate sequence (about 44 m); and (4) an upper carbonate sequence (about 52 m).

The Oke unit is predominantly composed of the ribbon calcisiltite lithofacies (Section 4.4.3; Plates 16; 17a, c; 18; 19a, b). Ribbon calcilutite, calcarenite beds and lenses (Section 4.5.2), and limestone conglomerate (Plates 16e; 30e) occur sporadically throughout

³⁰ On the Lake Louise West map sheet (Price *et al.*, 1980), this section is wrongly shown to traverse all of the upper middle Chancellor (Oke unit) and part of the lower middle Chancellor (Duchesnay unit).

OKE UNIT

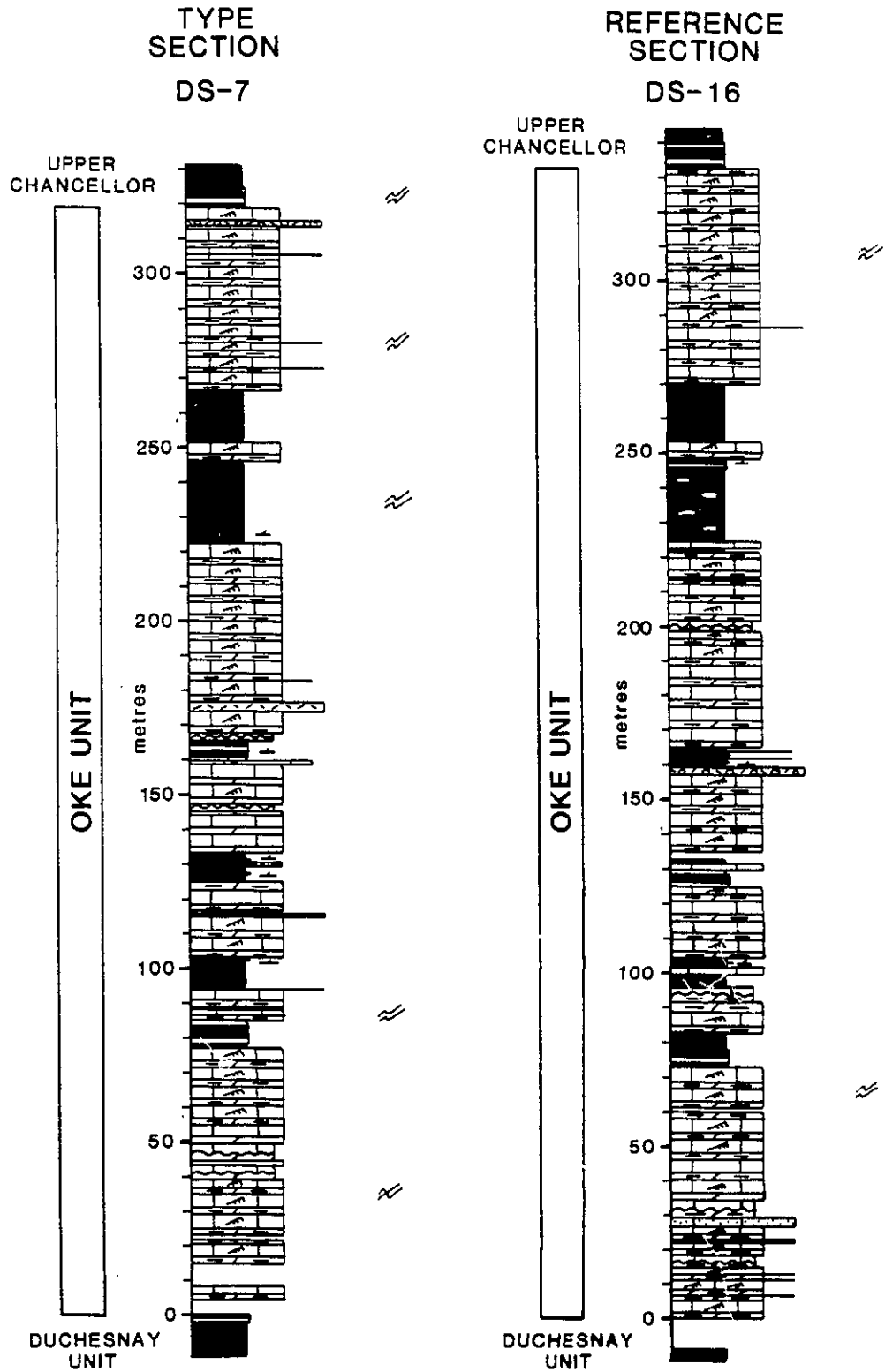


Figure 30. Type and reference sections of the Oke unit, based on sections 7 and 16 on Mt. Oke and Misko Mountain respectively. See Fig. 20 for legend.

the unit (Fig. 30). The conglomerate beds range up to 5.5 m in thickness, and locally contain deformed clasts and rafts of ribbon limestone. At Hamilton Lake, the basal Oke unit contains a laterally extensive megaconglomerate, with megaclasts up to 50 m in maximum dimension (section 32; Plate 57). Two types of megaclasts are present: Epiphyton boundstone, and peloid-intraclast grainstone/packstone containing ?Girvanella strands and tubules.

The argillaceous parts of the section range in composition from argillaceous argillite or slate to laminated/crosslaminated argillaceous siltstone. Convolute laminae, recumbent folded laminae, and deformed ripples are present in some of these rocks. Contacts with the bounding ribbon calcisiltite beds are always sharp (Plate 16c).

5.9.4 Contacts

The upper contact of the Oke unit is conformable, and is placed at the top of the last major carbonate sequence. This contact is usually quite obvious, and is expressed by a marked topographic break (Plate 58b, d).

5.9.5 Distribution and thickness

The Oke unit can be traced throughout the study area. Largely undeformed exposures can be traced southeastward from Mt. Duchesnay to Mt. Oke. Complexly deformed sections of the Oke unit can be seen at Hamilton Lake (Plate 57), above Marble Canyon, and along parts of Hawk Ridge (Fig. 5). Near Miller Pass, the basal Oke unit is well exposed (Plate 58c), but again, most of the sequence is strongly deformed.

The Oke unit is 319.1 m thick at the type section on Mt. Oke (section 7; Fig. 30), and 332.3 m thick at the reference section on nearby Misko Mountain (section 16; Fig. 30). These two sections can be correlated almost bed by bed. The incomplete section measured on the south side of Mt. Dennis (section 8; Appendix 2) has a thickness of 169.3 m. Visual estimation suggests that the total thickness of the Oke unit in the Mt. Dennis area is similar to that in the type area.

5.9.6 Age and Correlation

The Oke unit is almost completely unfossiliferous, and thus its age and correlation must be inferred from physical stratigraphic relationships. The lateral facies relationships in Hamilton cirque (Plate 57) indicate that the Oke unit is coeval with the Waterfowl Formation.

The agnostid genus Lejopyge was recovered by D.G. Cook from the upper Oke unit near Natural Bridge, west of Field (C-75311; Cook, 1975, p. 71). This genus has a narrow range in the upper Bolaspidella Zone near the Middle-Upper Cambrian boundary (Fritz in Cook, 1975, p. 26; Fritz, 1981, his Fig. 9). On the shelf, the contact between the Waterfowl and Sullivan formations occurs a short distance above the top of the Bolaspidella Zone. This suggests that the Oke/upper Chancellor and Waterfowl/Sullivan contacts are roughly the same age. Correlation of these contacts makes sedimentological sense, as the abrupt change from carbonate to siliciclastic sedimentation on the shelf would have obvious consequences for the type of sediments deposited on the adjoining upper slope.

5.9.7 Basic interpretation of the Oke unit

The general style of sedimentation introduced at the commencement of Duchesnay unit time continued during deposition of the Oke unit. Sedimentation continued on a relatively deep-water slope, as indicated by the abundance of gravity flow deposits and the presence of sedimentary features suggestive of sediment instability (syndimentary deformation, slide masses). Carbonate turbidite deposition greatly predominated over siliciclastic sedimentation during this period, reflecting the expansion of carbonate sources on the adjoining shelf. These sediments were only slightly modified by southeastward-directed contour currents (Section 4.4.4.2; Plates 17c; 18b, c). Significant quantities of siliciclastic silt continued to reach the slope due to the continued proximity of the cratonal shoreline (Fig. 12).

5.10 UPPER CHANCELLOR

5.10.1 Definition

The upper Chancellor is a predominantly slate sequence of Late Cambrian age. It lies stratigraphically between relatively resistant carbonate strata of the Oke unit and overlying Ottertail Formation, and is the upper of the three Chancellor divisions defined by Cook (1975).

The upper Chancellor was not examined during this study. With a single exception (described below), stratigraphic sections were impossible to obtain due to intense structural deformation.

5.10.2 Section localities

The only known complete section of the upper Chancellor is situated on the north ridge of Mt. Laussedat, in the northwestern extremity of the study area (Fig. 2; Plate 59a). This section was measured by J.D. Aitken in 1966 (section AC-150/154; Aitken, unpubl. data). The section is continuous and well exposed (except for two, apparently minor normal faults about 575 m above base), and can be regarded as an unofficial type section for the upper Chancellor (Fig. 31).

Parts of the upper Chancellor can be viewed at numerous other localities. The basal upper Chancellor is readily accessible on Mt. Oke and Misko Mountain (sections 7, 16; Plates 58b, d). The middle and upper parts of this unit can be traversed on the southwest side of Mt. Hurd, south of Field (Fig. 5; Plate 59b). Numerous roadside outcrops are also present along the Trans-Canada highway at the foot of Mt. Hurd and nearby mountains.

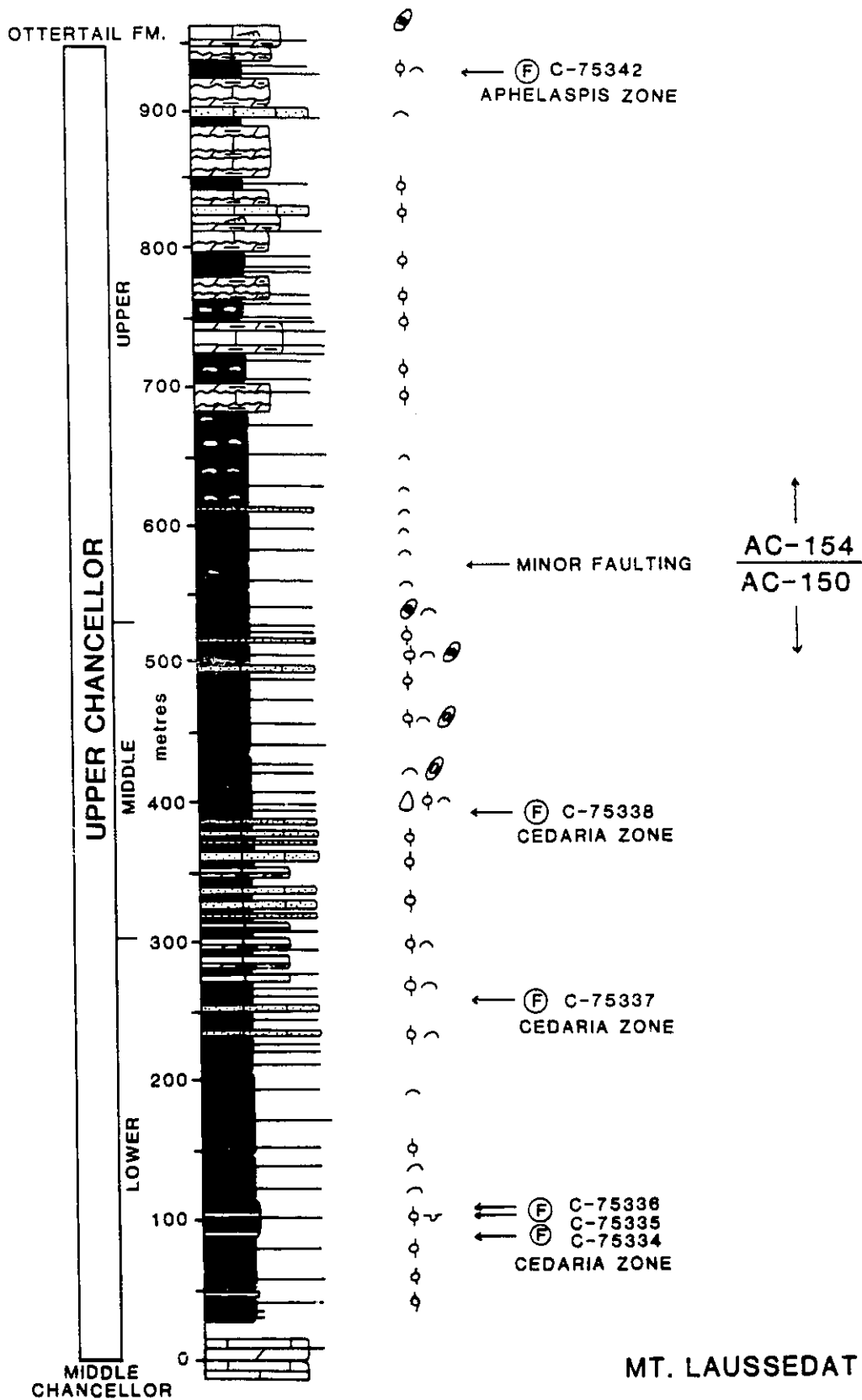
The transition between the upper Chancellor and Ottertail Formation is well exposed and structurally uncomplicated at the foot of the "Rockwall" (Fig. 5), a spectacular, laterally continuous cliff of Ottertail limestone in northern Kootenay National Park. The same stratigraphy is also particularly well exposed to the southeast on Mt. Daer and Mt. Harkin (Fig. 5; Plate 59c, d).

5.10.3 Lithology

Cook (1975, p. 23) subdivided the upper Chancellor into a lower grey slate unit, a middle slate and limestone sequence, and an upper grey slate unit. The middle unit stands out as a resistant rib relative to the underlying and overlying units (Plate 59a).

Figure 31. The upper Chancellor on Mt. Laussedat, based on section AC-150/154 measured by J.D. Aitken. The numbers pre-fixed by "C-" are fossil localities, which are described in the report by Cook (1975, p. 68-70). See Fig. 20 for legend.

UPPER CHANCELLOR



The lower unit is composed of soft, grey, colour-banded, calcareous slate. Very thin interbeds and interlaminae of rusty, silty dolostone are present at the base (Cook, 1975). Near Mt. Laussedat, this unit contains minor lenses and thin to medium interbeds of oolitic and bioclastic grainstone (Aitken, unpubl. data; Fig. 31). Trace fossils were recognized near the base of the unit, and numerous trilobites, including many agnostids, have also been recovered (see Appendix in Cook, 1975, p. 71-72).

At Mt. Oke (section 7; Appendix 2), the basal upper Chancellor is composed of laminated, grey-weathering slate and minor ribbon limestone. The sequence also contains minor limestone conglomerate and large slide blocks of ribbon limestone. The largest of these is 37 m thick, and appears to extend hundreds of metres along strike.

The middle unit of the upper Chancellor is most distinctive in the Blaeberry River area, where it is composed of very thickly interbedded slate and oolite (Cook, 1975). Apparent lateral facies changes in this unit have been described by Cook (1975, p. 23-24). In the Mt. Laussedat section, medium to very thick (up to 3 m) interbeds of oolitic and bioclastic grainstone and lesser ribbon limestone are prominent in this unit (Aitken, unpubl. data; Fig. 31). Trilobite debris is very abundant in some of the limestone beds, and inarticulate brachiopods are common in the slates.

The upper unit of the upper Chancellor is composed of brown and grey calcareous slate, with minor, thin limestone interbeds (Cook, 1975). At Mt. Laussedat, this unit contains interbeds and lenses of bioclastic, intraclastic and oolitic limestone and minor limestone conglomerate. Most interbeds are less than 1 m thick, but exceptional oolitic beds have thicknesses of up to 4 m (Aitken, unpubl. data).

The transition from the upper Chancellor to the Ottertail Formation is marked by a topographically resistant unit that was mapped as part of the Chancellor by Price *et al.* (1978a,b; 1979, 1980) and Balkwill (1980).³¹ At Mt. Laussedat, the uppermost Chancellor contains thick intervals (up to 35 m) of ribbon limestone, including ribbon calcisiltite (Aitken, unpubl. data; Fig. 31). Along the Rockwall and at Mt. Daer and Mt. Harkin, ribbon limestone appears at the base of the transition beds, and thickens upward until it dominates the sequence (Plate 59d). At Mt. Wardle, some of these beds resemble the ribbon calcisiltite in the Oke unit. Other ribbon limestone beds wedge out laterally, and are probably large-scale slide masses.

5.10.4 Contacts

If the transition beds are regarded as part of the upper Chancellor, the upper contact of this unit is placed at the top of the last major slate unit. The contact is thus conformable and gradational by interbedding. The base of the continuous ribbon limestone forming the Ottertail Formation is generally marked by a distinct, topographic break.

5.10.5 Distribution and thickness

The upper Chancellor is exposed along the southwestern margin of the entire study area. Northwest of the Trans-Canada Highway, the outcrop belt is narrow (averaging about 1.5 km). Southeast of that highway, the upper Chancellor belt widens to as much as 9 km in places, mainly as a result of thrust repetition and broad folding (see Cook, 1975; Price *et al.*, 1978a,b; 1979, 1980; Balkwill, 1980). Southwest of Field, the upper Chancellor is

³¹ Cook (1975) mapped the same unit as part of the Ottertail Formation.

complexly folded and penetratively deformed over a broad zone in the Porcupine Creek Anticlinorium (Balkwill, 1972; Fig. 8).

Complex deformation makes the thickness of the upper Chancellor difficult to estimate. The only control point is the Mt. Laussedat section, which is 948.7 m thick.³² Of this total thickness, the lower slate unit is 304.5 m thick, the middle carbonate-slate sequence is 226.9 m thick, and the upper slate unit (including the transition beds to the Ottertail Formation) is 417.3 m thick. At Mt. Hurd, Cook (1975) estimated that the upper Chancellor is at least 1370 m thick. Thus, the upper Chancellor may thicken southeastward.

How closely these values represent the original depositional thicknesses of the upper Chancellor is unknown. Cook (1975, p. 55-61) presented microscale and mesoscale evidence to suggest that the slate-dominated portions of the Chancellor have been tectonically thickened in response to horizontal compression. He tentatively estimated that the sediments were thickened by a factor of at least 1.7 times, although he emphasized that this figure was based on too few measurements to be considered representative.

5.10.6 Age and Correlation

Fossil evidence indicates that the upper Chancellor is entirely of Late Cambrian age. Cedaria Zone trilobites have been collected 89 m above the base of the upper Chancellor at Mt. Laussedat (Aitken, unpubl. data; Cook, 1975, p. 72). Trilobites from the same zone have also been recovered within about 90 m of the upper Chancellor-Ottertail contact (R. A. Price in Cook, 1975, p. 27). Thus, the Cedaria Zone appears to span most of the upper Chancellor.

³² Two, apparently minor normal faults may have removed some strata from the middle part of the section, but the missing part is believed to be minor (Aitken, unpubl. data).

The uppermost Chancellor contains younger faunal assemblages. Trilobites collected "near" the Ottertail contact at the base of the Rockwall have been tentatively assigned to the Crepicephalus Zone (W.H. Fritz in Cook, 1975, p. 68). At Mt. Laussedat, fossils recovered about 60 m below the top of the upper Chancellor have been referred to the Aphelaspis Zone (W.H. Fritz in Cook, 1975, p. 71). Finally, a collection from the lower 10-20 m of the Ottertail Formation in the Blaeberry River area has been tentatively assigned to the Dunderbergia Zone (Gardner, 1977, p. 30-31). Hence, a single age cannot be assigned to the Chancellor-Ottertail contact. Regional stratigraphic relationships indicate that the Ottertail Formation is part of a huge carbonate lithosome that prograded southwestward as far as the Windermere High (Lyell - Ottertail - Jubilee formations; Fig. 10). The base of this lithosome must become younger in that direction. Thus, the apparent discrepancies in the age of the uppermost Chancellor probably reflect this diachronous relationship.

Some fossil collections reportedly derived from the upper Chancellor do not fit into the above framework. Trilobites definitely or questionably assigned to the Bolaspidella Zone have been collected from at least five localities near the Rockwall (Cook, 1975, p. 27).³³ Four collections came from strata mapped by Cook (1975) as lower upper Chancellor, and one came from strata mapped by him as middle upper Chancellor. The area in question is largely vegetated and topographically subdued, and may be structurally more complex than present mapping suggests. Thrust-repeated slates and carbonate rocks of the distal Duchesnay or Oke units may well have been the source of the anomalous trilobite collections. This suggestion is speculative, and further field studies will be required to sort out the structural and stratigraphic relationships.

³³ These are: C-75306, 75302, 68859, 72962, and 68863; Fritz in Cook, 1975, p. 68-70).

The upper Chancellor is clearly correlative with the Sullivan Formation on the adjoining shelf. According to Fritz (1981, p. 32), the lower Sullivan contains Cedaria Zone fossils, while the upper Sullivan contains fossils referable to the Crepicephalus Zone. Aphelaspis Zone fossils occur locally in the uppermost part of the formation.

5.10.7 Basic interpretation of the upper Chancellor

The upper Chancellor probably accumulated in relatively deep-water in slope and outer shelf environments. The slates in this succession closely resemble those observed by the author in parts of the underlying lower and middle Chancellor. They are accordingly inferred to be the deposits of distal, muddy turbidites. The oolitic and bioclastic grainstone interbeds and lenses in the Mt. Laussedat section resemble the calcarenite beds and lenses documented in this thesis (Section 4.5.2), and were probably deposited by high-concentration turbidity currents. The debris flows and large slide blocks in the basal upper Chancellor at Mt. Oke further testify to sedimentation, at least initially, on a deep-water slope. Due to subsequent rapid slope progradation, the later stages of Sullivan sedimentation presumably reflect shallower depositional conditions. The sedimentology of this sequence still remains to be worked out in detail.

5.11 OTTERTAIL FORMATION

5.11.1 Definition, distribution and thickness

The Ottertail Formation is a massive, cliff-forming limestone unit situated conformably between recessive slate belonging to the upper Chancellor succession and McKay Group (Allan, 1914). It is entirely of Late Cambrian age. The Ottertail is prominently exposed along the southwestern margin of the study area, and is a particularly

useful structural and stratigraphic marker in the Porcupine Creek Anticlinorium southwest of Field (Balkwill, 1972, p. 617).

The Ottertail Formation was reported by Cook (1975, p. 24) to be 460-610 m thick near the study area. This value includes the transitional unit at the top of the Chancellor, and thus the true thickness of the formation, as defined in this thesis, would be slightly less. According to Gardner (1977, p. 29), the formation thins westward from about 360 m near Mt. Laussedat to about 330-370 m in the western Van Horne Range north of Golden (Gardner, 1977, p. 29). The Ottertail also thins to about 120 m towards the north (Balkwill *in* Gardner, 1977).

5.11.2 Lithology

The Ottertail Formation is composed of thick-bedded to massive grey limestone. No stratigraphic sections have been measured through it, but observations by the writer at Mt. Wardle and other localities along the Rockwall suggest that the more massive parts of the formation are composed mainly of burrow-stratified and burrow-mottled limestone. North of Golden, the lower 250-300 m of the formation comprise medium- to very thick-bedded dolomitic calcisiltite and calcilutite with rarely occurring, thin interbeds of oolitic biocalcarenite, limestone conglomerate and quartz siltstone (Gardner, 1977). The upper 30-70 m of the Ottertail Formation contain a variety of shallow-water sediments, including cryptalgal laminite (Gardner, 1977).

5.11.3 Age and correlation

The Ottertail Formation has been correlated with the Lyell Formation on the basis of lithology, stratigraphic position, and limited fossil control (Cook, 1975, p. 24). It is also correlative with Jubilee Formation on the flank of the Windermere High (Reesor, 1973; Fig. 10). The Jubilee Formation is composed of unfossiliferous dolostone, and is about 610 m thick at its type section on Jubilee Mountain (about 48 km northwest of Radium Hot Springs).

5.11.4 Basic interpretation of the Ottertail Formation

The Ottertail Formation is composed of shallow subtidal and peritidal carbonate sediments forming part of a huge carbonate lithosome measuring at least 400 km across depositional strike (Aitken, 1978). The lithosome nucleated over the Kicking Horse Rim near the close of Sullivan time, and subsequently expanded rapidly both cratonward and basinward. The reason for the sudden and remarkable westward progradation of the carbonate platform over the former deep-water trough is not fully understood. A decline in tectonic subsidence rates and a eustatic sea level fall have been cited as important contributing factors by Bond *et al.* (1988, 1989).

CHAPTER 6

MEGATRUNCATION SURFACES IN THE ZONE OF FACIES CHANGE: EVIDENCE FOR LARGE-SCALE OUTER PLATFORM COLLAPSE

6.1 INTRODUCTION

The zone of facies change between the platform and slope successions is preserved at only a few critical localities. Without exception, these exposures reveal that large-scale collapse was an important process at various times in the history of the platform margin. The morphological features formed by this process are the subject of this chapter.

The most spectacular features observed at the margin are **megatruncation surfaces**. These are large-scale erosional features that cut out tens to hundreds of metres of platform strata vertically, and extend kilometres to perhaps tens of kilometres parallel to depositional strike. Their lateral extent across depositional strike is difficult to evaluate due to limitations of exposure, but modern and ancient analogues suggest that it is probably on the order of tens of kilometres. These features are an order of magnitude larger than the morphologically similar intraformational truncation surfaces found throughout the slope succession.¹ The megatruncation surfaces are inferred to be large-scale slide scars, analogous to those recently identified in seismic reflection profiles from the west Florida carbonate platform (Mullins *et al.*, 1986, 1988).

¹ This terminology differs from that implicit in the volume edited by Cook and Enos (1977a), in which the term "intraformational truncation surface" was applied to truncation surfaces of all scales.

Megatruncation surfaces are observed or inferred to affect the Cathedral, Eldon/Pika and Waterfowl platform margins. They are most prominently displayed in a series of cross-strike exposures at the level of the undifferentiated Eldon/Pika margin. It is from these exposures that the regional geometry of the megatruncation surfaces has been inferred.

In the sections that follow, the critical cross-strike exposures at the Eldon/Pika level will be described and illustrated on an individual basis. These features will then be compared with both modern and ancient examples of morphologically similar features, and a general model for the development and collapse of the Eldon/Pika margin will be presented. The chapter will conclude by applying these concepts to the interpretation of the Waterfowl margin. The Cathedral margin will be described and interpreted in Chapter 7.

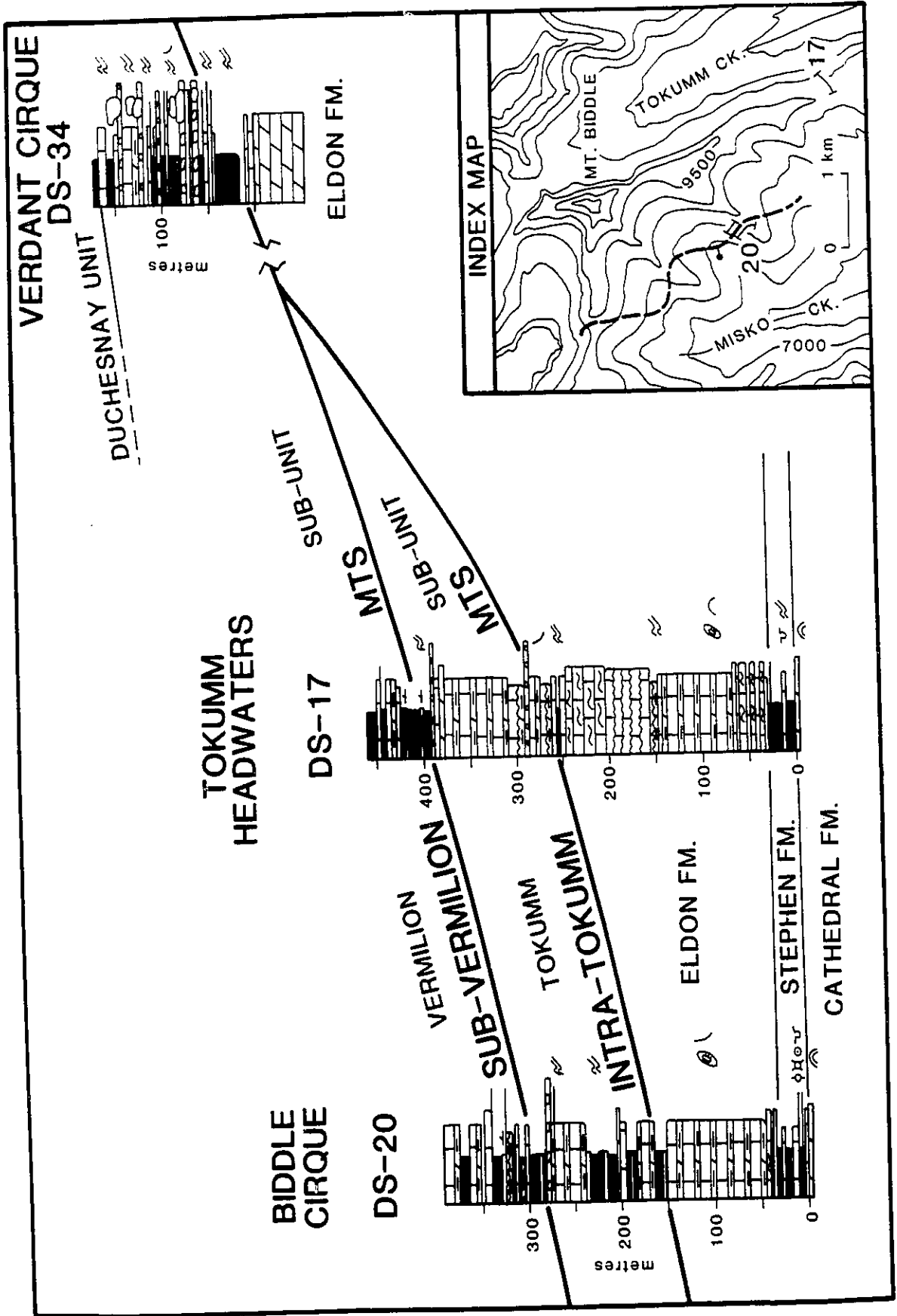
6.2 ELDON-PIKA MEGATRUNCATION SURFACES: DESCRIPTIONS

6.2.1 Mt. Biddle megatruncation surface

6.2.1.1 Location and local stratigraphy

The megatruncation surface near Mt. Biddle is exposed on a series of divides separating three cirques near the headwaters of Misko Creek (Plate 46). This surface has been traversed by two stratigraphic sections (sections 20, 21; Fig. 2). It is best exposed on the southeast side of Biddle cirque, below the ridge linking Mt. Biddle and Curtis Peak (section 20; Plate 46). Additional stratigraphic control is provided by section 17 in the headwaters of Tokumm Creek, on the opposite (east) side of Biddle-Curtis ridgeline (Figs. 2, 32; Plate 45). The stratigraphic relationships at this locality are diagrammatically illustrated in Fig. 33.

Figure 32. Stratigraphic relationships in the Tokumm Creek headwaters - Biddle cirque area. The Eldon-Pika stratigraphy is traversed by the intra-Tokumm and sub-Vermilion megatruncation surfaces, which are inferred to converge laterally based on relationships observed in a more proximal exposure in Stephen cirque (Fig. 35). As the platformward ends of the megatruncation surfaces are not preserved east of the Tokumm headwaters area, the stratigraphic configuration in Verdant cirque is assumed to be representative. See Fig. 20 for legend.



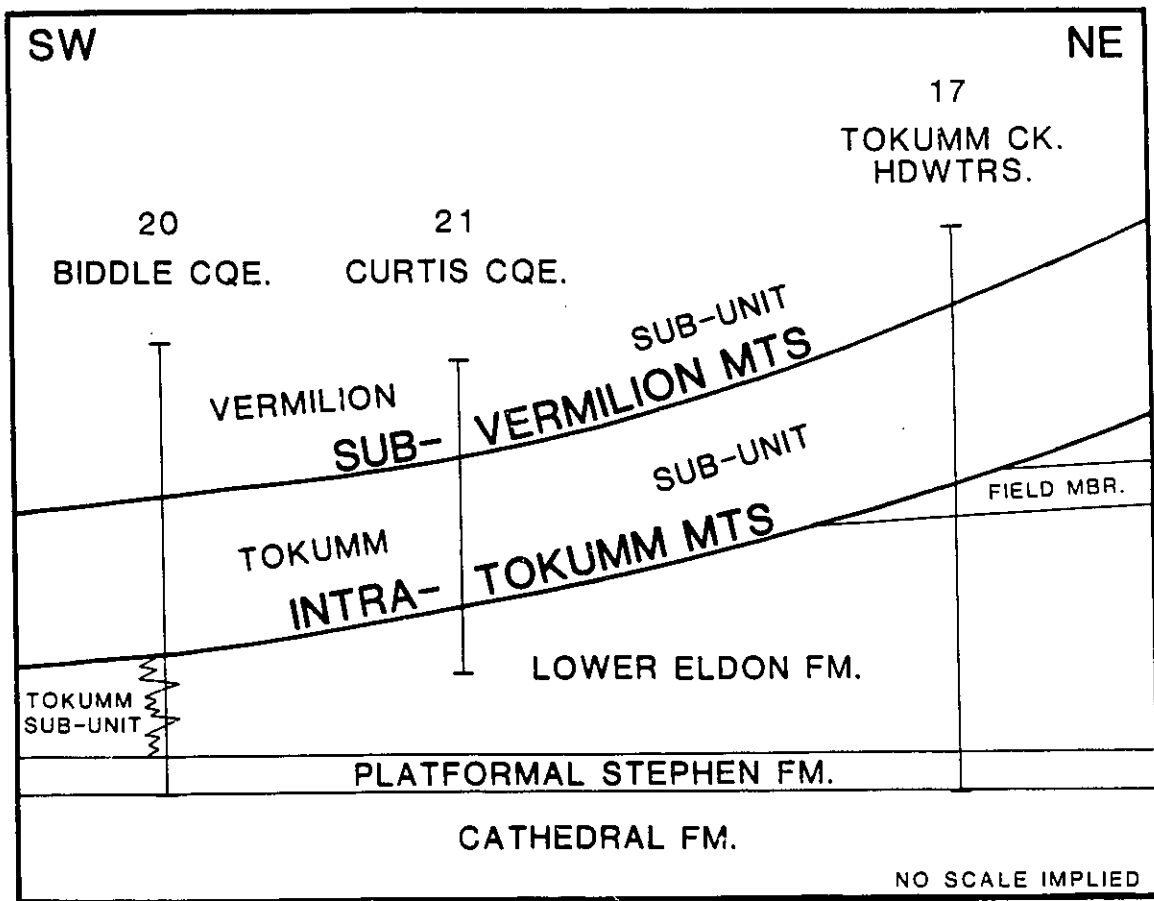


Figure 33. Diagrammatic stratigraphic relationships in the Tokumm Creek headwaters - Biddle cirque area.

The slope sequence on the northeast side of Misko Valley is underlain by a normal shelf succession. Massive dolostones of the upper Cathedral Formation are exposed together with a complete section of the "platformal" Stephen Formation on the lower east wall of Biddle cirque (Plate 46). The Stephen Formation is succeeded by thin-bedded, dark grey-weathering limestones of the "basal Eldon black band", which contains scattered phosphatic brachiopods, sponge spicules, and a trilobite assemblage referable to the Bathyuriscus adaeus faunule of the Bathyuriscus-Elrathina Zone (C-166700; Appendix 1). This succession also contains a number of indistinct slide masses, and is lithologically gradational to rocks typical of the Tokumm sub-unit. It passes gradationally upward into medium grey-weathering, burrow-mottled limestone. High on the cirque wall, the burrow-mottled limestone sequence passes westward into dark grey-weathering strata of deeper water origin (Plate 46).

The lower Eldon is sharply overlain by a recessive, brown-weathering unit, assigned herein to the Tokumm sub-unit (Plate 46). The lowermost part of the sub-unit is composed of ribbon limestone and argillite, and was correlated with the Field Member of the Eldon Formation by Aitken (in press, a) in section 17.² The remainder of the recessive interval is composed mainly of ribbon limestone and its dolomitized equivalent.

The megatruncation surface is visible on the lower part of the divide, and is cut by a minor, southwest-side-down normal fault (Plate 46). By matching the overlying stratigraphy on either side of the fault, it can be demonstrated that the megatruncation surface continues to the southwest, just below the top of the talus. The visible part of the megatruncation surface cuts downward into the lower Eldon Formation (Plate 46). As the lower Eldon is known to change facies westward into the lower Tokumm sub-unit, this feature becomes an **intra-Tokumm megatruncation surface** westward (Fig. 33). The stratigraphic level at

² This section corresponds to Aitken's (in press, a) section AC-160.

which the surface originated is not known. It could not be identified with certainty in section 17, but may be related to a series of intraformational truncation surfaces and associated, irregular and disturbed ribbon limestones immediately above the Field Member in that section (Appendix 2).

In Biddle cirque, the strata overlying the megatruncation surface have been assigned to the Tokumm and Vermilion sub-units. These sub-units are not easily distinguished in the recessively exposed strata on the southwest side of the normal fault. They are, however, easily distinguished in the Tokumm headwaters area (Plates 45, 55b), and on the south wall of Curtis cirque (Plate 48d).

In section 20, the megatruncation surface is directly overlain by massive, dark grey, vaguely laminated argillite with very thin interbeds and nodules of dolostone (Plate 48c). This unit contains a number of small-scale intraformational truncation surfaces. There is no evidence of tectonic deformation, and the lower contact of the argillite is clearly depositional. The remainder of the Tokumm sub-unit is composed of argillite, ribbon argillite, and ribbon limestone (Fig. 32). A more typical section of this sub-unit is found above the megatruncation surface in Curtis cirque, 1.5 km to the southeast (section 21). There, the sequence is composed mainly of ribbon limestone.

In all sections, the Tokumm sub-unit is capped by limestone conglomerate and calcarenite, and is succeeded abruptly by argillites and slates of the Vermilion sub-unit. The contact appears to be concordant in exposures oriented parallel and perpendicular to depositional strike (Plates 45, 48d). However, it will be suggested later from regional evidence that this contact is, in fact, a second megatruncation surface (the "sub-Vermilion megatruncation surface").

The overlying argillite- and slate-rich Vermilion sequence is similar in sections 17, 20 and 21. It is composed of argillite and ribbon argillite, together with subordinate ribbon limestone and limestone conglomerate.

6.2.1.2 Surface configuration and visible extent

The short, visible segment of the intra-Tokumm megatruncation surface is relatively flat, and has only minor irregularities (Plate 46).³ It has an average inclination of about 12°, and a visible length of about 240 m northeast of the normal fault in Biddle cirque.

The megatruncation surface can be traced along depositional strike for about 2.5 km. It is faulted out of view in the northwest, and disappears beneath younger strata in the southeast due to structural dip. The lateral extent of the surface across depositional strike is unknown, as both its platformward and basinward limits are not preserved.

6.2.1.3 Stratigraphic package traversed by the surface

As the intra-Tokumm megatruncation surface is not completely preserved, the total stratigraphic package it traverses is unclear. The highest strata it visibly intersects belong to the Field Member, about 171 m above the base of the Eldon Formation (as estimated from photographs). The surface cuts down to a level about 87 m above the base of the Eldon Formation, and thus a minimum of 84 m of lower Eldon strata have been removed along its

³ Foreshortened views, such as Plate 46, tend to exaggerate the irregularities in the surface. Its true form is best seen from a vantage point along strike.

visible length. The total stratigraphic thickness removed along the full length of the megatruncation surface across depositional strike probably substantially exceeds this figure.

6.2.2 Stephen cirque megatruncation surfaces

6.2.2.1 Location and local stratigraphy

In Stephen cirque, megatruncation surfaces occur at the base of and within the Vermilion sub-unit. A third surface occurs at the base of the Tokumm sub-unit in the eastern part of the cirque, and within the Tokumm sub-unit in the western part of the cirque (Plates 49, 50; Fig. 34). These features will be referred to below as the sub-Vermilion, intra-Vermilion, and intra-Tokumm megatruncation surfaces, respectively. The intra-Vermilion megatruncation surface is also exposed on the opposite side of the ridge in Duchesnay Basin (Plate 51). The relationships of these megatruncation surfaces to the stratigraphy in Stephen cirque are shown diagrammatically in Fig. 35.

The southeast wall of Stephen cirque is composed almost entirely of undivided upper Eldon and Pika strata. The Field Member, first identified by McIlreath (1977a), is exposed near the base of this wall (Plate 49). The same stratigraphy is also prominently displayed on the upper northwest face of Mt. Stephen (Plate 38b).

Measurements from photographs (the exposure is vertical and inaccessible) indicate that approximately 470 m of upper Eldon and Pika strata overlie the Field Member on the southeast wall of the cirque. This estimated thickness agrees closely with a measured thickness of 460 m for the upper Eldon/Pika on the south side of Mt. Stephen (Aitken, unpubl. data; section AC-159). In the same section, Aitken's best estimate for the thickness

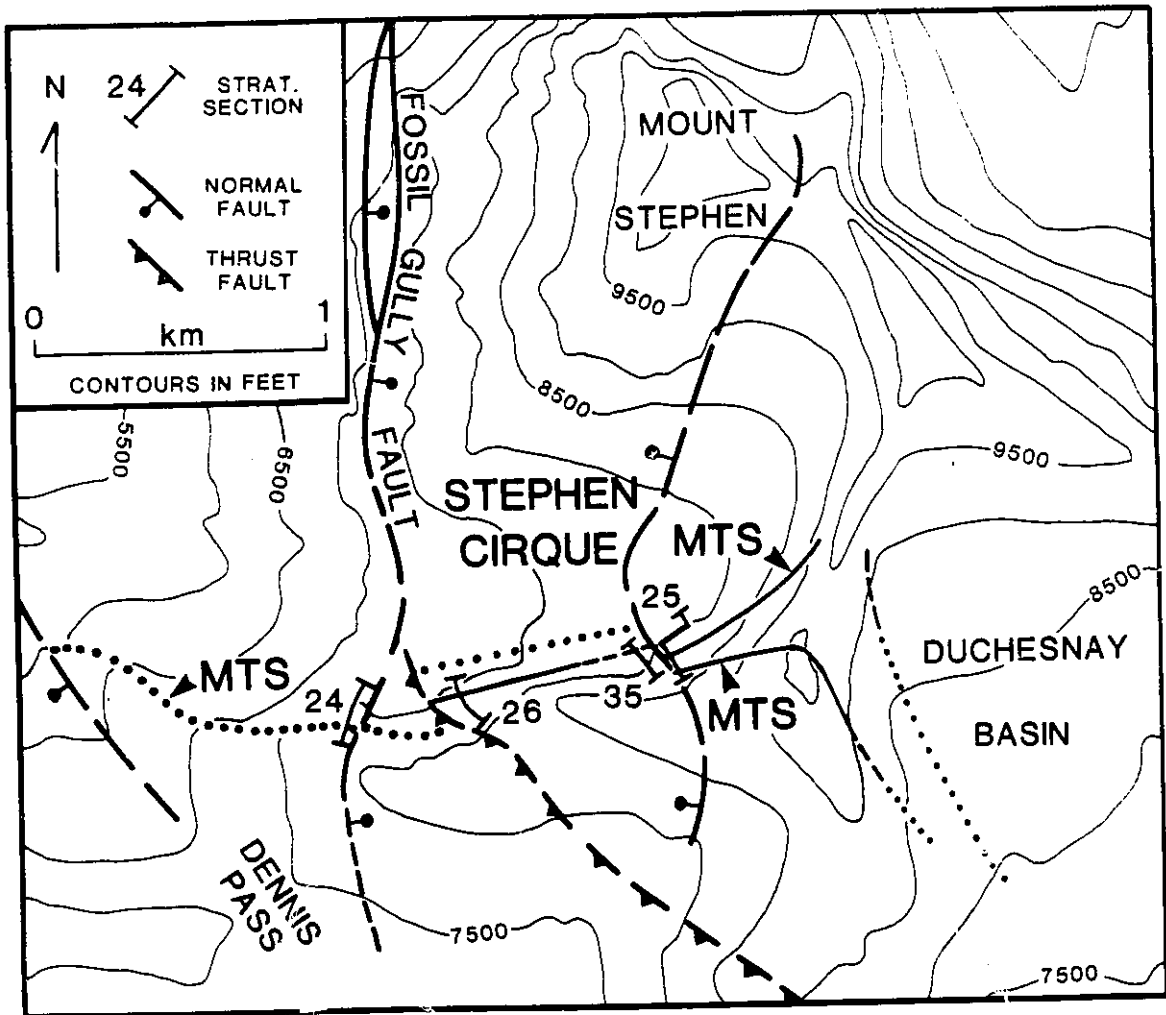


Figure 34. Detailed map showing locations of stratigraphic sections and their relationship to megatruncation surfaces in Stephen cirque.

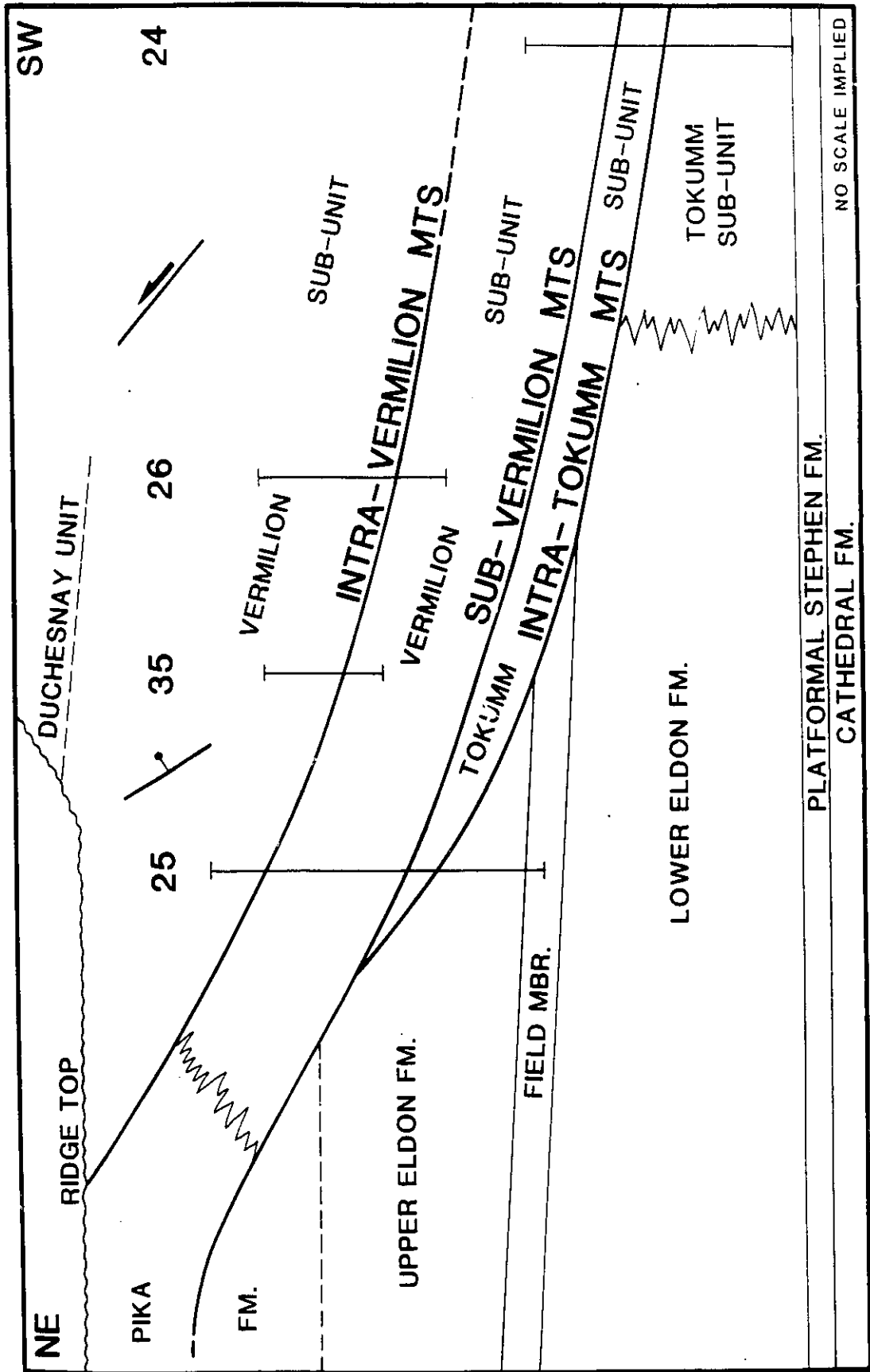


Figure 35. Diagrammatic stratigraphic relationships on south wall of Stephen cirque.

of the Pika Formation was about 265 m.⁴ The Pika Formation is assumed to have the same thickness on the southeast wall of Stephen cirque.

The Eldon/Pika sequence is composed mainly of massive, structureless dolostone, but ex-burrow-mottled limestone, ex-intraclast rudstone and laminated dolostone are locally preserved. From a distance, the entire sequence has a bedded appearance (Plate 49). Wherever original bedding can be discerned from preserved fabrics, it is always parallel to this apparent bedding.

The slope sequence exposed in northeastern and central Stephen cirque has been subdivided into the Vermilion sub-unit and Duchesnay unit (Plates 49, 50). The stratigraphy in that part of the cirque was described previously (Section 5.7.4).⁵

The stratigraphy at the western end of Stephen cirque differs substantially from that to the northeast (Plate 47; Fig. 35). In western Stephen cirque, the slope succession is exposed in the hanging wall of a minor, northeast-verging thrust fault (Cook, 1975; McIlreath, 1977a; Price *et al.*, 1980; Fig. 34).

The most westerly stratigraphic section in the cirque (section 24; Appendix 2) is underlain by the "platformal" Stephen and Cathedral formations (Plate 47). The Stephen Formation is overlain by about 180 m of dolomitized ribbon limestone assigned to the Tokumm sub-unit. This sequence contains a 20 m thick slate interval, and is overlain by a southwesterly-dipping, monotonous slate sequence referred to the Vermilion sub-unit. The slate continues to the top of the ridge, and is intermittently exposed southwestward across

⁴ Not 240.5 m, as stated by Aitken (in press, a).

⁵ The perplexing stratigraphic and structural relationships along the southeast wall of this cirque have been discussed by Cook (1975) and McIlreath (1977a). The conclusions presented here differ substantially from their interpretations.

Dennis Pass. On the west side of the pass, it is overlain by the massive limestone marking the upper contact of the Vermilion sub-unit (Plate 55c; Section 5.7.4). East of section 24, the Tokumm and Vermilion sub-units are thrust over the Vermilion sub-unit section traversed by section 26 (Plate 47). The thrust fault thus superimposes lower Vermilion over upper Vermilion strata.

6.2.2.2 Surface configuration and visible extent

The **intra-Tokumm megatruncation surface** has an average inclination of about 28° . It is exposed over a distance of about 200 m across depositional strike, and is broadly concave-upward (Plate 49).

Northeast of section 25, the intra-Tokumm megatruncation surface separates sub-horizontally bedded dolostone of the upper Eldon Formation from dipping, faintly bedded dolostone of the Tokumm sub-unit (Plate 49). The upper (northeastern) end of this surface is truncated by the sub-Vermilion megatruncation surface. The intra-Tokumm megatruncation surface appears to project through section 25 at the base of a very thick-bedded dolomite sequence with thin, laminated argillite interbeds (Appendix 2). The remainder of the Tokumm sub-unit consists of ex-ribbon limestone and minor massive dolostone, and contains at least some synsedimentary deformed beds.

The **sub-Vermilion megatruncation surface** has an average inclination of about 18° , which locally increases to about 20° . It has a visible extent of about 800-900 m across depositional strike, and is gently undulatory in places. As the megatruncation surface is only exposed on either side of the narrow ridge separating Stephen cirque from Duchesnay basin

(Fig. 34), its lateral extent parallel to depositional strike cannot be determined directly. Southwest of the normal fault separating sections 25 and 35, the surface is not exposed.

In the cirque wall east of section 25, the sub-Vermilion megatruncation surface appears as a sharp contact between massive or faintly bedded dolostone below, and onlapping, brown-weathering, laminated argillite above (Plate 49). As the megatruncation surface is traced farther northeastward toward its point of origin, the overlying argillite pinches out, and the surface separates massive or sub-horizontally bedded dolostone below from massive or westerly-dipping dolostone above. Foresets are faintly visible high on the cirque wall above the surface (Plate 49). In section 25, the megatruncation surface is overlain by green-weathering, non-calcareous, locally laminated argillite (Appendix 2). The parallel-sided dolostone interbeds immediately above the surface in that section are probably destructively dolomitized calcarenites.

The **intra-Vermilion megatruncation surface** has an average inclination of about 25° northeast of section 25 (Plate 49). It is inclined as little as 16° in places, and locally steepens to as much as 42°.

Northeast of section 25, the intra-Vermilion megatruncation surface is a clearly defined contact between vaguely bedded dolostone below, and brown-weathering, argillaceous strata above (Plate 49). The argillaceous succession contains scattered, grey-weathering periplatform talus blocks. The same surface is also exposed on the opposite side of the ridge in Duchesnay basin (Fig. 34; Plate 51). There, it visibly truncates bedded dolostone of the upper Eldon/Pika formations, and is overlain by brown-weathering, argillaceous strata (ribbon argillite and ribbon limestone). Laterally discontinuous megaconglomerate, intraclast grainstone, and ribbon limestone occur locally above the

surface (Plate 51). The megaconglomerate contains Epiphyton boundstone megaclasts, some of which exceed 10 m in maximum dimension. Pebble-sized clasts of oolith-intraclast grainstone and subordinate lime mudstone also occur in the same deposit.

In section 25, the intra-Vermilion megatruncation surface appears to underlie a series of dolomitized megaconglomerates separated by thin interbeds of dolomitic argillite and ex-ribbon limestone (Appendix 2; Plate 49). The megaconglomerates contain megaclasts up to 3-4 m in diameter, and are as much as 7 m thick.

Southwest of section 25, the intra-Vermilion megatruncation surface disappears beneath talus, and is cut off by a minor, west-side-down normal fault (Plate 49). Stratigraphic markers were successfully traced across the fault, permitting direct correlations between sections 25 and 35.⁶ The intra-Vermilion megatruncation surface could then be identified with reasonable certainty high on the cirque wall west of section 35 (Plate 50). There, the surface is essentially bedding-parallel, and is overlain by a large, lens-shaped body of megaconglomerate up to 40 m thick. A megaclast projecting from its top is estimated to be at least 60 m long. This deposit is comparable in scale and stratigraphic position to the megaconglomerate identified in Duchesnay basin.

Despite the prominence of the intra-Vermilion megatruncation surface on the southeast wall of Stephen cirque, it is a remarkably subtle feature in sections 35 and 26. It illustrates how easily a near-bedding-parallel megatruncation surface bounded by similar sediments above and below can be missed in individual stratigraphic sections.

⁶ This resolved a crucial difference in structural interpretation between McIlreath (1977a, his Plate 3-1E) and Cook (1975, his Fig. 9), which led to McIlreath's erroneous correlation of the Field Member with the lower middle Chancellor.

6.2.2.3 Stratigraphic package traversed by the surfaces

The upper (northeastern) end of the **intra-Tokumm megatruncation surface** is cut out by the sub-Vermilion megatruncation surface about 175 m above the top of the Field Member (Plate 49). The southwestern end of the intra-Tokumm megatruncation surface intersects section 25 about 92 m above the top of the Field Member (Fig. 35). Hence, about 83 m of upper Eldon strata are **visibly** cut out by this megatruncation surface.

The ultimate basinward extent of the intra-Tokumm megatruncation surface is unknown, but it too probably intersects section 24 in western Stephen cirque. The most obvious lithological break where the surface might intersect this section is at the base of a 20 m thick slate interval in the upper Tokumm sub-unit (Fig. 35; Appendix 2). If this is correct, the total thickness of Eldon and equivalent strata cut out by the intra-Tokumm megatruncation surface in the vicinity of Stephen cirque is estimated to be at least 200 m.⁷

The **sub-Vermilion megatruncation surface** is by far the most impressive feature in Stephen cirque. The upper (northeastern) end of the megatruncation surface disappears into horizontal platform bedding an estimated 335 m above the top of the Field Member (Plate 49; extreme left). Based on the thicknesses estimated earlier (Section 6.2.2.1), this places the upper end of the megatruncation surface at about mid-Pika level (approximately 135 m below the projected top Pika contact). The lower (southwestern) end of the megatruncation surface intersects section 25 about 120 m above the top of the Field Member (Fig. 35). Hence, about 215 m of upper Eldon and Pika platform strata have been cut out by the sub-Vermilion megatruncation surface northeast of section 25.

⁷ This value represents the approximate stratigraphic distance from the upper end of the sub-Tokumm megatruncation surface to the lowest exposed level in the Field Member northeast of section 25. It thus represents a minimum value, as the surface appears to have cut downward below this stratigraphic level in section 24 (Fig. 35).

The ultimate, basinward extent of the sub-Vermilion megatruncation surface in Stephen cirque is unknown, but it almost certainly passes through section 24 in the western part of the cirque (Fig. 35). There, strata assigned to the Vermilion sub-unit (equivalent in age to the upper Pika Formation) are inferred to unconformably overlie the upper Tokumm sub-unit (equivalent in age to upper Eldon and/or younger strata; Fig. 16), which in turn rests unconformably on the lower Tokumm sub-unit (lower Eldon equivalent). If the Tokumm-Vermilion contact in section 24 is the basinward extension of the sub-Vermilion megatruncation surface, then it is situated at least 142 m stratigraphically below the trace of this surface in section 25.⁸ Thus, the total relief of the sub-Vermilion megatruncation surface is thought to be at least 360 m.

The **intra-Vermilion megatruncation surface** is well defined in both Stephen cirque and Duchesnay Basin (Fig. 34; Plates 49, 51). The upper (northeastern) end of the megatruncation surface intersects the skyline an estimated 425 m above the top of the Field Member. On the basis of the thickness estimates outlined earlier, this level should correspond to the uppermost Pika Formation. The megatruncation surface appears to intersect section 25 about 264 m above the top of the Field Member (Appendix 2). Thus, the surface had a vertical relief of about 161 m northeast of section 25.

⁸ This value is the stratigraphic distance from the sub-Vermilion megatruncation surface to the lowest exposed level in the Field Member in section 25. It is thus a **minimum** value, as the surface appears to have cut downward below this stratigraphic level in section 24 (Fig. 35).

6.2.3 Verdant cirque megatruncation surfaces

6.2.3.1 Location and local stratigraphy

Verdant cirque is situated immediately northeast of the headwaters of Verdant Creek (Figs. 4, 36). The upper Eldon-Pika platform margin is magnificently exposed on the southeast wall of the cirque, and is cut by at least three megatruncation surfaces (Plate 54). The margin is not preserved on the opposite (northwest) wall of the cirque due to faulting and erosion (Plates 52, 53). However, the slope sequence preserved on that wall contains the most accessible and spectacular megaconglomerates in the entire Chancellor succession. The observed stratigraphic relationships in Verdant cirque are diagrammatically illustrated in Fig. 37.

The stratigraphy exposed on the southeast wall of Verdant cirque is essentially identical to that in the eastern part of Stephen cirque. Regional mapping (Price and Mountjoy, 1972) and aerial reconnaissance by the writer indicate that a virtually complete Eldon-Pika section is present to the northeast, on the opposite side of the Continental Divide. These strata can be visually traced southwestward into Verdant cirque. Estimates from photographs (the cirque wall is vertical and inaccessible) indicate that about 300 m of Eldon-Pika strata are exposed near the megatruncation surfaces. Cross-section construction suggests that approximately the top 50 m of the Eldon-Pika succession have been eroded from the cirque wall. Thus, it can be safely established that the platform strata exposed in the southeast wall of Verdant cirque belong to about the upper 350 m of the Eldon-Pika sequence (Plate 54).

Separation of Pika-aged strata from Eldon-aged strata is critical for determining the approximate ages of the megatruncation surfaces in Verdant cirque. Aitken (in press, a) did

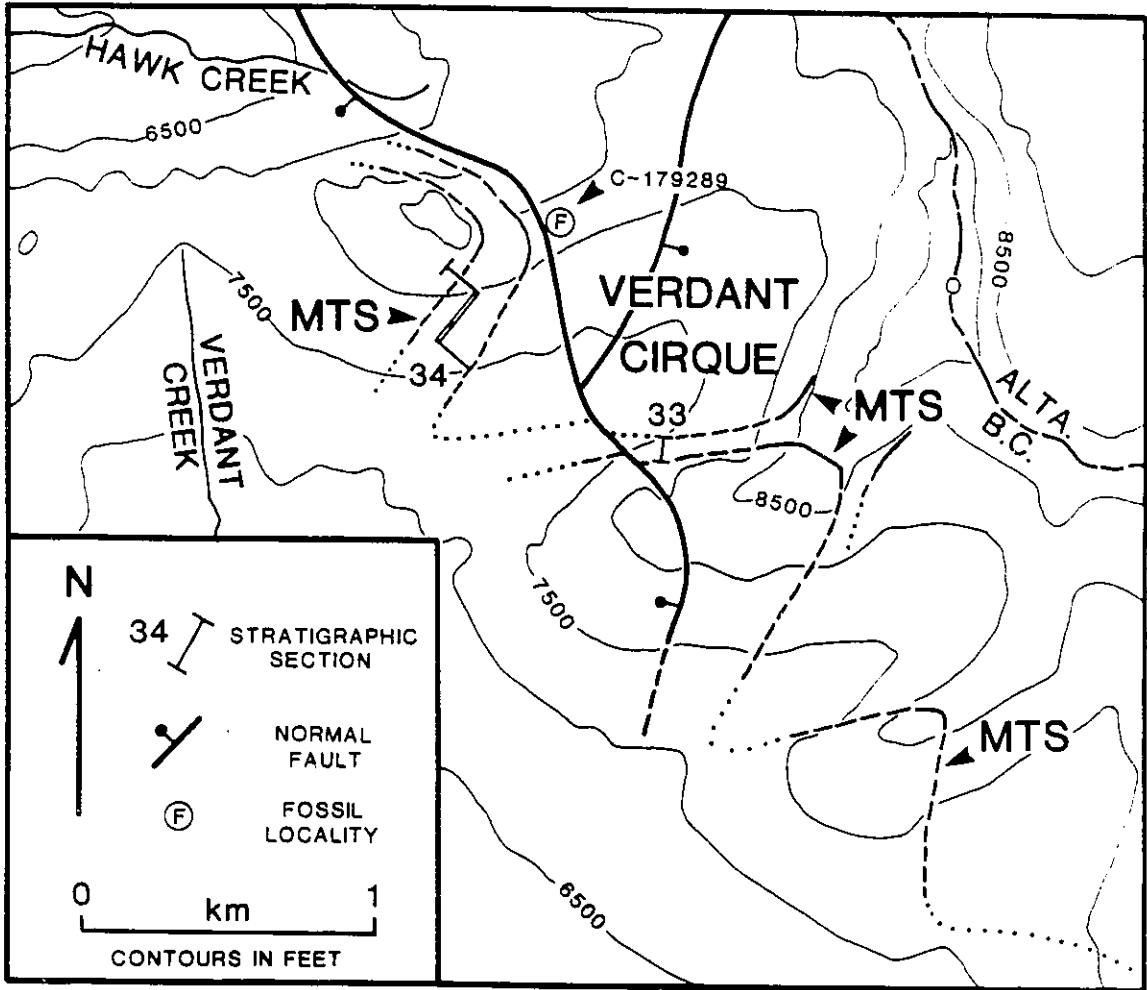


Figure 36. Detailed map showing locations of stratigraphic sections and their relationship to megatruncation surfaces in Verdant cirque.

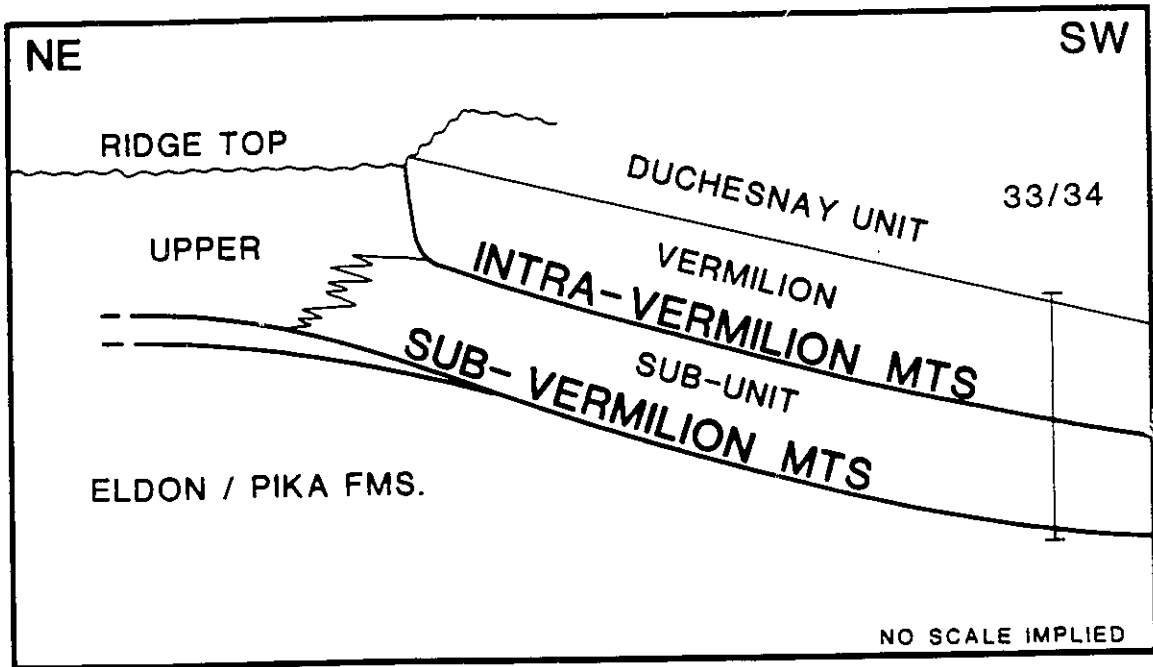


Figure 37. Diagrammatic stratigraphic relationships on the southeast wall of Verdant cirque.

not attempt to separate Pika-equivalent rocks from Eldon-equivalent rocks in his section at Vermilion Pass (section AC-53/55; Fig. 2), 14 km to the northwest, although he did include a "best pick" of 695 ft (212 m) for the Pika in his isopach map. This value is quite reasonable in view of the fact that regionally, the Pika constitutes an average of about 35% of the total Eldon-Pika succession.⁹ In the absence of other data, the Pika Formation is assumed to have the same thickness in Verdant cirque. Thus, about the upper half of the southeastern cirque wall (left side, Plate 54) is inferred to be composed of Pika-equivalent rocks.

On the northwest wall of the cirque, the lower Eldon Formation crops out in a horst block, which is capped at the skyline by the Field Member (Plate 52; fossil locality C-179289; Appendix 1). The undivided upper Eldon-Pika sequence crops out on the downthrown (southwest) side of the normal fault, where it is overlain by the upper slope sequence.

The absence of the Field Member on the southeast wall of Verdant cirque is puzzling, especially since it is known to occur in the upfaulted block on the opposite wall (Plate 52). At Vermilion Pass, the Field Member is situated 257.9-338.3 m below the top of the Eldon-Pika sequence (Aitken, in press, a). Assuming that it occurs in a similar stratigraphic position in Verdant cirque, the Field Member should be exposed on the southeast wall.

At least three possibilities can be suggested to explain the apparent absence of the Field Member on the southeast wall. First, the Field Member is known to pinch out platformward (Aitken, in press, a). Depending on the exact orientation of depositional strike

⁹ The sole exception is at Eon Mountain, where the Pika constitutes about 21% of the total Eldon-Pika thickness (115.5 m out of a total 538.3 m; Aitken, in press, a). However, there were obvious difficulties in picking the base of the Pika in this section, as Aitken's (in press, a) isopach map shows a higher thickness value for the Pika (554 ft. = 169 m), which is more compatible with regional trends.

at Verdant cirque, its absence could thus be attributed to facies change. Second, the Field Member could have been destructively dolomitized, rendering it indistinguishable from strata above and below. Third, and most likely, the Field Member could be thinner than at Vermilion Pass, and thus its top could conceivably occur at a lower stratigraphic level. If this is correct, the member probably lies beneath the talus apron at the base of the cirque wall.

The platform rocks in Verdant cirque are strongly dolomitized, and original depositional textures have largely been erased. Much of the sequence is peritidal in origin, as indicated by the scattered preservation of fenestral dolostone in association with oolitic grainstone, intraclastic-oolitic grainstone/packstone, "Yoholaminites", and layers of small, domal stromatolites.¹⁰ Ex-burrow-mottled and ex-burrow-stratified limestone have also been observed in talus, suggesting local, shallow subtidal conditions.

The upper slope sequence in Verdant cirque is assigned to the Vermilion sub-unit and Duchesnay unit. The Vermilion sub-unit directly overlies Eldon-Pika strata, and the Tokumm sub-unit is notably absent (Fig. 37). It contains spectacular megaconglomerates, slide masses, and channellized calcarenites, in addition to argillite, ribbon argillite and minor ribbon limestone (sections 33, 34; Appendix 2). In contrast, the Duchesnay unit is composed of monotonous, silty dolomitic argillite with crosslaminated, silty lenses. It is distinctly massive and cleaved, and resembles the exposures of the Duchesnay unit in Prospectors Valley and Stephen cirque (Plates 44, 50).

¹⁰ These rock types are remarkably similar to those in the Cathedral Formation in the Stephen-Field, Natalko Lake and Monarch areas (Sections 4.8.3, 4.8.4).

The strata immediately overlying the lower two megatruncation surfaces on the southeast wall of the cirque are only partly accessible.¹¹ The bedding surfaces immediately above the lower megatruncation surface appear to be inclined at about the same angle as the surface itself, and are probably remnants of formerly thicker foresets. Large-scale foresets are preserved in dolomitized strata above the upper part of the second megatruncation surface (Plate 54). They are concave-upward, and have a maximum dip of about 34°. The foresets pass platformward into massive carbonate rocks, and are overlain by horizontally bedded strata. The pattern is one of a classic offlapping margin (cf. Bosellini, 1984). The foresets pass downslope into a spectacular megaconglomerate with megaclasts up to 60 m in maximum dimension. The megaclasts in this deposit are composed of poorly preserved Epiphyton boundstone, suggesting that Epiphyton buildups once inhabited the platform margin above the foreset tops.

The lower part of the sub-Vermilion megatruncation surface is overlain by deep-water strata of the Vermilion sub-unit. This is easily visualized on the southeastern wall of the cirque, although the actual surface is not exposed (Plate 54). Near section 33, the megatruncation surface was overlapped by at least 58 m of strata prior to deposition of the lowest, laterally extensive megaconglomerate. These strata contain a series of stacked, channellized, oolitic-intraclastic grainstones (0.4-2.3 m thick) separated by thin, laterally discontinuous, laminated argillites (Section 33; Appendix 2). The grainstone bodies are identical to those occupying megachannels in the Prospectors Valley sections (Section 4.5.3). The remainder of the overlapping sequence consists of argillite, ribbon argillite, ribbon limestone, and minor limestone conglomerate.

¹¹ The upper parts of these megatruncation surfaces appear to be more accessible on the opposite side of the divide, but this could not be evaluated on the ground due to time constraints.

As these strata are traced up the megatruncation surface, calcarenite and limestone conglomerate become volumetrically more significant, and a few periplatform talus blocks appear. One strongly dolomitized periplatform talus block contained remnant patches of fenestral dolostone and ex-oolitic grainstone, in contrast to the Epiphyton-bearing megaclasts typical of nearby megaconglomerate units.

The remainder of the Vermilion sub-unit is most easily traversed on the northwest wall of the cirque (Section 34; Plates 52, 53). There, the sequence is composed mainly of variably dolomitized argillite and ribbon argillite. Ribbon limestone becomes volumetrically more important in about the upper third of the sub-unit. The sequence is punctuated by numerous limestone conglomerates, including at least five, spectacular megaconglomerates with Epiphyton boundstone megaclasts up to 50 m long (Plate 53).

Additional features exposed on the southeast wall of the cirque include a large-scale slide mass and a thick talus wedge (Plate 54). The slide mass is a laterally tapering body of ribbon limestone, at least 200 m long and as much as 25 m thick. The talus wedge abuts the headwall of the intra-Vermilion megatruncation surface (see below), and is estimated to be about 170 m long and up to 50 m thick. The wedge appears to contain a large number of platform-derived blocks ranging up to a few tens of metres in diameter.

6.2.3.2 Surface configuration and visible extent

At least three megatruncation surfaces are exposed on the southeast wall of Verdant cirque (Plate 54). The lower two originate in the platform sequence, and converge basinward to form a single, sub-Vermilion megatruncation surface. The upper, intra-Vermilion

megatruncation surface has a near-vertical headwall, and becomes bedding-parallel basinward.

The **lower two (sub-Vermilion) megatruncation surfaces** are very similar in form, and are separated by about 30 m of strata at their platformward ends. Both are gently concave-upward, but roll over platformward to merge imperceptibly with the horizontally bedded platform sequence. The lower surface has an inclination of about 11° , whereas the upper surface has an inclination of about 17° . Basinward of their convergence point, the angle of inclination increases to about 20° . This convergence is presumably the result of the upper surface truncating the lower.

The upper megatruncation surface has an **exposed** length of at least 300 m. The basinward extension of the surface is not exposed, but it is probably present just beneath the top of the talus apron at the base of the cirque wall (Plate 54). The megatruncation surface probably steepens to as much as 27° along this segment. Exposures on the opposite (northwest) side of the cirque indicate that the surface becomes essentially bedding-parallel farther basinward. Thus, the sub-Vermilion megatruncation surface has an overall listric form.

The sub-Vermilion megatruncation surface extends perhaps 600-700 m from its point of origin to where it plunges from view in the southwestern part of the cirque. Its ultimate basinward extent is unknown. The megatruncation surface can be traced at least 2 km along depositional strike before the exposure ends.

The **intra-Vermilion megatruncation surface** is the most obvious feature on the southeast wall of the cirque, and is markedly different in form from the lower two

megatruncation surfaces (Plate 54). It is composed of two parts: an upper, near-vertical headwall, and a lower, near-bedding-parallel ramp. As this surface is almost entirely inaccessible, its description is based on close observation by binoculars, and the examination of enlarged photographs.

The upper headwall is a near-vertical interface between light-coloured, peritidal dolomites, and dark-coloured, upper slope strata containing a major talus wedge (Plate 54). The lower part of the headwall truncates a series of foresets above the sub-Vermilion megatruncation surface, and the upper part of this feature truncates horizontally bedded strata.

At the base of the headwall, the surface becomes concave-upward and the dip decreases rapidly to about 15° (relative to platform bedding). Over this segment, the surface separates light-coloured dolomitized strata (foreset toes and megablocks) below, from dark grey ribbon limestone above. Farther basinward, the surface becomes near bedding-parallel and more indefinite as the overlying ribbon limestone becomes more argillaceous. The megatruncation surface therefore has an overall listric form. It probably continues at about the same stratigraphic level beneath the major ribbon limestone slide mass described earlier, and eventually plunges from view on the southwest side of a minor normal fault (Plate 54).

The intra-Vermilion megatruncation surface has tentatively been identified on the opposite (northwest) wall of the cirque (Plates 52, 53). There, it separates predominantly brown-weathering dolomitic argillite below, from predominantly grey-weathering ribbon limestone strata above. Although the surface was traversed by section 34, there was no obvious evidence of a significant unconformity (slide surface) at that stratigraphic level.

Thus, the megatruncation surface is a very subtle feature at outcrop scale, and could be easily missed in the absence of extensive lateral exposure.

The intra-Vermilion megatruncation surface can be traced at least 600 m basinward on the southeast wall of Verdant cirque (Fig. 36). Its ultimate basinward extent is unknown. Along depositional strike, it can be traced for approximately 3-4 km before the exposure ends.¹²

6.2.3.3 Stratigraphic packages traversed by surfaces

The stratigraphy traversed by the **lower two (sub-Vermilion) megatruncation surfaces** is difficult to determine precisely due to a lack of reliable stratigraphic markers. The upper (northeastward) end of the second megatruncation surface merges with platform bedding an estimated 95 m below the top of the cirque wall (and thus an estimated 145 m below the top of the Eldon-Pika sequence). The first megatruncation surface merges with platform bedding about 30 m lower. Assuming a thickness of about 212 m for the Pika Formation (Section 6.2.3.1), the two megatruncation surfaces appear to originate from lower to middle Pika-equivalent strata. The upper megatruncation surface cuts out at least 200 m of upper Eldon- and Pika-equivalent strata over its traceable extent on the southeastern wall of the cirque.

The near-vertical headwall of the **intra-Vermilion megatruncation surface** visibly truncates about 80 m of Pika-equivalent strata. The surface becomes essentially bedding-parallel farther basinward.

¹² This feature was mapped as a southwest-side-down normal fault by Price and Mountjoy (1972).

6.2.4 Summary of megatruncation surface characteristics

The Mt. Biddle, Stephen cirque and Verdant cirque exposures contain cross-sectional views of what are clearly very large-scale features. The essential characteristics of the observed megatruncation surfaces are summarized below:

1. The megatruncation surfaces are sharply defined, fairly smooth, and **visibly** truncate up to 215 m of strata. The sub-Vermilion megatruncation surface in Stephen cirque is inferred from indirect evidence to have a relief of at least 360 m over its traceable extent.
2. The overlying strata show **no** evidence of tectonic dislocation.
3. Where preserved, the updip (platformward) ends of the megatruncation surfaces disappear imperceptibly into horizontally bedded platform strata, or are cut off by younger megatruncation surfaces. The sole, known exception to this is the intra-Vermilion megatruncation surface in Verdant cirque, which terminates at a near-vertical headwall.
4. The megatruncation surfaces are relatively flat or broadly concave-upward, and at least some are demonstrably listric in form. Minor undulations and locally steepened segments are also common.
5. The surfaces are directly overlain and overlapped by sediments of inferred deep-water origin (e.g. laminated argillite, ribbon limestone, channellized calcarenite, and limestone conglomerate).

6. The surfaces themselves are relatively free of debris, and are only locally overlain by periplatform talus blocks or megaconglomerate.
7. The surfaces dip between 12° and 28° (locally up to 45°), but are generally inclined less than about 20° .
8. The maximum **visible** extent of any one surface **across** depositional strike is about 800-900 m. The sub-Vermilion megatruncation surface in Stephen cirque is inferred to extend at least twice that distance basinward. The maximum **visible** extent of any one surface **along** depositional strike is about 3-4 km. In each example, the overriding impression is that only a small piece of a much larger-scale feature is actually visible.

6.3 ELDON-PIKA MEGATRUNCATION SURFACES: INTERPRETATION

6.3.1 Introduction

The intra-Tokumm megatruncation surface at Mt. Biddle and the intra-Vermilion megatruncation surface in Verdant cirque were previously mapped as low-angle, southwest-side-down normal faults (Price *et al.*, 1980; Price and Mountjoy, 1972). The sub-Vermilion megatruncation surface in Stephen cirque was mapped as a thrust fault by McIlreath (1977a).¹³ Indeed, the writer's initial reaction on seeing these features for the first time during reconnaissance was also to dismiss them as faults. The fundamental role played by megatruncation surfaces in shaping the Middle Cambrian margin did not become apparent

¹³ D.G. Cook recognized this feature in Stephen cirque during Operation Bow-Athabasca in the 1960's, and was the first to suggest to the writer that it was some form of large-scale erosional feature rather than a thrust fault.

until the second field season, and their true vertical and lateral extent did not become apparent until the third.

The cross-strike exposures in Biddle, Stephen, and Verdant cirques provide cross-sectional views of the Eldon-Pika margin. The recognition of megatruncation surfaces at these localities led to the realization that significant, yet subtle disconformities must also be present in the numerous stratigraphic sections measured through the upper slope sequence along depositional strike. Once the scale of these surfaces became apparent, a conceptual model for the Middle Cambrian margin could be developed. The following sections outline the basis for this model, which represents a radical departure from previously held ideas.

6.3.2 Consideration of a possible late tectonic origin

In view of the fact that at least some of the megatruncation surfaces superficially resemble normal or thrust faults, the possibility that they are Mesozoic-Cenozoic tectonic features must be assessed. The main arguments against a late tectonic origin are summarized below.

Where contacts are fully exposed and accessible, it can be demonstrated in the field that the sediments above and below the megatruncation surfaces are in sedimentary contact, and that there is no evidence of any tectonic dislocation. The contact is an angular unconformity along the upper part of the surface, and usually a bedding-parallel disconformity along its lower part. Perhaps the best example of this unconformable relationship is the intra-Tokumm megatruncation surface in Biddle cirque. There, undeformed argillites of the basal Tokumm sub-unit sharply overlie similarly undeformed,

thin-bedded limestone of the lower Eldon Formation (Section 6.2.1; Plates 46, 48c).

Structural features such as slickensides, gouge, breccia, and veining are absent.

In Stephen and Verdant cirques, the accessible portions of the megatruncation surfaces are not as well exposed as at Mt. Biddle. However, the surfaces are magnificently exposed high on the cirque walls, where close examination through binoculars was possible. Again, structural deformation is lacking above and below these features. This is remarkable, given that the megatruncation surfaces are favourably oriented relative to the direction of regional shortening. In contrast, small-scale structural deformation was clearly visible in strata overriding a minor thrust fault in Stephen cirque.

While the angle and orientation of the megatruncation surfaces often mimics the pattern of thrust faults, the manner in which most of the surfaces terminate platformward does not. The sub-Vermilion megatruncation surfaces in Stephen and Verdant cirques visibly flatten out and merge imperceptibly with horizontal platform bedding (Plates 49, 54). Superficially, this resembles the ramp and flat configuration common in thrust faults. However, the geometrically necessary hanging wall anticline is missing, and thus these features cannot be thrust faults.

The intra-Vermilion megatruncation surface in Verdant cirque (Plate 54) is quite different in configuration, but also fails to conform to a late-stage fault interpretation. The physical continuity of strata beneath the headwall of this feature has been confirmed by careful observations through binoculars. In addition, if a fault were present, its configuration would be completely unlike that of other late-stage normal faults in the study area.

Sedimentological evidence also supports the contention that the megatruncation surfaces are syndimentary features. In Verdant cirque, the sub-Vermilion megatruncation surface is overlapped by well-defined foresets (Plate 54). Similar, though much less obvious foresets are also visible above the sub-Vermilion megatruncation surface in Stephen cirque (Plate 49). The foresets clearly overlie a primary, sloping surface.

6.3.3 Basic interpretation of the megatruncation surfaces

The physical attributes of the megatruncation surfaces indicate that they are Cambrian erosional features affecting the outer platform, platform margin, and upper slope. They are inferred to be submarine in origin, and are considered to be large-scale, gravity slide structures.

The submarine interpretation for these features is based largely on negative evidence. Comprehensive stratigraphic work by J.D. Aitken and local observations by the writer found no obvious evidence (e.g. karstification, pedogenesis) that the Eldon-Pika platform was ever subaerially exposed. There is also no evidence for subaerial exposure at localities where the megatruncation surfaces could be closely examined. The sharp, smooth contacts so prominently displayed on the inaccessible cirque walls make it unlikely that even the uppermost parts of the megatruncation surfaces were ever exposed to subaerial erosion and weathering.

The origin of truncation surfaces of all scales has been debated ever since Wilson (1969) described relatively small-scale "cut and fill" structures from European and North American deep-water limestone successions. Some examples can perhaps be explained in

terms of abrasive processes, but exposure is commonly insufficient, particularly in the elusive third dimension, to allow an unequivocal interpretation (e.g. Yurewicz, 1977).

Davies (1977, p. 242) forcefully argued for a gravity slide origin for spectacularly exposed megatruncation surfaces in the Hare Fiord Formation of the Sverdrup Basin. This interpretation has been reinforced in recent years by the documentation, in seismic reflection profiles, of similar, large-scale truncation features on the west Florida carbonate platform (Mullins *et al.*, 1986, 1988). These features have compelling similarities to the spoon-shaped slide scars documented so widely in deep-water siliciclastic settings (e.g. Embley and Jacobi, 1977; Moore, 1978; Jacobi, 1984).

"Scalloped" embayments and limited seismic reflection data are increasingly showing that large-scale gravity collapse is a common process affecting carbonate platform margins (Mullins and Hine, 1989; Mullins *et al.*, 1990). This process can also be inferred from the occurrence, in seismic reflection profiles or outcrop, of enormous megabreccia (or megaconglomerate) bodies containing megaclasts of platform margin and/or inner platform origin (e.g. Cook *et al.*, 1972; James, 1981; Johns *et al.*, 1981; Bosellini, 1984; Seguret *et al.*, 1984; Heck and Speed, 1987; Hine *et al.*, 1990; Hine *et al.*, 1991). Hence, megatruncation surfaces in the carbonate slope environment can usually be credibly interpreted as large-scale submarine slide scars (e.g. Castellarin *et al.*, 1978; Cook and Mullins, 1983; Enos and Moore, 1983; McIlreath and James, 1984; Coniglio, 1986; Bosellini, 1989).

On the basis of their physical characteristics and depositional setting, the megatruncation surfaces in the study area are inferred to be submarine slide scars, formed by repeated, catastrophic collapse of the upper Eldon-Pika platform margin. In view of the fault-like characteristics of these features (sharp, smooth surfaces cross-cutting early-lithified

sediments), they could alternatively be viewed as low-angle, listric, synsedimentary normal faults, the hanging walls of which have disappeared downslope into the basin (cf. James *et al.*, 1988).

It must be emphasized that only short, generally two-dimensional segments of these features are visible in the study area, despite the availability of spectacular mountainside exposures. The three-dimensional geometry and ultimate lateral extent of the megatruncation surfaces cannot be determined directly in the field, and thus it is necessary to seek out morphologically similar features in the modern and ancient record for comparison.

6.3.4 Collapse features on the outer west Florida carbonate platform and in the Caribbean region

Seismic reflection profiles across modern and ancient carbonate margins are very valuable, as the three-dimensional configuration of large-scale collapse features can be mapped out over large areas. This technique has been used by Mullins *et al.* (1986, 1988) on the west Florida carbonate platform margin (Fig. 38, right).

The west Florida platform is a distally steepened carbonate ramp that dips gently (1-2°) to depths as great as 2000 m.¹⁴ Farther seaward, the sea floor plunges to abyssal depths across the Florida Escarpment at dips of 20-30° or more (Mullins *et al.*, 1988; see also Paull *et al.*, 1990; Twichell *et al.*, 1990). Seismic reflection profiles over a portion of the outer ramp have revealed a series of sub-parallel Miocene truncation surfaces, which were inferred by Mullins *et al.* (1986) to be submarine slide scars (Fig. 38, left). The largest of these

¹⁴ Twichell *et al.* (1990) differentiate three bathymetric provinces: (1) the West Florida Shelf (water depths <200 m); (2) the West Florida slope (200 m to top of Florida Escarpment at 1500-2250 m); and (3) the Florida Escarpment.

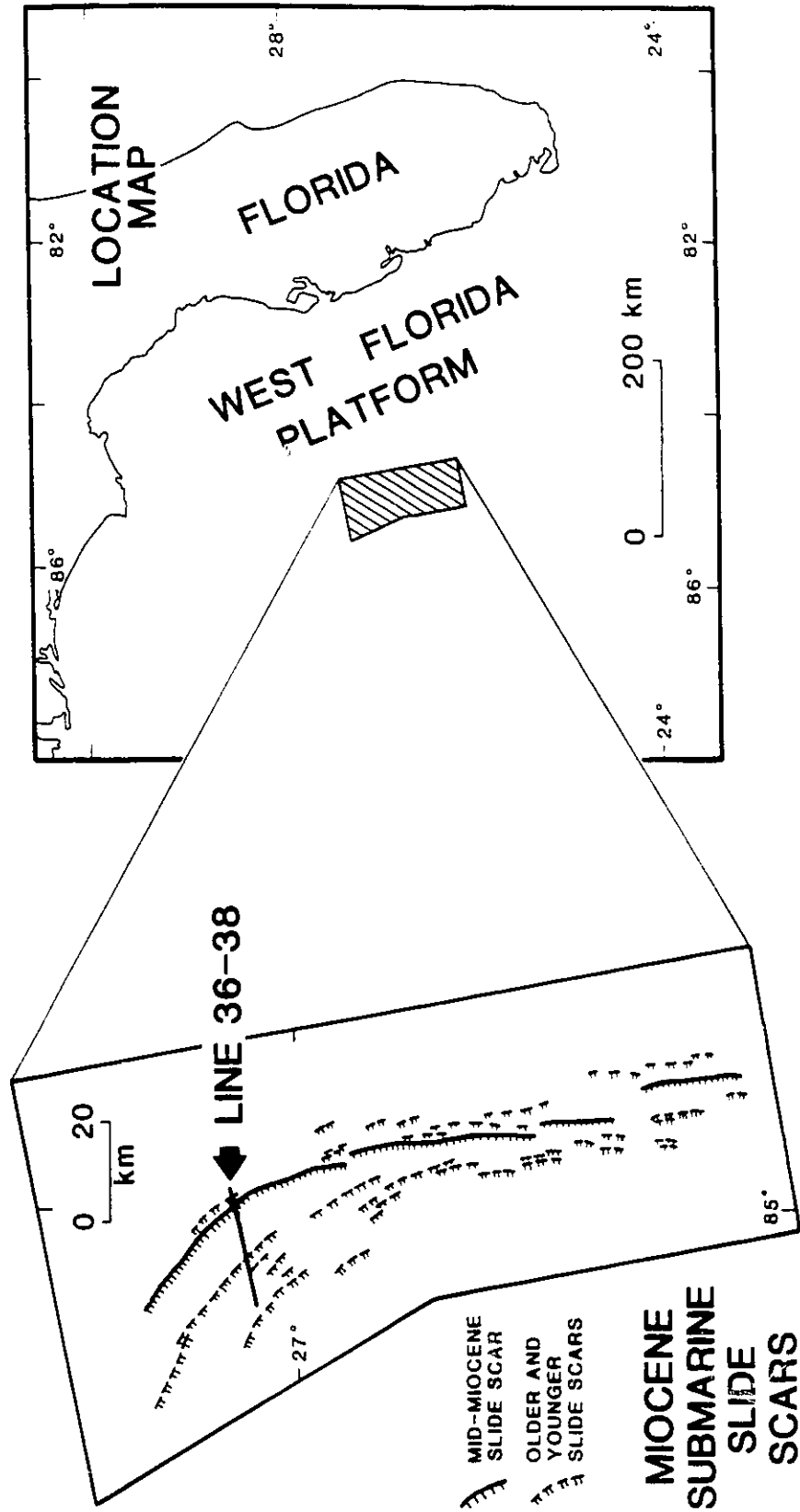


Figure 38. Location map showing area of seismic reflection coverage on the outer west Florida platform (based on Mullins *et al.*, 1986). Inset shows the traces of the Miocene submarine slide scars mapped in this area, and the location of the seismic line on which Figure 39 is based.

abruptly truncates 300-350 m of late Paleogene and early Neogene strata below the mid-Miocene unconformity (Fig. 39). The feature is concave basinward, and can be followed more than 100 km along strike across a series of en-echelon offsets. Bathymetrically, it is expressed as a major embayment up to 30 km wide in the outer platform. The truncation surface is listric in cross-section, and has a maximum dip of about 23° . It represents the removal of many cubic kilometres of sediment. Most of the displaced material was transported tens of kilometres downslope to abyssal depths at the foot of the Florida Escarpment.¹⁵

The west Florida truncation surface shows strong similarities to slide scars in deep-water siliciclastic settings. Side-scan sonar imagery of siliciclastic slopes has revealed amphitheater-like depressions which open downslope into linear sediment chutes (Farre et al., 1983). In longitudinal cross-sections, these features have listric profiles. Slope angles range from about 10° to more than 16° (Jacobi, 1984), and some examples from the middle Atlantic margin of the United States are reported to have vertical headwalls (Farre et al., 1983). These erosional scarps range up to at least 200-250 m in height. Many scars have step-like floors, which give rise to ramp and flat profiles in cross-sectional views parallel to the slide scar axis. The steps apparently reflect multiple detachment planes parallel to bedding (Farre et al., 1983).

In siliciclastic settings, the largest slide scars have widths of as much as a few hundred kilometres in the headwall region. The unlithified and semi-lithified material removed along these surfaces may be transported hundreds of kilometres downslope, leaving behind bare "zones of removal" hundreds to thousands of square kilometres in extent

¹⁵ The slide block shown in Fig. 39 (lower right) is one of the few examples where slide material was actually recognized in the area studied by Mullins et al. (1988).

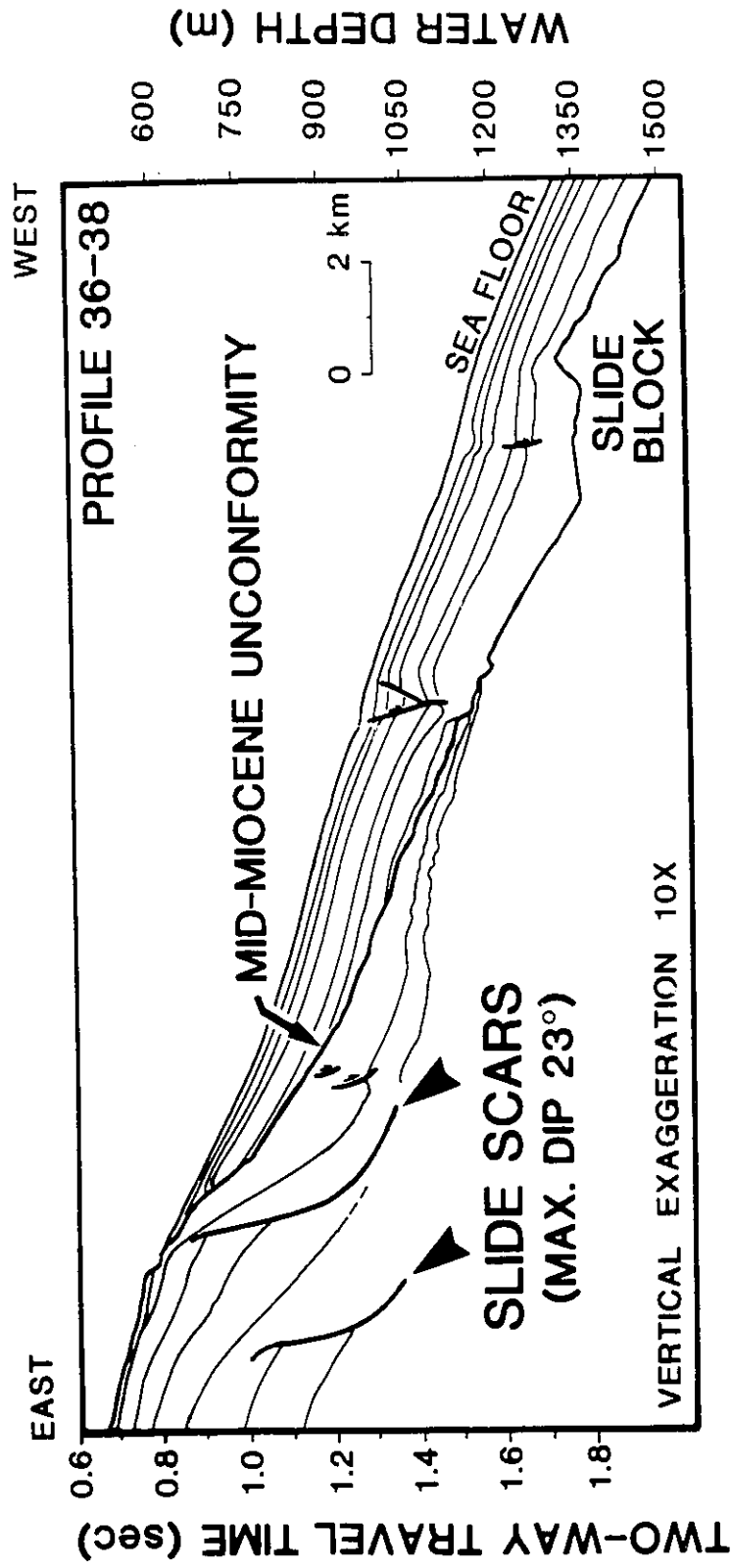


Figure 39. Line drawing from seismic reflection profile 36-38 (Figure 38), showing large-scale, Miocene slide scars truncating strata of the outer west Florida platform (redrawn from Mullins et al., 1988). Note the 10x vertical exaggeration, and the fact that the slide scar head walls have a maximum inclination of about 23°.

(Moore, 1978; Embley and Jacobi, 1977; Jacobi, 1976, 1984). Smaller scale scars comparable in scale to the west Florida platform example are also quite common in siliciclastic settings.

It is now becoming apparent that the collapse feature on the outer west Florida platform is only one of a series of similar structures of various scales in the Gulf of Mexico and Caribbean region. Smaller, scalloped embayments (10-20 km wide) are also present on the southern margin of Pedro and Walton banks, southwest of Jamaica (Mullins and Hine, 1989; Fig. 40). These features have clear bathymetric expressions, although it should be cautioned that more extensive documentation (seismic reflection profiling, reflector mapping, and bottom sampling) will be needed to fully document their origin. The single seismic reflection profile published by Mullins and Hine (1989, their Fig. 3) shows a 135 m high marginal escarpment inclined at about 40°. Large, isolated periplatform talus blocks appear to be scattered on the 2° slope at its base. Scalloped margins have also been reported by Mullins *et al.* (1990) in the southeast Bahamas.

Elsewhere along the Nicaragua Rise, Hine *et al.* (1990, 1991) have also documented major megabreccia sheets attributable to catastrophic platform margin collapse. The largest reported megabreccia sheet is about 28 km wide, 16 km long, and up to 100 m thick. Individual platform-derived blocks up to 400 m across have sea floor reliefs of more than 100 m (Hine *et al.*, 1991). Erosional escarpments up to 120 m high are also evident in seismic reflection profiles (Hine *et al.*, 1990).

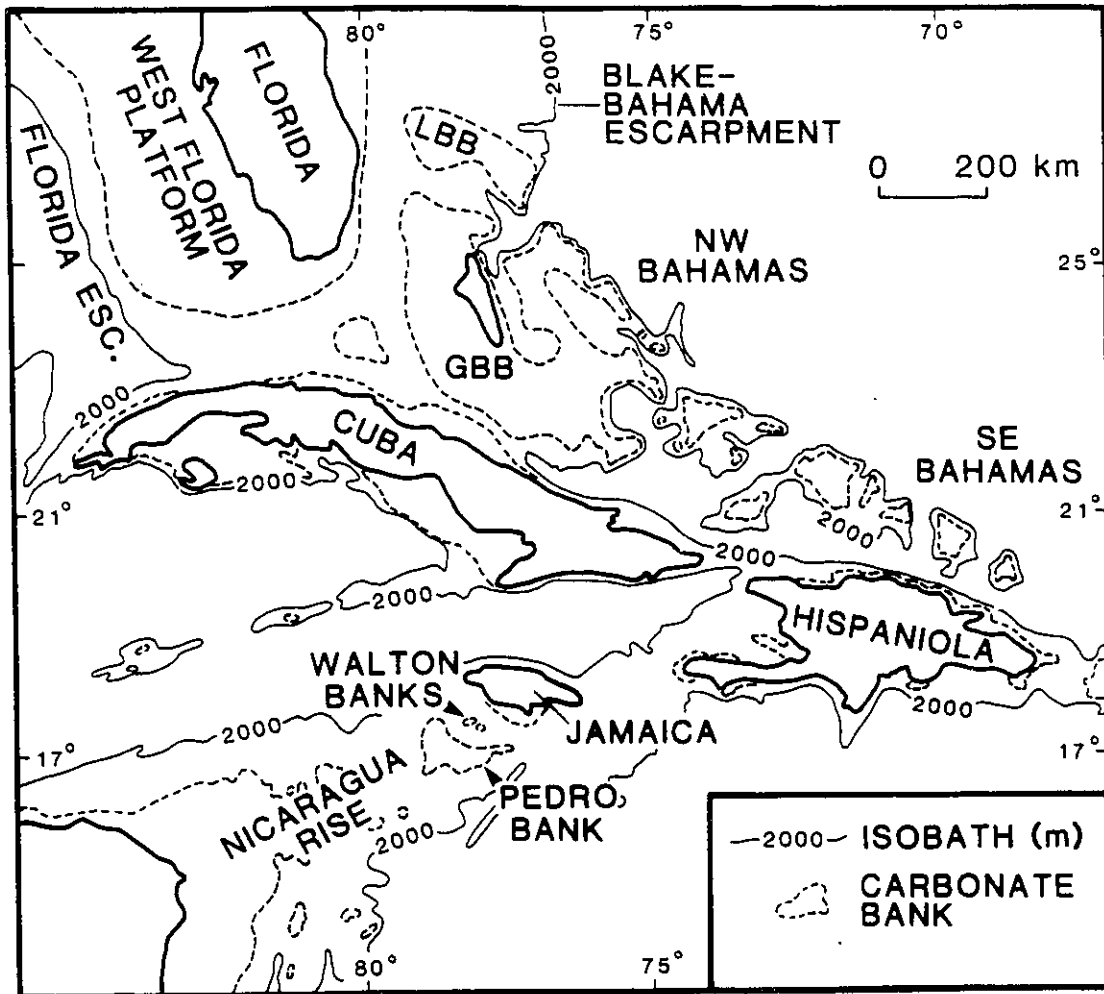


Figure 40. Location map for the Caribbean and adjoining areas.

6.3.5 Outcrop examples of megatruncation surfaces

Megatruncation surfaces have been described from the rock records of North America, Greenland, Europe, and Australia (Table 6.1). Most of these examples directly affect the margins of shallow-water carbonate platforms, and are therefore comparable to the Eldon-Pika megatruncation surfaces in terms of depositional setting. All are exposed in only two dimensions, and thus their areal extent and three-dimensional geometry are unknown. Although submarine gravity sliding was probably instrumental in forming most of the megatruncation surfaces, some appear to have been substantially modified by other agents of submarine erosion.

The megatruncation surfaces described by Davies (1977) from exceptional cliff exposures of the **Hare Fiord Formation in the Sverdrup Basin** (Table 6.1) have become textbook examples of probable submarine slide scars. The scale, listric geometry, and smooth, regular nature of the surfaces compare well with submarine slide scars in deep-water siliciclastic settings (e.g. Moore, 1978; Jacobi, 1984). The Hare Fiord examples are also similar in many respects to the Eldon-Pika megatruncation surfaces, although they are situated well down the carbonate slope, and thus do not directly affect the Permian carbonate margin.

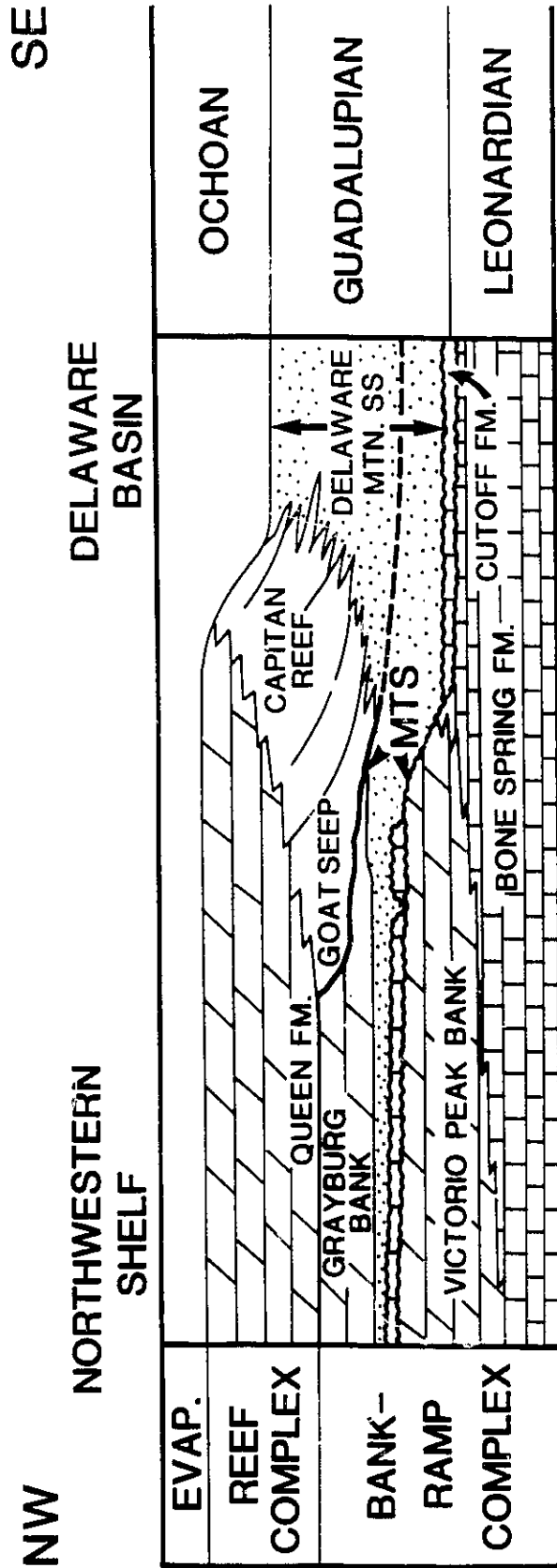
Large-scale submarine erosion features affecting the platform margin have been recognized for some time in the **Permian Basin of New Mexico and West Texas** (Fig. 41). Although these features have been described numerous times in a series of theses, abstracts and guidebooks (e.g. Pray, 1971; Pray *et al.*, 1980; Fekete *et al.*, 1986; Kirkby, 1988; Harris, 1988a, b), detailed descriptions have been published only recently (Franseen *et al.*, 1989).

TABLE 6.1
MEGA TRUNCATION SURFACES IN THE ROCK RECORD

<u>LOCATION / AGE</u>	<u>GEOMETRY AND SCALE</u>	<u>COMMENTS</u>	<u>SOURCE(S)</u>
Hare Fiord Fm., Sverdrup Basin (Permian)	Listric; smooth, locally downstepping surface without visible scouring or channeling; maximum dip 15°. Bedding-discordant segments up to 1.5 km long; maximum vertical truncation about 150 m.	Located on a carbonate slope about 15 km from the platform margin. Breccia, rotated blocks and visibly disturbed bedding have not been observed above or below the surface. The depositional dip of the overlying sediments progressively decreases upwards, and the thickness of this sedimentary package increases downslope.	Davies (1977)
Grayburg truncation surface, Guadalupe Mountains, New Mexico/West Texas (Permian)	Listric; headwall truncates about 115 m of middle to uppermost Grayburg Fm. at angles of up to 80°; basinward, an additional 60-70 m of strata appear to be truncated over a horizontal distance of 900 m. The maximum vertical truncation is estimated to be 285 m over 3 km. The surface has major "step" with 30-40 m relief, about 500 m basinward of the headwall.	Truncation surface parallels the inferred margin of the Delaware Basin. The surface is underlain by apparent incipient slump structures, and overlain by laterally discontinuous dolomite breccia and angle-of-repose foresets belonging to the Goat Scap Fm. Shelfward, the surface connects with a flat, locally scoured and channelized shelf erosion surface.	Franseen <i>et al.</i> (1989); Fekete <i>et al.</i> (1986)
Pre-Cutoff surface, Guadalupe Mountains, New Mexico/West Texas (Permian)	Listric; truncates 100-150 m of upper Victoria Peak and Bone Spring Fms. at angles up to 15°. Channel-like features 100's of metres wide and up to 50 m deep occur on the surface.	Connects with planar, gently basinward-dipping (1°) surface that bevels underlying strata.	Kirkby (1988); Pray (1971); Harris (1988a, 1988b); Sarg (1988).

TABLE 6.1 (CONTINUED)

<u>LOCATION/ AGE</u>	<u>GEOMETRY AND SCALE</u>	<u>COMMENTS</u>	<u>SOURCE(S)</u>
Post-Cutoff surface, Guadalupe Mountains, New Mexico/West Texas (Permian)	Listric; truncates more than 200 m of Cutoff and upper Victorio Peak Fms. over 3 km at angles up to 30°. Contains channel and "scoop" -shaped features hundreds of metres wide and up to 50 m deep.	Connects with a shelf erosion surface containing a 100 m deep, U-shaped, channel-like feature (Bartlett Channel), 1.5 km shelfward from the margin.	Kirkby (1988); Pray (1971); Harris (1988a, 1988b); Sarg (1988).
Pillara Limestone, Canning Basin (Devonian)	Exposed portion apparently straight; truncates an unspecified thickness (<100 m) of Pillara Limestone at "steep" angle (about 60°).	Geometry of truncation surface thought to have been controlled by a network of neptunian dikes. These were either earthquake-related or the product of large-scale, differential compaction and/or creep.	Playford, (1984); Playford et al., (1989); Kerans et al.,(1986)
Tethyan platforms, Italy (Mesozoic - Tertiary)	At least some are listric, and truncate 100's of metres of platform strata.	Formed in a tectonically active environment, and are associated with huge megabreccia bodies in the adjoining basins. Olistoliths and megabreccias occur locally along the surfaces and in overlying, deep-water strata.	Bosellini (1984, 1989); Castellarin et al., (1978)
North Greenland (Upper Ordovician - Lower Silurian)	Listric; truncates 300-400 m of shallow subtidal to peritidal strata at angles up to 30°.	Platform margin originally developed as a steeply-dipping (45°) escarpment in response to platform aggradation and differential subsidence along the underlying, deep-seated Navarana Fjord Fault Zone.	Surlyk and Hurst (1984); Hurst and Surlyk (1984); Surlyk and Ineson (1987)



PERMIAN SHELF-MARGIN COMPLEXES GUADALUPE MOUNTAINS

Figure 41. Schematic cross-section across the northwestern margin of the Delaware Basin, New Mexico and west Texas (redrawn and modified from Fransen et al., 1989). Major erosion surfaces truncate the Grayburg and Victorio Peak/Bone Spring formations in the area. MTS: megatruncation surface.

The most important submarine erosion surfaces documented in that area are the Grayburg truncation surface, and the pre- and post-Cutoff truncation surfaces (Table 6.1; Fig. 41).

The **Grayburg truncation surface** is notable for its smooth, listric geometry, and its steep (up to 80°) and high (115 m) headwall (Fig. 42; Table 6.1). Franseen *et al.* (1989) argued forcefully for a submarine origin for this feature. It is almost certainly a gravity slide surface, although erosion by bottom currents and sediment gravity flows may have played some role in its formation. The shelfward component of the surface is locally scoured and channelled on a scale of tens of metres. The Grayburg truncation surface is considered to be a type 1 sequence boundary, formed in part by extensive, slope-front erosion following a rapid relative sea level fall (Sarg and Lehmann, 1986; Sarg, 1988). Evidence for platform exposure is, however, equivocal (Franseen *et al.*, 1989).

The processes responsible for creating the **pre- and post-Cutoff truncation surfaces** (Fig. 41) are currently ill-defined. These surfaces truncate hundreds of metres of strata, and have overall listric forms. Large-scale gravity sliding probably played a major role in their formation. However, their basinward components are characterized by irregular, channel-like and spoon-shaped features with reliefs up to 50 m, suggesting substantial modification by bottom currents, sediment gravity flows, or other, as yet unrecognized agents (Pray, 1971; Kirkby, 1988; Harris, 1988a, b). Both surfaces have also been designated as type 1 sequence boundaries (Sarg and Lehmann, 1986; Sarg, 1988). However, this interpretation may require revision, as evidence for subaerial exposure (or even significant shallowing) of the platform is lacking (Kirkby, 1988).

The collapsed margins in the **Devonian Canning Basin of Western Australia** have not been described in detail (Table 6.1). Their significance lies in the fact that platform

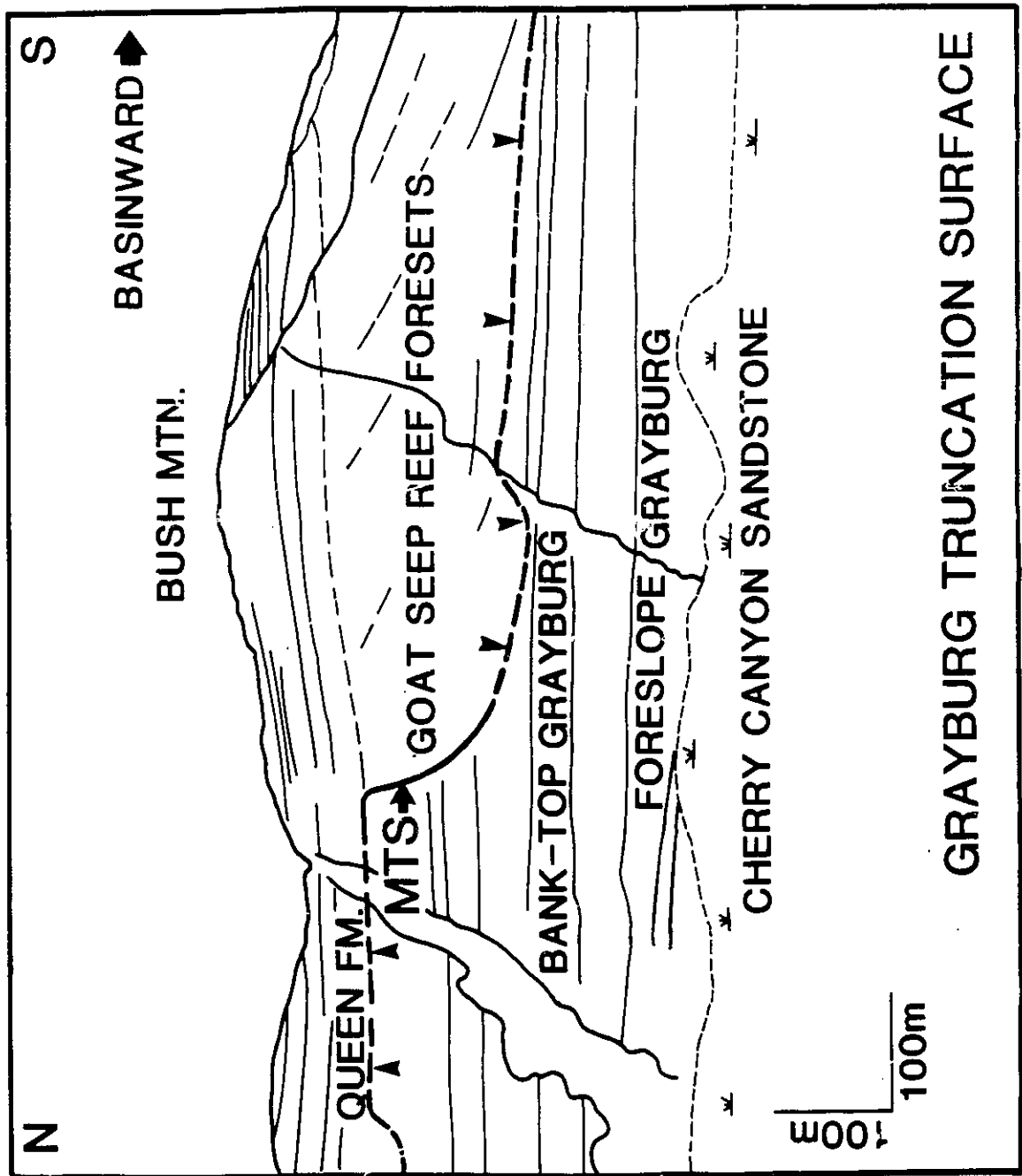


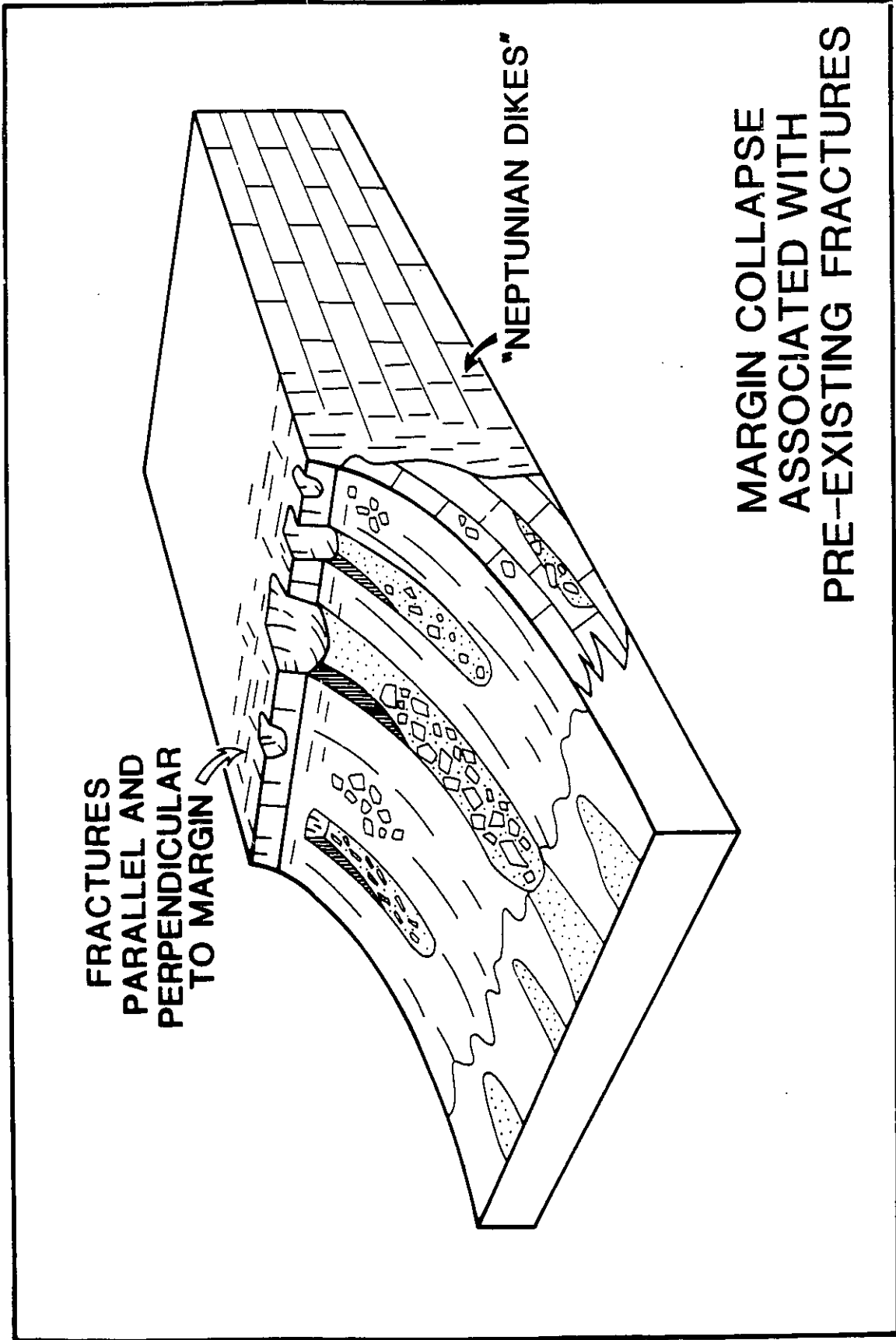
Figure 42. Line drawing of Grayburg truncation surface along the western escarpment of the Guadalupe Mountains (redrawn from Franseen *et al.*, 1989). The megatruncation surface and associated platform top disconformity are indicated by a series of arrows. The surface is overlain by prograding foresets of the Goat Seep Formation. MTS: megatruncation surface.

margin collapse was apparently linked to dilation along steeply-dipping, submarine fracture zones parallel to the platform margin (neptunian dikes, Fig. 43; Playford, 1984; Playford *et al.*, 1989). Fractures of this type may well be one of the vital prerequisites for the development of steep headwalls.

Megatruncation surfaces are also known in the **Tethyan platforms of the Alpine-Mediterranean region**, where many are thought to have formed in response to seismic activity (Bosellini, 1984, 1989; Castellarin *et al.*, 1978). The morphology of some of these features was probably directly controlled by synsedimentary faulting, which also would produce steep headwalls.

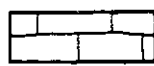
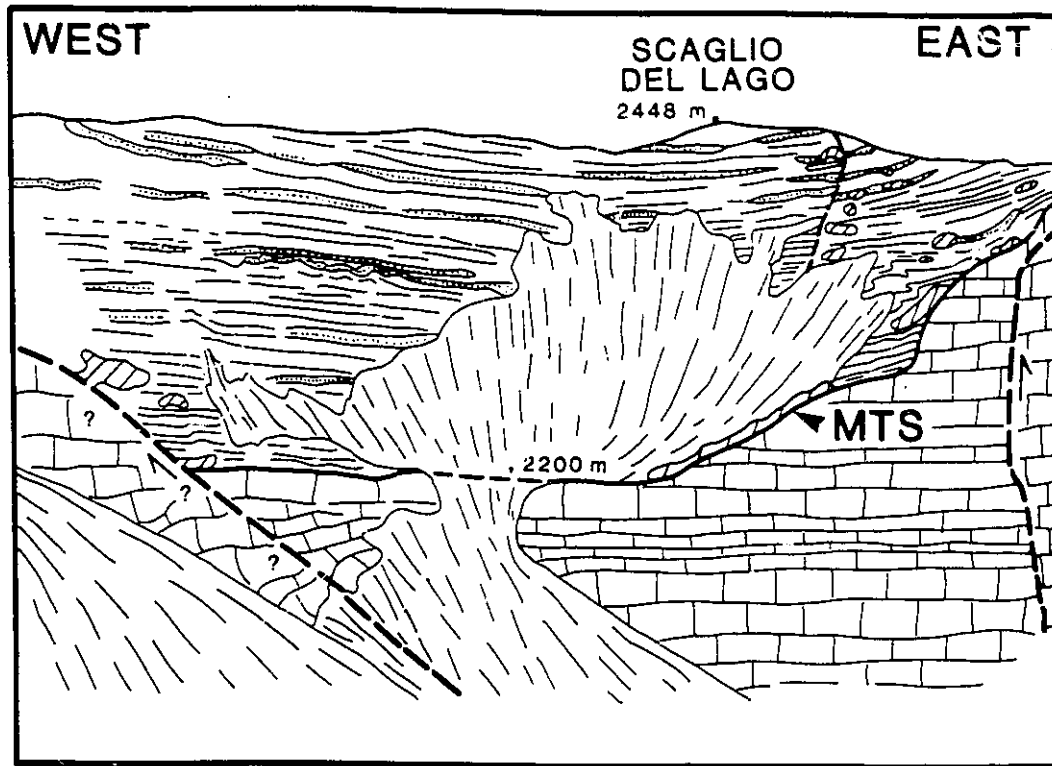
Gigantic platform margin scars, presumed to be related to major seismic events, have been observed at a number of localities in the Dolomites of northern Italy (Bosellini, 1984). Unfortunately, they have not been described in detail. Similar features of Late Cretaceous and Eocene age in southern Italy are thought to have formed during significant lowstands in sea level (Bosellini, 1989).

A spectacular megatruncation surface described by Castellarin *et al.* (1978) in the Apennines of central Italy has an overall listric geometry, and truncates approximately 200 m of bedded peritidal strata belonging to the Calcare Massiccio Formation (Fig. 44). Its headwall has an apparent dip of about 35°, and is distinctly stepped. The megatruncation surface is overlapped by a hemipelagic sequence containing megabreccia bodies and periplatform talus blocks, which were presumably shed during periodic, retrogradational failure following the main collapse event.



**MARGIN COLLAPSE
ASSOCIATED WITH
PRE-EXISTING FRACTURES**

Figure 43. Schematic diagram of local platform margin collapse associated with pre-existing fractures perpendicular and parallel to the shelf margin (redrawn from Playford et al., 1989).



CALCARE MASSICCIO FM. -
PERITIDAL PLATFORM STRATA



CORNIOLA FM. - CARBONATE TURBIDITES (a)
AND MAJOR CHANNELLED TURBIDITES (b)



CORNIOLA FM. - MEGABRECCIAS AND
OLISTOLITHS (a); SLUMPED HEMIPELAGITES (b)



QUATERNARY COVER

Figure 44. Line drawing of megatruncation surface cutting into carbonate platform strata of the Calcare Massiccio Formation in the Liassic of Italy (redrawn from Castellarin *et al.*, 1978). Nearly 200 m of peritidal strata have been truncated by this inferred slide scar, which has a steep headwall and a bedding-parallel lower portion. The overlying Corniola Formation contains interbedded hemipelagites and carbonate turbidites, together with numerous megabreccia units and periplatform talus blocks.

Equally impressive truncation of the **Late Ordovician - Early Silurian platform margin in northern Greenland** has been illustrated by Surlyk and Ineson (1987; see also Surlyk and Hurst, 1984; Hurst and Surlyk, 1984). The platform margin is a steeply-dipping (45°) escarpment, comparable in scale to the Florida and Blake-Bahamas escarpments. The upper 300-400 m of the platform sequence are truncated by a large, listric surface (Surlyk and Ineson, 1987, their Figs. 9, 10). The surface dips about 30° basinward, and is overlapped by siliciclastic turbidites with interbedded carbonate conglomerates. This feature was vaguely attributed to "strong headwards erosion" by Surlyk and Ineson (1987), and has all the earmarks of a major slide scar.

6.3.6 Synthesis

6.3.6.1 Introduction

Seismic reflection profiles and natural exposures have provided important insights into the scale, three-dimensional geometry, and origin of large-scale truncation surfaces. Clearly, these features form in a variety of depositional settings. For example, the megatruncation surface on the west Florida platform represents large-scale collapse of an outer deep-water ramp in more than 500 m of water. In siliciclastic settings, morphologically similar slide scars are found on the continental slope and rise at depths ranging from 200 m to 5400 m (Jacobi, 1984). In contrast, most of the surfaces described in Table 6.1 were formed by collapse of early-lithified, rimmed platform margins. Despite these differences in depositional setting, all of these examples can be used to develop a conceptual model for the megatruncation surfaces observed in the study area.

6.3.6.2 Summary of slide scar characteristics

Three-dimensional geometry: seismic reflection data and outcrop observations from a number of areas indicate that slide scars have listric profiles in longitudinal cross sections. Geophysical mapping and side-scan sonar imagery confirm that the surfaces are spoon-shaped in three dimensions, and are bounded by erosional scarps on three sides. They should also ramp upward at their toes (*cf.* Gawthorpe and Clemmey, 1985), although this is rarely seen. Local ramps and flats need also occur at intervals along the slide profile where detachment occurs at more than one stratigraphic horizon. These multiple detachments may occur between layers of differing lithology or induration (Farre *et al.*, 1983).

Headwall configuration: geophysical mapping and side-scan sonar studies indicate that the slide scar headwalls are arcuate features (Mullins *et al.*, 1986; Farre *et al.*, 1983). Their slopes range from less than 10° to nearly vertical, but are commonly less than about 20° - 25° . Headwall declivity probably depends on: (1) the degree of induration of the strata being truncated; (2) the existence of vertical or lateral inhomogeneities in these rocks; (3) the presence of suitably oriented, pre-existing fractures or joints related to seismic activity or large-scale creep processes (Fig. 43); and (4) the presence of syndimentary faults.

Style of truncation: footwall beds tend to be sharply and smoothly truncated, and erosional irregularities are generally absent. This style of truncation is characteristic of shear planes. However, the initial slide surface could be significantly modified by retrograde failure or erosion by density and/or bottom currents. Little or no deformation of the footwall sediments may occur during the slide event, suggesting that little energy is transmitted across the surface by the overriding sediments. This has been noted in both siliciclastic (Jacobi,

1984) and carbonate (Davies, 1977) settings, and is also generally true of the study area. In at least some instances, however, small-scale, plastic or brittle deformation (entirely unresolvable by seismic methods) occurs in shear zones immediately beneath the slide surfaces (Coniglio, 1986).

Scale of vertical truncation: megatruncation surfaces commonly truncate hundreds of metres of strata. The 215-360 m of truncation inferred to occur in the study area compares favourably with the scale of vertical truncation in platform margin settings (185-300 m: Permian Basin and Greenland), on carbonate slopes (150 m: Hare Fiord Formation), on deep carbonate ramps (300-350 m: Mullins *et al.*, 1986), and in deep-water, siliciclastic settings (200-250 m: Farre *et al.*, 1983; Jacobi, 1984). The upper parts of these surfaces are obvious angular unconformities, whereas their lower parts are essentially bedding-parallel disconformities.¹⁶ Similar configurations are evident in the study area (e.g. sub-Vermilion megatruncation surface in Stephen cirque -- Plates 49, 50; intra-Vermilion megatruncation surface in Verdant cirque -- Plate 54).

Lateral dimensions: seismic reflection profiling and side-scan sonar imagery are the only viable means of assessing the true lateral extent of megatruncation surfaces. They provide a lesson in scale that is humbling to outcrop geologists. The mid-Miocene megatruncation surface on the west Florida platform, for example, can be traced more than 100 km sub-parallel to the ramp margin (Mullins *et al.*, 1988). The sediments displaced along this slide scar were transported on the order of tens of kilometres downslope. On siliciclastic slopes, the largest slide scars range up to a few hundred kilometres wide in the headwall region, and the slide material is commonly transported tens to hundreds of

¹⁶ The time gaps across these surfaces can be significant, depending on the scale of truncation. For example, Mullins *et al.* (1988) reported a hiatus of 7.8 to 10.6 m.y. (based on calcareous nannofossils) across a slide scar on the west Florida platform. In siliciclastic settings, time gaps on the order of 0.25 to 2.5 m.y. are typical (Jacobi, 1984).

kilometres downslope (Moore, 1978; Embley and Jacobi, 1977; Jacobi, 1984). The enormous olistostromes found in many basins adjoining carbonate platforms indicates that sediment failures of comparable scale occur in carbonate settings as well (e.g. Seguret *et al.*, 1984).

Zone of removal: The upper parts of slide scars in both carbonate and siliciclastic settings are essentially free of allochthonous debris generated during the original slide event (Mullins *et al.*, 1986, 1988; Jacobi, 1984). In siliciclastic settings, these "zones of removal" commonly have areas of hundreds to thousands of square kilometres (Jacobi, 1976). The megatruncation surfaces in the study area are similarly clean of allochthonous debris, except for local deposits inferred to have been generated by retrogradational failure and other, post-slide processes.

Abrupt thickening of sediments in slide scar depression: seismic reflection profiles from the west Florida platform reveal an abrupt thickening of sedimentary sequences into the Miocene slide scar depression (Mullins *et al.*, 1988). A similar relationship should be apparent on shallow truncated margins as well. Due to limited accommodation space on the platform, excess sediments would be preferentially funnelled into the slope basin created by margin collapse.

Post-slide sedimentation: slide scars in deep-water settings are passively overlapped by fine-grained hemipelagic sediments and sediment gravity flow deposits. The depositional dip of these sediments progressively decreases upward. This relationship is clearly evident in seismic reflection profiles from the west Florida platform (Mullins *et al.*, 1988), and in the spectacularly exposed Hare Fjord Formation in the Canadian Arctic (Davies, 1977; Table 6.1). It is also true of the study area (e.g. Plate 54). If the slide scar directly truncates a

shallow-water carbonate margin, subsequent margin progradation into the depression would result in the deposition of large-scale clinoforms (cf. the "descending progradation" of Bosellini, 1984). This process is well illustrated by the Gargano Platform of southern Italy (Bosellini, 1989), and by the Goat Seep foresets above the Grayburg truncation surface in the Permian Basin (Fig. 42; Franseen *et al.*, 1989). Similar, though smaller scale clinoforms are visible above the upper sub-Vermilion megatruncation surfaces in Stephen and Verdant cirques (Plates 49; 54).

Fate of the slide material: observations from modern slopes confirm that slides can be transported tens of kilometres or more downslope. These allochthonous masses can be essentially undeformed except around their bases and edges (Nardin *et al.*, 1979), although internal deformation can occur at any scale (e.g. Mullins and Neumann, 1979; Cook, 1979; Cook and Mullins, 1983; Jacobi, 1984; Gawthorpe and Clemmey, 1985; Alvarez *et al.*, 1985; Coniglio, 1986). A wide variety of materials would be generated during platform margin collapse, including early-lithified platform margin rocks (ranging in size from granules to enormous olistoliths measuring thousands of metres across), uncemented or partly cemented carbonate sands, and semi-lithified to unlithified slope sediments. If unlithified slope sediments and water become incorporated into the moving slide mass in sufficient quantities, it will evolve into a debris flow downslope (Hampton, 1972; Cook and Mullins, 1983; Alvarez *et al.*, 1985).

Dating the time of margin failure: in the study area, the time of margin failure cannot be inferred from the age of the sediments immediately overlying the slide scar, due to poor fossil control and insufficient biostratigraphic resolution. Thus, the surfaces must be dated from cross-cutting relationships. The youngest bed cut by a particular surface is assumed to approximate the sediment/water interface at the time of failure.

6.3.6.3 Factors influencing platform margin collapse

Several factors could contribute to catastrophic platform margin collapse (Fig. 45). Commonly, failure thresholds are achieved when several factors act together or in sequence. In general, however, it is impossible to specify the factor or combination of factors responsible for a particular failure.

Strong, but infrequent **earthquake shocks** are probably a direct cause of fracturing and eventual failure of early-lithified platform margin and upper slope sediments (Cook *et al.*, 1972). They are also a major cause of failure of semi-lithified or unlithified slope sediments (Embley and Jacobi, 1977; Jacobi, 1984; Prior and Coleman, 1984). Direct evidence for contemporary earthquakes in passive margin settings is rarely preserved. The "neptunian dikes" documented in the Canning Basin of western Australia (Kerans *et al.*, 1986; Figs. 43, 45) are inferred to be extensional features related to earthquake activity (Playford *et al.*, 1989). However, these fractures could also have been generated by other processes, such as differential compaction (Hurley *in* Kerans *et al.*, 1986) or large-scale creep. Seismically-induced platform retreat can be inferred with greater confidence in active tectonic regimes, as in the case of the Jurassic Tethyan platforms (Flugel, 1982, p. 232; Bosellini, 1984, 1989).

Progressive failure of the slope (Embley and Jacobi, 1977) can also lead to platform margin collapse. In this process, sediment removal from the lower, less stable parts of the slope by physical erosion or other means (e.g. Embley and Jacobi, 1977; Mullins *et al.*, 1987, 1988) leads to stress disequilibrium. Subsequent progressive (retrogradational) failure

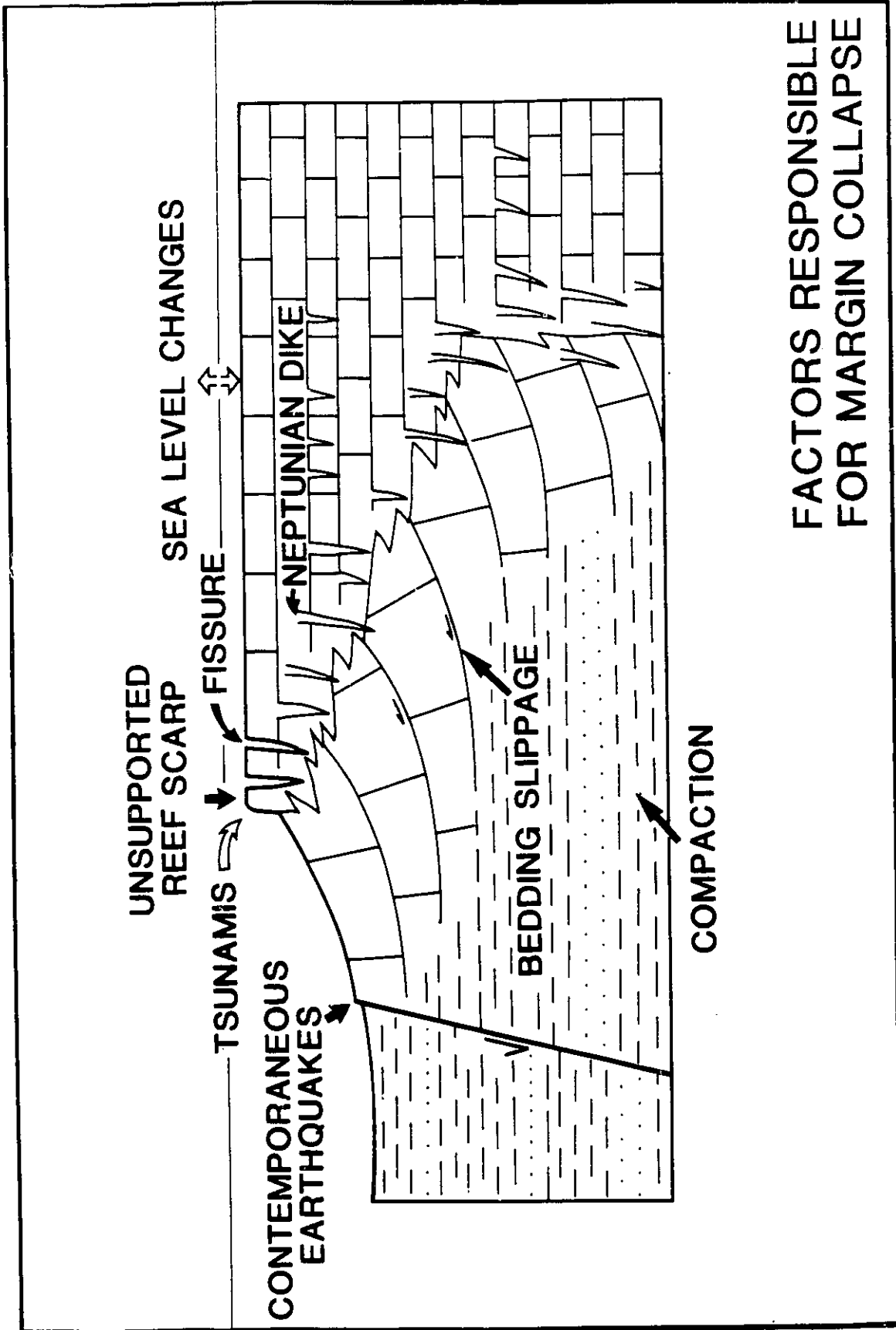


Figure 45. Factors contributing to platform margin or outer platform collapse (re-drawn and modified from Playford et al., 1989).

of the slope eventually undercuts the platform margin, making it gravitationally unstable and prone to failure.

Relative changes in sea level also contribute to platform margin instability. Carbonate sediment overproduction and rapid margin progradation over unstable slope sediments would lead directly to gravitational instability. Overloading and oversteepening of the margin would be favoured, for example, during periods of relative sea level rise or highstand (e.g. Mullins *et al.*, 1986; Yose and Hardie, 1990). During periods of relative sea level lowstand, platform exposure and karstification would tend to weaken the margin, and promote erosional processes at the margin and on the upper slope (Crevello and Schlager, 1980). These factors are inferred to have contributed to platform margin collapse in the Permian Delaware Basin of New Mexico and West Texas (Sarg, 1988; Franseen *et al.*, 1989), as well as in the Late Cretaceous-Tertiary succession (Gargano platform) in southern Italy (Bosellini, 1989).

A number of different processes may trigger the collapse of a structurally weakened margin. For example, pervasive, early cementation can increase the mass of the margin sediments, thereby enhancing the gravitational instability of the margin (Cook *et al.*, 1972). Extension and downslope movement would be further promoted by compaction of the subjacent slope deposits (Playford, 1984). Storm waves and tsunamis could further subject the margin to strong hydraulic forces (Cook *et al.*, 1972).

Large-scale creep is also undoubtedly an important factor in slope failure. Creep is a common process on both subaerial and subaqueous slopes, and commonly precedes catastrophic sliding (Radbruch-Hall, 1978). Sediment creep on the upper slope could conceivably impart an extensional stress on the adjoining platform margin, especially if the

margin has prograded significantly outward over unstable slope sediments. This process, perhaps in conjunction with sediment compaction on the slope (Playford, 1984), may contribute to the development of submarine fractures in the brittle margin sediments. Progressive dilation of these fractures would ultimately lead to catastrophic margin failure, with or without earthquake triggering.

It is not clear which factors were primarily responsible for collapse of the Eldon-Pika margin. Seismic activity may well have been an important factor, particularly if deep-seated faults were occasionally reactivated beneath the Kicking Horse Rim in response to regional lithospheric extension (Section 2.3.5.3). The sharp-cornered embayments characterizing the Eldon-Pika and Cathedral margins (see below) are evidence of at least some syn-sedimentary faulting along the margin, perhaps in conjunction with the contemporaneous horst and graben tectonics affecting the continental margin to the northwest (Section 2.3.4). Notably, there is no obvious evidence that platform exposure was a factor in the collapses.

6.3.7 Stratigraphic implications for the study area

6.3.7.1 Basic concept

The conclusion that large-scale submarine unconformities truncate hundreds of metres of platform and upper slope strata has important implications for regional stratigraphy. As these features are incompletely and tantalizingly exposed, their overall effects on the stratigraphy must be assessed on the basis of their inferred geometry and lateral extent, as determined from field observations and comparisons with modern and ancient analogues.

The cross-strike exposures at Stephen, Verdant and Biddle cirques indicate that megatruncation surfaces are present at the intra-Tokumm, sub-Vermilion and intra-Vermilion levels. These surfaces **visibly** truncate between 84 m and 215 m of strata, and at least one surface is inferred to have a relief of at least 360 m over its traceable extent. The **total** stratal thickness truncated by each surface can only be speculated on, as these features are clearly far larger than the mountainsides on which they are exposed.

It is probably significant that slide scars of comparable scale (in two-dimensional longitudinal profile) on the west Florida platform and in deep-water siliciclastic settings extend 100 km or more along strike, and several tens of kilometres basinward. In comparison, the distance from Stephen to Verdant cirque (parallel to depositional strike) is about 45 km, and the maximum, **continuous** cross-strike exposure over this distance is only about 2-3 km. This emphasizes an important concept: the megatruncation surfaces **cannot** be considered purely local features. They probably have areal extents **greater** than that of the entire study area, and thus the same three megatruncation surfaces probably intersect **all** of the stratigraphic sections measured through Eldon- and Pika-equivalent strata in the zone of facies change.

If this basic premise is accepted, the stratigraphic relationships across the platform margin and upper slope can be distilled into a simple model (Fig. 46). In it, three, laterally continuous megatruncation surfaces are inferred to traverse the platform margin and upper slope stratigraphy throughout the study area. Lateral facies changes also occur in the stratigraphy, for example the transition between the lower Eldon Formation and the lower Tokumm sub-unit. Due to the influence of these variables, different stratigraphic successions are encountered, depending on where along a cross-sectional profile a particular stratigraphic section is measured (Fig. 46). Further variations are to be expected along depositional strike,

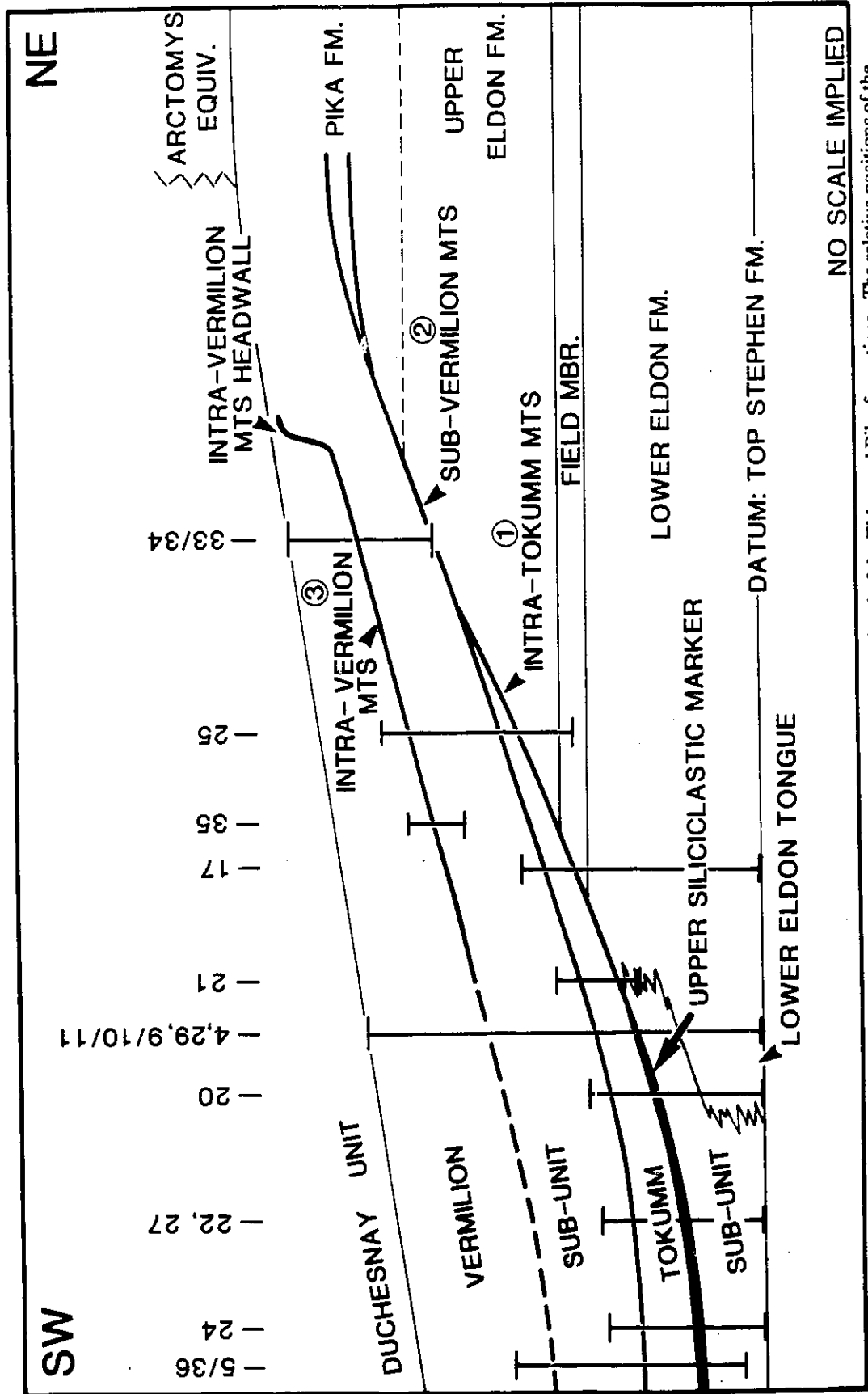


Figure 46. Regional stratigraphic relationships in the zone of facies change at the level of the Eldon and Pika formations. The relative positions of the stratigraphic sections measured during this project are shown. The numbers on the megatrust surfaces correspond to those in the line drawings accompanying the plates.

due to a combination of lateral changes in depositional thickness, and along-strike variations in the erosional level of the megatruncation surfaces. Although the overall, three-dimensional stratigraphic relationships cannot be illustrated in a single, two-dimensional diagram, the model shown in Fig. 46 illustrates all of the key stratigraphic relationships in a simple and elegant fashion.

6.3.7.2 Inferred areal extent of the megatruncation surfaces

The **intra-Tokumm megatruncation surface** is probably laterally continuous between Stephen cirque and The Monarch. However, positive identification of this surface in two dimensional strike section is difficult. In the cross-strike exposure at Biddle cirque, the intra-Tokumm megatruncation surface appears as an abrupt, truncational contact separating laminated argillite above from thin-bedded limestone below (Plate 46). In two-dimensional strike exposure, the same contact would look like a sharp bedding contact between argillite and thin-bedded limestone, and its cross-strike truncational nature would not be apparent. This precisely describes the abrupt, lower contacts of the two Tokumm siliciclastic markers (Section 5.6.3).

The upper siliciclastic marker unit occurs at comparable stratigraphic levels in Prospectors Valley (sections 9, 10, 11; Appendix 2), Haffner Creek (sections 4, 29), and at The Monarch (section 22). The base of this siliciclastic marker is inferred to be the trace of the intra-Tokumm megatruncation surface through all these sections (Fig. 46). The lower siliciclastic marker appears to be confined to Prospectors Valley, and probably overlies a less areally extensive truncation surface (Fig. 26).

If a single, intra-Tokumm megatruncation surface intersects all of the above stratigraphic sections, it would have an along-strike length of at least 56 km. The ultimate, lateral extent of this surface into the basin is unknown. Physical correlations suggest that it also passes through the Numa Mountain section (section 36, Appendix 2; Fig. 46). If this is correct, the megatruncation surface would have a basinward extent of at least 8 km relative to the upper Eldon-Pika margin.

The **sub-Vermilion megatruncation surface** is the easiest to identify and map throughout the study area. In strike section, it corresponds to the contact between the argillite-dominated Vermilion sub-unit above, and the limestone-dominated Tokumm sub-unit below (Plates 44, 45). This contact can be traced almost continuously between Park Mountain and The Monarch (Fig. 5). Its truncational nature is only visible in the cross-strike exposures in Stephen and Verdant cirques (Plates 49, 54). In a cross-strike exposure near Mt. Biddle (Plate 48d), the surface is sub-parallel to bedding in the underlying Tokumm sub-unit, and is difficult to differentiate from a simple stratigraphic contact. The sub-Vermilion megatruncation surface is also inferred to pass through the Numa Mountain section (section 36; Fig. 46). Thus, like the intra-Tokumm surface, the sub-Vermilion megatruncation surface is inferred to extend at least 56 km along depositional strike, and a minimum of 8 km across strike.

The **intra-Vermilion megatruncation surface** has only been identified in the cross-strike exposures in Stephen and Verdant cirques (Plates 49, 50, 54). In both of these exposures, the surface becomes a very subtle, bedding-parallel feature basinward. This simple fact probably explains why the intra-Vermilion megatruncation surface has not been positively identified in the extensive strike exposures between Stephen and Verdant cirques. If a continuous surface does indeed exist between these two localities, it would have a lateral

extent of at least 46 km parallel to depositional strike. The basinward extent of this feature is unknown.

6.4 MODEL FOR LARGE-SCALE COLLAPSE AND REGROWTH OF THE UPPER ELDON-PIKA PLATFORM MARGIN

6.4.1 Model summary

The platform-to-basin relationships during Eldon and Pika time must, of necessity, be reconstructed from fragmentary evidence. Present-day erosion has selectively removed much of the outer platform and platform margin, except for the three, cross-strike exposures described earlier. In these exposures, the original platform margin is missing due to large-scale collapse during the Middle Cambrian. The truncated margin that remains is largely inaccessible, and its internal structure has largely been obliterated by destructive dolomitization.

Despite these obstacles, an attempt has been made to construct a conceptual model of the upper Eldon-Pika margin, as modified by large-scale collapse (Fig. 47). The main components of the model are summarized below:

1. An outer platform shoal area characterized by shallow subtidal, intertidal and supratidal sedimentation. The shoal is bounded cratonward by a subtidal inshore basin, and seaward by the platform margin.
2. A platform margin occupied by two, parallel facies belts: an inner belt of carbonate sand shoals deposited in a high energy regime, and an outer belt of Epiphyton buildups deposited under deeper, less energetic conditions.

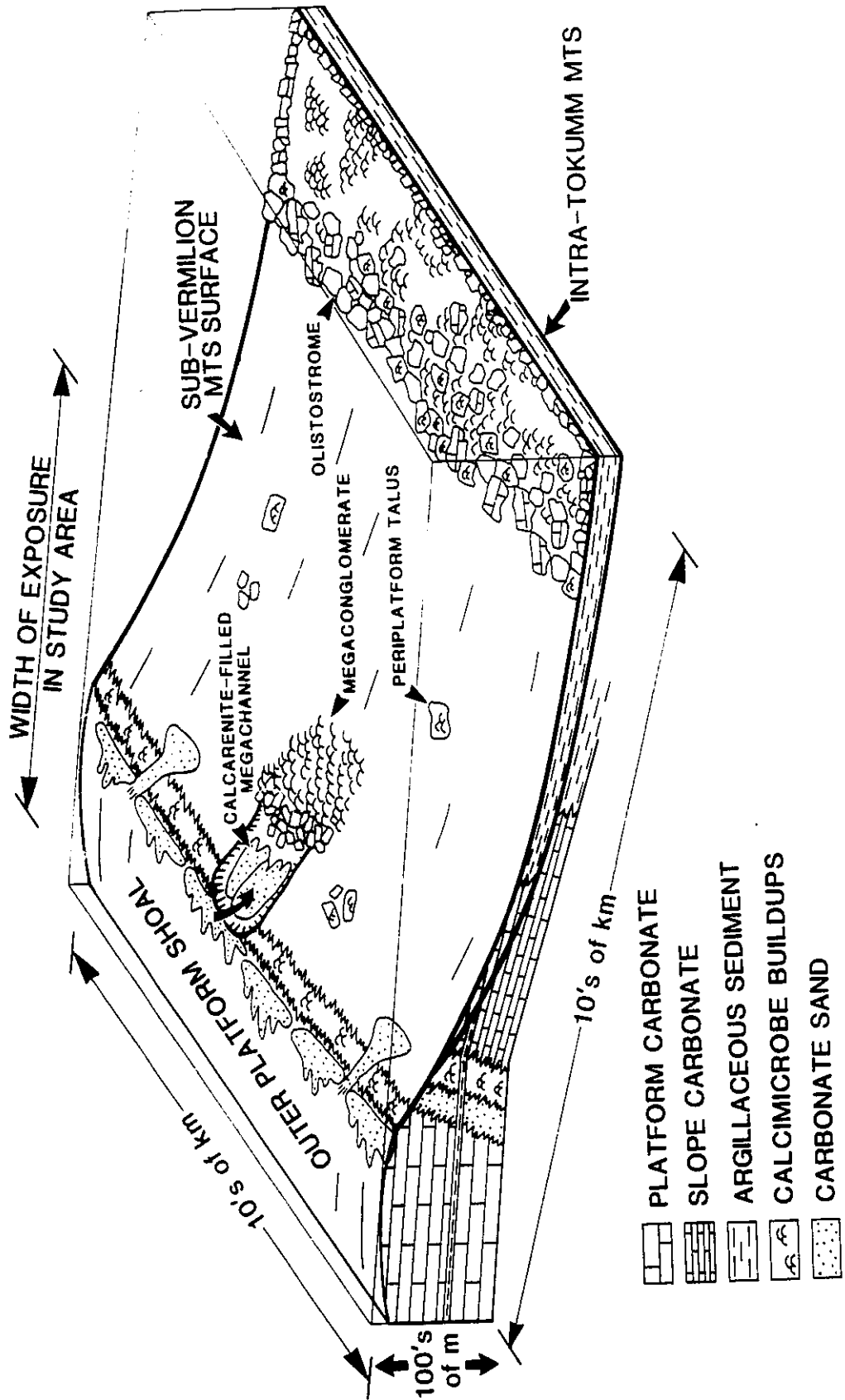


Figure 47. Regional model for the Pika margin shortly after the outer platform collapse that formed the sub-Vermilion megatrunconation surface.

3. Listric megatruncation surfaces cutting hundreds to thousands of metres back into the platform, and vertically truncating hundreds of metres of platform and upper slope strata. The surfaces have low-angle or near-vertical headwalls, and extend several tens of kilometres along and across depositional strike.
4. Minor slide scars affecting only the outer part of the rejuvenated platform margin.
5. A basin olistostrome situated several kilometres to tens of kilometres downslope from the truncated margin.

6.4.2 Discussion of model components

6.4.2.1 Nature of outer platform shoal area

Regionally, the outer platform shoal and adjoining margin area are no more than about 20 km wide (Aitken, 1978). There is unequivocal evidence for peritidal deposition across this zone where original depositional fabrics have been preserved. Near the top of **Mount Field**, the sequence is characterized by dolomitized cryptalgal laminite, stromatolites, scour-and-fill structures, rip-up clasts, and ex-fenestral limestone (section AC-162; Aitken, in press, a). At **Vermilion Pass**, this interval contains abundant cryptalgal laminite in association with fenestral limestone, burrow-mottled limestone, and minor pellet grainstone (section AC-155; Aitken, in press, a). In **Verdant cirque**, the accessible parts of the upper Eldon-Pika sequence are composed largely of fenestral dolostone in association with calcarenite, thin "Yoholaminites" layers, and layers of small, domal stromatolites (Section 6.2.3.1). "Yoholaminites"-bearing strata are also present at **Eon Mountain**, but the

associated sediments are too pervasively dolomitized to discern original depositional fabrics (section AC-102; Aitken, in press, a).

6.4.2.2 Platform margin composition as deduced from allochthonous downslope debris

The configuration of the upper Eldon-Pika platform margin, as modified by margin collapse at different stages in its history, can be evaluated from the three, cross-strike exposures in the study area. However, the composition of the margin must be inferred indirectly from allochthonous deposits preserved downslope. These include periplatform talus blocks, megaconglomerates, and calcarenite bodies.

It is important to distinguish between allochthonous debris derived from large-scale margin collapse, and debris derived from relatively small-scale erosional events affecting the already truncated margin. The scale of margin collapse was so large that allochthonous debris from the original margin and upper slope would have been transported well beyond the limits of exposure in the study area. Thus, the outer platform and margin compositions immediately prior to these large-scale failures cannot be assessed. The huge allochthonous blocks, megaconglomerates and calcarenite bodies in the Chancellor, however impressive they may seem in outcrop, are actually the products of relatively small-scale erosional processes on an already truncated margin (Fig. 47; see below). They therefore record the sediment types generated during **regrowth** of the collapsed margin.

Periplatform talus blocks and megaconglomerate megaclasts in the Tokumm and Vermilion sub-units are overwhelmingly composed of variously preserved Epiphyton boundstone (Section 4.6.2). Significantly, the primary void space in these rocks is almost exclusively filled with fibrous and blocky calcite cement, and infiltrated grains, such as

ooliths, are almost totally absent. Calcarenite megaclasts are comparatively rare, although cobble-sized and smaller clasts of this lithology are fairly common.

The megaconglomerate bodies are the products of minor margin collapse. The overwhelming predominance of Epiphyton-bearing megablocks in these bodies is evidence that the outer part of the margin was colonized by Epiphyton, which is known to have had a strong preference for platform margin settings (McIlreath, 1977a; Pfeil and Read, 1980; James, 1981; Read and Pfeil, 1983; Coniglio and James, 1985). The actual zone of Epiphyton buildups is rarely preserved or exposed, but limited evidence suggests that it was typically narrow (e.g. 150 m, Aitken, 1989; 500-1000 m, Barnaby and Read, 1990; Plate 39). In the platform interior, Epiphyton is absent, and Girvanella and Renalcis are much more common (e.g. Waters, 1988). The Appalachian Cambro-Ordovician carbonate platforms are quite similar in this respect (Pfeil and Read, 1980; James, 1981).

The occurrence of oolitic-peloidal grainstone clasts in the megaconglomerate bodies suggests a spatial link between the zone of Epiphyton buildups and an area of carbonate sand accumulation. However, unlike examples in the Cow Head Group of western Newfoundland (James, 1981; Coniglio and James, 1985), the void space in the Epiphyton framework was not infiltrated by carbonate sand, and no composite grainstone - Epiphyton boundstone blocks have been found. This suggests that the calcimicrobe buildups and carbonate sand shoals formed two parallel belts with only minimal overlap.

This "dual belt" configuration can probably be explained in terms of the net energy flux across the margin. Wave and storm attack on the outer belt of Epiphyton buildups presumably generated large quantities of carbonate sand (see Coniglio and James, 1985). If the net sediment transport due to wave, tide and storm activity was platformward, the outer

belt would have acted as a long-term, local source of carbonate sand for the inner belt. The sand that did reach the upper slope was not exported along a broad front, but would instead have been funnelled directly into slide scars or passes cut through the outer margin (Fig. 47).

6.4.2.3 Regional trend of the platform margin

Although the truncated Eldon-Pika margin is only locally preserved, its trend can be closely approximated from existing stratigraphic and reconnaissance data (Fig. 48). As the margin lies within a single thrust sheet, this trend approximates the original depositional configuration. Over the length of the study area, the margin has a broadly arcuate form.

Two major embayments interrupt the upper Eldon-Pika margin in the study area (Fig. 48). In the Verdant headwaters area, the margin swings abruptly northeastward for about 2 km, then turns southeastward again to pass through Verdant cirque. Near The Monarch, the margin is stepped back even further. Southeast of the latter area, the margin must swing southwestward again to rejoin the regional trend. Unfortunately, the appropriate stratigraphic level is not exposed, and the exact location of the offset is not precisely known. A margin backstep also appears to be present in the Stephen cirque area, although the embayment boundaries are poorly defined.

It is tempting to suggest that these embayments are the result of local collapses in the upper Eldon-Pika margin, and are analogous to the "scalloped margins" on carbonate banks in the Caribbean (Mullins and Hine, 1989). Notably, however, the backsteps in the Eldon margin coincide with major embayments in the underlying Cathedral margin (Section 7.3), and thus may simply reflect antecedent topography.

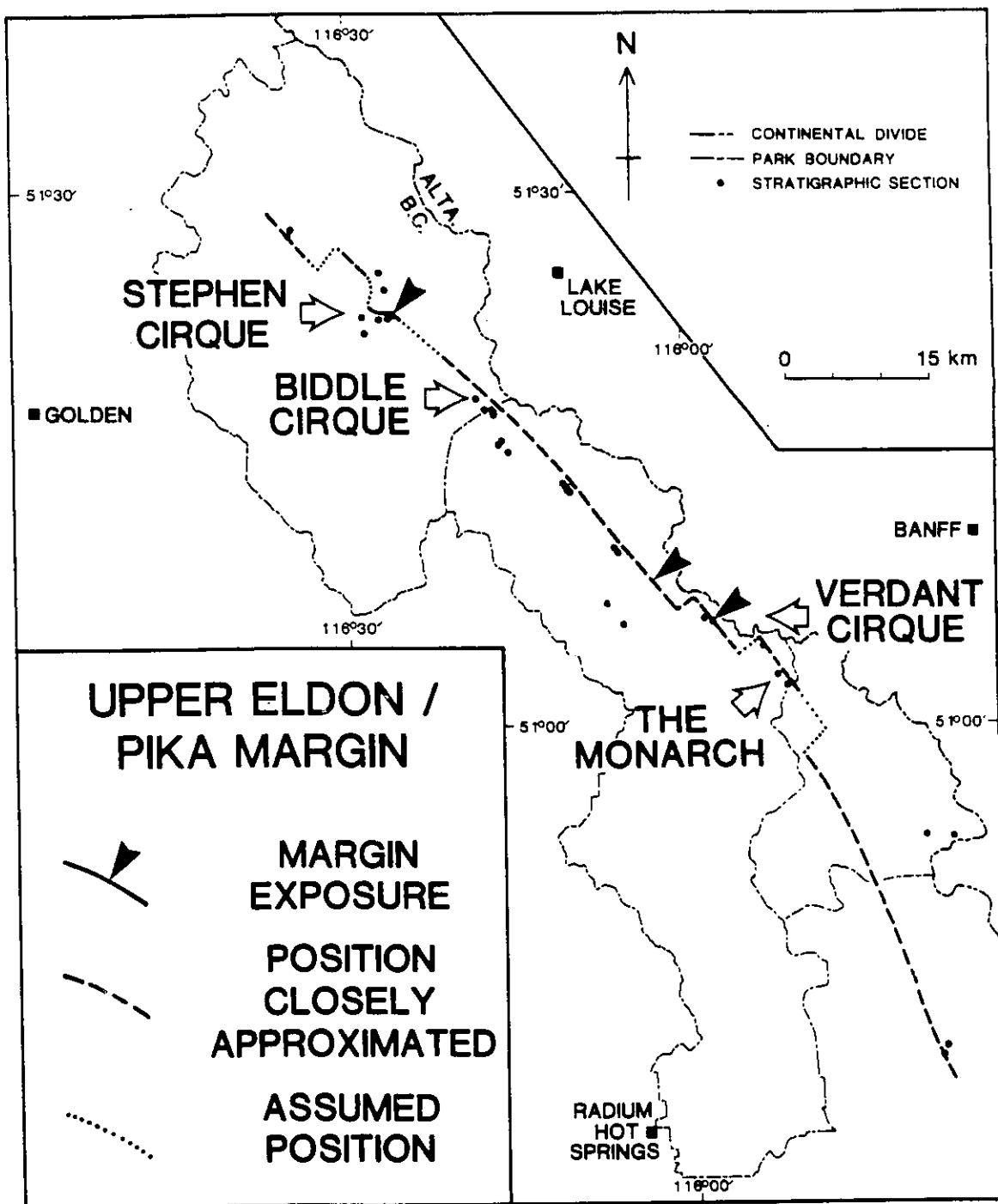


Figure 48. Regional trend of the upper Eldon/Pika margin.

6.4.2.4 Variations in megatruncation surface geometry

In Stephen and Verdant cirques, the sub-Vermilion megatruncation surface levels out and disappears into horizontally-bedded peritidal sediments at about the mid-Pika level (Plates 49, 54). This configuration contrasts markedly with the near-vertical headwall of the intra-Vermilion megatruncation surface in Verdant cirque (Plate 54). Clearly, different controls were operative during formation of these two megatruncation surface styles.

Near-vertical headwalls are atypical of slide scars on modern deep-water slopes, where even so-called "steep" headwalls are generally inclined at angles of less than about 20°-25° (Farre *et al.*, 1983; Jacobi, 1984; Mullins *et al.*, 1986). The key to the origin of near-vertical headwalls probably lies in the fact that the upper parts of the megatruncation surfaces traverse early-lithified carbonate margins, rather than semi-lithified slope deposits. Early-lithified margins are likely to be crisscrossed by steeply-dipping fractures, formed in response to seismic activity, differential compaction, and/or large-scale creep of the upper slope and margin (Fig. 45). These fracture systems would have a direct control on headwall geometry and orientation.

The manner in which the sub-Vermilion megatruncation surface merges platformward with horizontal bedding is not easily explained, but may be a function of large-scale creep processes affecting the upper slope and platform margin. Translational movement of upper slope sediments along low-angle detachment surfaces (sub-parallel to the surface slope) would remove lateral support of the margin, and could conceivably result in the propagation of low-angle creep fractures through the carbonate mass. Failure along one of these surfaces would yield a megatruncation surface without a vertical headwall. The

validity of this proposed mechanism cannot be assessed until the mechanics of large-scale failure at and near carbonate margins have been studied in more detail.

6.4.2.5 Minor collapse features

The numerous megaconglomerate bodies and calcarenite-filled megachannels in the Vermilion sub-unit (Sections 4.5.3; 4.6) are inferred to be the products of repeated, relatively small-scale failures of the platform margin (Fig. 47). The material mobilized by these failures evolved into debris flows a short distance downslope (Section 4.6.7), and was deposited in the form of broadly channellized megaconglomerates. The failures affected mainly the outer margin, as implied by the predominance of Epiphyton boundstone clasts in these deposits. However, at least some of the slide scars evacuated by this material cut far enough back into the margin to tap the inner belt of carbonate sand shoals, and were subsequently infilled by stacked, channellized sand bodies deposited by high-concentration turbidity currents (Section 4.5.3.4). These slide scars are all less than about 400 m wide (Section 4.5.3.1). Although the megaconglomerate bodies and calcarenite-filled megachannels are impressive features in outcrop (e.g. Plates 21, 44, 53), the scale of margin collapse they imply pales in comparison to that of the megatruncation surfaces (Fig. 47).

6.4.2.6 Nature of olistostrome

Platform margin collapse on the scale indicated by the Eldon-Pika megatruncation surfaces implies the presence of major olistostromes downslope. The origin and nature of these bodies can only be speculated upon, as they are not exposed. This is the opposite problem to that faced by workers encountering enormous olistostromes in basinal successions. The presence of the olistostromes implies large-scale failure of a nearby

carbonate platform, which is commonly no longer preserved or exposed (e.g. Seguret *et al.*, 1984; Heck and Speed, 1987).

Margin collapse would have mobilized a considerable volume of early-lithified carbonate sediment, which probably disintegrated into variously sized, angular to sub-rounded clasts like those found in the megaconglomerates. Due to the large-scale of the collapse, this allochthonous material would have been derived from a range of depositional environments. Clasts types would presumably include peritidal carbonate rocks from the outer platform, oolitic-peloidal grainstones from the inner margin, Epiphyton boundstone from the outer margin, and platy lime mudstone from the upper slope. If known examples of olistostromes are any guide, these megablocks could have been tens to perhaps thousands of metres in size (Johns *et al.*, 1981; Heck and Speed, 1987). Given that individual collapses involved 56 km or more of the Middle Cambrian margin, the resultant olistostromes would be expected to contain tens of cubic kilometres of debris.

6.5 EVIDENCE FOR DROWNING AND LARGE-SCALE TRUNCATION OF THE ARCTOMYS-WATERFOWL MARGIN

6.5.1 Introduction

Stratigraphic investigations in the Vermilion Pass area (Aitken and Greggs, 1967; Waters, 1986; Aitken, in press, a) and reconnaissance near Cross River (Aitken, 1966, p. 426; G. Leech, oral communication, 1991) confirm that the predominantly siliciclastic and evaporite-bearing strata of the Arctomys Formation pass southwestward into massive dolostones of the Waterfowl Formation along the Kicking Horse Rim. This margin is not preserved intact anywhere in the study area. Like the underlying upper Eldon-Pika margin, it has been preferentially eroded, and largely corresponds to the axes of a series of NW-SE-

trending valleys. The approximate trace of the Arctomys-Waterfowl margin is shown in Fig. 49.

The Arctomys and Waterfowl formations have largely been removed by erosion from the study area, except for the prominent exposures at Mt. Whympier, near Miller Pass, and in the President Range (Fig. 5). In contrast, the equivalent Duchesnay and Oke units are almost continuously exposed along the length of the study area. The zone of facies change between the platform and upper slope successions is partly preserved at only one locality near Hamilton Lake (Section 5.8.4; Plate 58).

The Hamilton Lake exposures provide the only direct evidence as to the original configuration of the Arctomys-Waterfowl margin. Although the stratigraphy is traversed by a thrust fault and is eroded at a critical spot, sufficient evidence is available to suggest that this margin also experienced large-scale collapse. It is not known whether the relationships observed at Hamilton Lake are representative of the margin as a whole. Notably, however, the interpretation of these exposures has been useful in deciphering the enigmatic stratigraphic relationships exposed at the same stratigraphic level near Miller Pass (sections 12, 13).

6.5.2 Interpretation of the stratigraphic sequence in northern Hamilton cirque

The stratigraphy of Hamilton cirque was described previously in Section 5.8.4. In the northern part of the cirque, the sequence records: (1) a sudden change from shallow subtidal to deep-water sedimentation (platform carbonate rocks succeeded by ribbon limestone and monotonous, laminated argillite); (2) a long-term shoaling trend, culminating in the return of shallow subtidal conditions (signified by the appearance of burrowed argillite

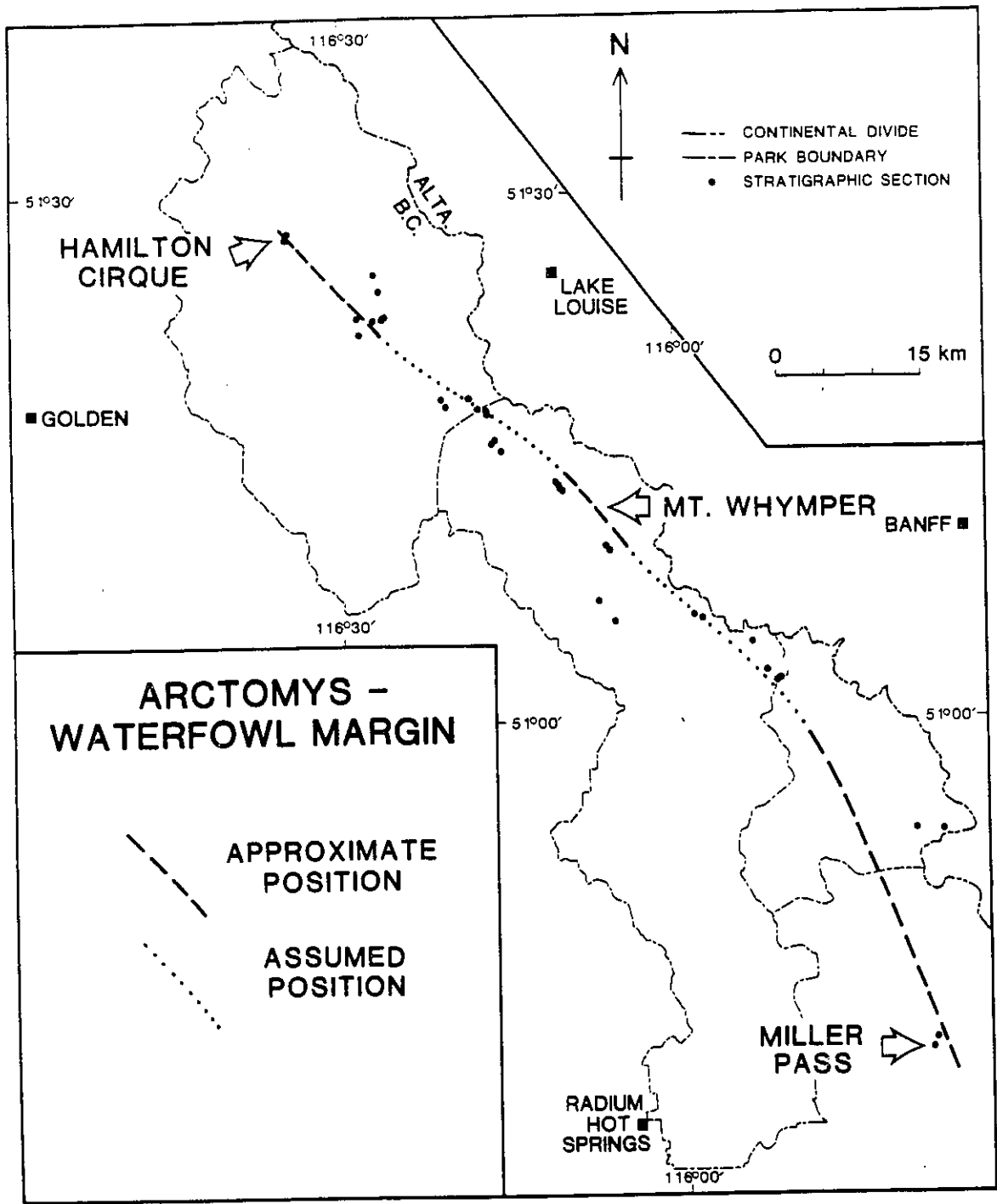


Figure 49. Regional trend of the Arctomys/Waterfowl margin.

and argillite-based, metre-scale shallowing-upward cycles); and (3) an abrupt return to deep-water sedimentation, with evidence for local margin failure (laminated argillite, megaconglomerate, and ribbon limestone). A discussion of possible mechanisms and events follows.

At the close of Pika time, carbonate sedimentation was taking place under predominantly shallow subtidal conditions, as indicated by the thick sequence of burrow-stratified and burrow-mottled limestones exposed in the lower part of the cirque (Plate 57). Local peritidal conditions are suggested by the presence of thin, cryptalgal laminite layers and local, intercalated crossbedded grainstone units. The platform margin was presumably situated southwest of Hamilton cirque at this time.

The appearance of ribbon limestone with abundant agnostid trilobites above this sequence marks a change to deep-water carbonate sedimentation. On the south ridge of Mt. Carnarvon, this change is gradual (Plate 56e; Section 5.8.4), suggesting that deeper water conditions were introduced by platform drowning. The subsequent, abrupt change to long-term, fine-grained, siliciclastic turbidite deposition (laminated argillite; Plate 8b) presumably reflects the cessation of widespread carbonate generation on the platform, and the commencement of Arctomys deposition.

The postulated drowning event appears to have been restricted to the outer platform. No conspicuous sedimentological changes have been reported in the uppermost Pika Formation elsewhere on the platform (Aitken, 1966, 1978, in press, a). This event may have been analogous to the temporary drowning of the outer Eldon platform during deposition of the Field Member. It may reflect a rapid pulse of sea level rise, or possibly synsedimentary

faulting in the vicinity of the platform margin. There is, however, no independent evidence to evaluate either possibility.

The argillite-dominated Duchesnay unit in the Hamilton Lake area probably accumulated on a deep, essentially horizontal outer shelf, created by drowning and subsequent backstepping of the platform margin. The preservation of fine laminae and the lack of biogenic structures in the fine-grained, turbiditic and hemipelagic sediments of the lower Duchesnay unit indicate deposition in a quiescent environment below maximum storm wave base. The virtual absence of synsedimentary deformation, even on a small-scale, implies a lack of the gravitational instability normally associated with deposition on a slope.

Overall sedimentation rates on the outer shelf exceeded the rate of relative sea level rise, resulting in vertical aggradation and a long-term shoaling trend. The first indication of a nearby, shallow-water carbonate margin was the deposition of oolitic-intraclastic grainstone lenses, presumably derived from carbonate sand shoals. The shoaling-upward trend becomes more obvious with the subsequent appearance of horizontal and vertical burrows, and the development of argillite-based, "clearing-upward" cycles. In northern Hamilton cirque, this shoaling-upward trend culminates with metre-scale, carbonate-dominated cycles assigned to the Waterfowl Formation. These cycles mark the return of flat-topped carbonate platform sedimentation, similar to that which prevailed during Pika deposition.

6.5.3 Interpretation of the stratigraphic sequence in southern Hamilton cirque

Identical argillite-based, metre-scale shallowing-upward cycles are recognizable in the upper Duchesnay unit on either side of the thrust fault separating northern and southern Hamilton cirque (Plate 57). Notably, this sequence has about the same thickness (as

estimated from photographs) on both sides of the fault. This suggests that the overlying megaconglomerate-bearing argillite and ribbon limestone sequence in the hangingwall of the fault is coeval with the cyclical carbonate sequence (Waterfowl Formation) composing the upper half of Mt. Carnarvon.

The megaconglomerate-bearing argillite marks an abrupt return to deep-water slope sedimentation. Soft-sediment deformation and slide masses in this sequence provide ample evidence of gravitational instability. The laterally extensive megaconglomerate encountered in section 32 (Appendix 2) testifies to the presence of local failures in the nearby Waterfowl margin.

The allochthonous debris in Hamilton cirque provides virtually the only evidence as to the composition of the Waterfowl margin. The megaconglomerate contains a mixture of calcarenite and Epiphyton boundstone megaclasts. Calcarenite megaclasts appear to be more abundant, in contrast to the predominance of Epiphyton boundstone megaclasts in the Vermilion sub-unit megaconglomerate units. The associated allochthonous calcarenite bodies are peloidal-skeletal grainstones, and contain a substantial proportion of poorly preserved Girvanella. Thus, the Waterfowl margin, in the Hamilton Lake area at least, was characterized by a combination of Epiphyton buildups and carbonate sand shoals. There is insufficient evidence to determine whether these two components formed two parallel belts, or whether they were more intimately associated.

The abrupt change from shallow-water platform sedimentation to deep-water slope sedimentation could be accounted for by sudden platform drowning, or by large-scale, outer platform collapse. Sudden platform drowning by eustatic means seems unlikely. Neither of

the two **incipient** drowning events documented by Waters (1986) on the Waterfowl platform were of sufficient magnitude to explain the major change in depositional environment indicated by the Hamilton cirque exposures. Also, simple drowning of a flat-topped platform would create an essentially horizontal, deep, outer platform, and would not explain the abrupt appearance of slope deposits above the upper Duchesnay unit.

A more attractive alternative is to interpret this abrupt change in sedimentation style in the context of the large-scale margin failure known to have affected the underlying Eldon-Pika margin. The sudden appearance of Oke unit slope strata (containing fine-grained turbidites, megaconglomerate, and allochthonous calcarenite) over upper Duchesnay platform sediments is strongly reminiscent of the relationship between the Vermilion subunit and the truncated Eldon-Pika margin in Verdant cirque (Plate 52). Large-scale collapse of the Waterfowl margin would explain the abrupt sedimentological change to a slope environment, and the sudden establishment of a shallow margin platformward of its previous location.

A major problem with this interpretation is that truncation of the Waterfowl margin cannot be demonstrated due to erosion of the critical part of the exposure. The exposed segment of the Oke-Duchesnay contact appears to be bedding-parallel over its visible extent, and there is no independent evidence (e.g. subsurficial shear zone) that this is a slide surface. In this respect, the contact resembles the lower, bedding-parallel segment of the sub-Vermilion megatruncation surface in Verdant cirque. Until additional supporting evidence is found, the interpretation that the Oke-Duchesnay contact in southern Hamilton cirque is a megatruncation surface cannot be confirmed.

6.5.4 Comparison with Miller Pass stratigraphy

In the southeastern extremity of the study area near Miller Pass (section 12; Figs. 2, 5), the undivided Eldon-Pika platform sequence is abruptly succeeded by a predominantly argillite sequence of deep-water origin assigned to the Duchesnay unit (Plates 56b, c). The contact is planar, parallel to underlying bedding, and appears to be structurally concordant.

Near Miller Pass, the basal Duchesnay unit is composed of dolomitic ribbon argillite with common, medium-scale intraformational truncation surfaces, ribbon limestone, and slate (section 12; Appendix 2). Although the overlying succession is complicated by a thrust fault and attendant complex deformation, there is no evidence for a shallowing-upward trend like that observed in Hamilton cirque.

Again, there are two possible reasons for this abrupt change from shallow platform to deep-water sedimentation: platform drowning and large-scale, outer platform collapse. If the contact was a drowning surface, it did not produce a flat, deep-water shelf. The overlying sediments show ample evidence for gravitational instability, and thus were probably deposited on a slope. If the contact is a megatruncation surface, it does not crosscut underlying bedding, and it is not associated with features such as megaconglomerate or periplatform talus blocks. Thus, the precise nature of this contact remains unclear. Notably, the contact occurs at the same stratigraphic level as the postulated drowning surface at the base of the Duchesnay unit in Hamilton cirque. Therefore, outer platform drowning, perhaps in conjunction with synsedimentary tectonism, is the more likely of the two interpretations.

6.6 SUMMARY: EVIDENCE FOR LARGE-SCALE PLATFORM MARGIN COLLAPSE

The Eldon-Pika platform margin and adjacent upper slope strata are traversed by at least three large-scale erosional structures: the intra-Tokumm, sub-Vermilion and intra-Vermilion megatruncation surfaces. These features are exposed in the three cross-strike exposures at Stephen, Biddle and Verdant cirques, and significantly affect the regional stratigraphy of the outer platform and upper slope sequences.

The megatruncation surfaces are sharp, relatively smooth, and **visibly** truncate up to 215 m of strata. At least one example is inferred from indirect evidence to have a relief of at least 360 m. They are flat to broadly concave-upward, and at least some are demonstrably listric in form. Most are inclined at angles less than about 20°. The platformward ends of the megatruncation surfaces generally disappear imperceptibly into horizontally bedded platform strata, or are cut out by younger surfaces. An important exception to this is the intra-Vermilion megatruncation surface in Verdant cirque, which terminates platformward in a near-vertical headwall. These features have a maximum **visible** extent of about 800-900 m across depositional strike, and a maximum **traceable** extent of about 3-4 km along depositional strike. Their ultimate lateral extent cannot be determined directly, and must be inferred from comparisons with modern and ancient analogues.

The megatruncation surfaces are large-scale submarine gravity slide structures, comparable to those widely documented in deep-water siliciclastic and carbonate settings. Seismic reflection records have revealed the three-dimensional geometry of physically

similar features in the Gulf of Mexico and Caribbean regions. Numerous ancient analogues have also been recognized. Collectively, these modern and ancient analogues clearly demonstrate that megatruncation surfaces of the scale observed in the study area may well extend a hundred or more kilometres along depositional strike, and on the order of tens of kilometres into the basin. Outer platform collapse of this magnitude probably occurred in response to one or a combination of mechanisms, including seismic activity, progressive failure due to slope undercutting, structural weakening of the platform during sea level lowstands, hydraulic forces exerted by waves and tides, and large-scale creep processes.

The megatruncation surfaces are large-scale submarine unconformities that significantly affect the regional stratigraphy. If they are as laterally extensive as comparisons with modern and ancient analogues suggest, the megatruncation surfaces probably have areal extents greater than that of the study area, and thus would traverse all stratigraphic sections measured in the zone of facies change. The effects on the regional stratigraphy can be rationalized into a single, comprehensive stratigraphic model (Fig. 46), which then can be used to reconstruct the upper Eldon-Pika margin (Fig. 47).

These concepts appear to be applicable to the Arctomys-Waterfowl margin as well. At the only locality where the platform-to-basin relationships have been partially preserved, deep-water slope sediments of the basal Oke unit are superimposed on outer platform strata of the upper Duchesnay unit. This configuration is strongly reminiscent of the relationships observed across the megatruncation surfaces in the underlying Eldon-Pika sequence, and suggests that the Waterfowl margin may similarly have suffered large-scale collapse. If this

is correct, platform margin collapse was not unique to the Eldon-Pika margin, and similar structures are probably present at other stratigraphic levels.

CHAPTER 7

THE CATHEDRAL MARGIN

7.1 HISTORY OF STUDY

The configuration of the upper Cathedral margin has been a source of fascination and controversy ever since Ney (1954, p. 123-124) wrote:

"A striking change occurs at the top of the Cathedral Formation. Here there is a steep west-facing precipice of dolomite nearly 400 feet high, against which shales on the west terminate abruptly Strata are continuous above and below the precipice, so there is no possibility of it being a fault feature It seems to be an original feature of deposition, originally built between limestone and shale The structure resembles that of a reef."

This feature, now known as the Cathedral Escarpment, was rediscovered more than a decade later by J.D. Aitken and W.H. Fritz on the basis of physical stratigraphic and structural relationships. Fossil control, apparently confirming the presence of a Middle Cambrian submarine cliff, was acquired during the same field season (Aitken and Fritz, 1968). A detailed analysis of the paleontology was subsequently published by Fritz (1971). Careful documentation of the Cathedral Escarpment on Mt. Stephen, Mt. Field and Fossil Ridge soon followed in the form of a Ph.D. dissertation by McIlreath (1977a). The lithostratigraphic and biostratigraphic relationships reported by these workers have since

engendered considerable controversy (Ludvigsen, 1989, 1990; Aitken and McIlreath, 1990; Fritz, 1990).

Newly discovered exposures of the Cathedral Escarpment in the Nataalko Lake/Monarch area have provided a different perspective on the origin of this feature. The new examples are considered to be headwall exposures of a large-scale collapse feature comparable in scale and geometry to the megatruncation surfaces documented in the overlying Eldon-Pika sequence. This interpretation has obvious implications for the origin of the Cathedral Escarpment throughout the study area, including the classical exposures near Field. To facilitate comparison between the new and classical examples of this feature, all known exposures of the Cathedral margin will be described below.

7.2 DESCRIPTIONS

7.2.1 Configuration of Cathedral margin on Mt. Stephen and Mt. Field

The classical exposures of the Cathedral Escarpment are situated on Mt. Stephen and Mt. Field (Fig. 50; Plates 38a, b; 39a, b). Until recently, it has been underemphasized that the escarpment represents the westward termination of no more than about the upper third of the Cathedral platform on these mountains. Below this, the platform is bounded by a depositional margin rimmed by what Aitken (in press, a) has referred to as the "embedded reef".

The earliest carbonate sediments to nucleate over the Kicking Horse Rim were oolitic shoals, which acted as a foundation for the establishment of the embedded reef and the peritidal shoal complex behind it (McIlreath, 1977a, p. 161, 163; Aitken, 1989). Today, the reefal zone is seen only as a massive, destructively dolomitized zone about 100-140 m

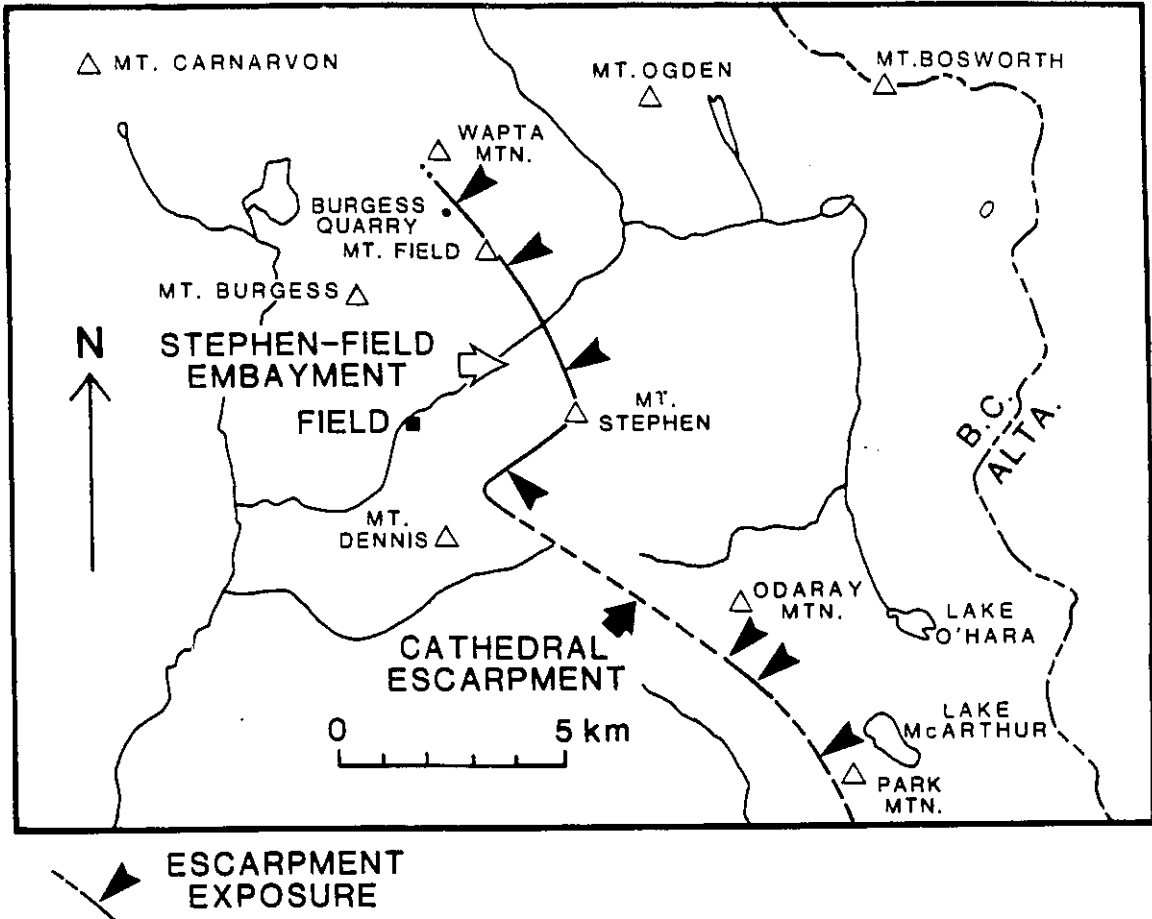


Figure 50. Detailed map of the Cathedral Escarpment and Stephen-Field Embayment in the Field area.

wide. It separates bedded peritidal strata of the Cathedral Formation to the east from the upper slope deposits of the Takakkaw Tongue to the west (Sections 4.8.4, 5.3.3; Plate 39a, b).

In this area, the reefal zone prograded modestly outward over the adjoining slope strata (Plate 39a-c). The low-angle of dip in the basal Takakkaw Tongue indicates that the initial slope profile was very gentle. Unfortunately, it is impossible to trace individual bedding horizons through the massive zone to directly determine platform margin relief. The ribbon limestones exposed a few hundred metres downslope in Wedge Gully (Plate 39c) accumulated below effective storm wave base, implying a minimum relief of perhaps several tens of metres. These rocks also lack biogenic structures, suggesting the presence of an elevated oxygen-minimum zone impinging on the upper slope. The well developed clinofolds higher in the Takakkaw Tongue probably signal a further increase in platform margin relief (Plate 39).

The lower Cathedral margin is a classic example of an offlap margin, which results when carbonate accretion outpaces the rate of relative sea level rise (James and Mountjoy, 1983). The initial low-angle at which the reef zone advanced outward and upward over adjoining slope strata suggests that the rate of carbonate accretion was high relative to the rate of relative sea level rise. The increase in the angle of climb higher in the sequence implies a decrease in the rate of carbonate accretion, or an increase in the rate of relative sea level rise.

About 340 m above the base of the Cathedral Formation, the platform margin steps back an estimated 150 m (Plate 39).¹ At this point, the massive zone is abruptly overlain by

¹ These and all other cited figures have been estimated from photographs.

ribbon limestones of the Takakkaw Tongue. The margin-slope relationship in the overlying 100 m of strata is unclear due to poor exposure and severe dolomitization of outcrops at the critical juncture. The remaining 140 m to the top of the Cathedral Formation is the classical Cathedral Escarpment, at least as designated by McIlreath (1977a).

Different values have been cited by different workers for the height of the Cathedral Escarpment. McIlreath (1977a, p. 127) stated that the escarpment is 213 m high at Fritz's (1971) Paradox section on Fossil Ridge, 190 m high on Mt. Stephen, and 137 m on Mt. Field. Aitken (in press, a) reported that the height of the dolomite wall on Mt. Field is 223 m, but he defined the escarpment differently in that this figure represents the entire thickness from about the level of the apparent backstep to the top of the Cathedral Formation. Hence, the lower part of the Cathedral Escarpment, as envisaged by Aitken (in press, a), is abutted by the Takakkaw Tongue, and not solely by the "basinal" Stephen Formation as classically presented (e.g. Aitken and McIlreath, 1984; Aitken, 1989, p. 320).

The Cathedral Escarpment on Mt. Field is not backed by a continuous massive zone, contrary to the assertion by Aitken and McIlreath (1990, p. 113) that "the distinctive, well-bedded, shallow-water, cyclical reef-flat facies . . . passes westward into massive, coarse, featureless dolomite like that of the less contentious, prograding reef beneath". Oblique aerial photographs of Mt. Field reveal that bedding either intersects or closely approaches about the lower two thirds of the carbonate wall. Although no sedimentary textures are preserved in the gully bordering the escarpment, these strata are a direct extension of the "reef flat facies" documented laterally by McIlreath (1977a; see also Aitken, 1989). The massive dolomites alluded to by Aitken and McIlreath (1990) appear to be confined to about the upper third of the escarpment.

7.2.2 Configuration of the Cathedral margin between Mt. Stephen and Nataalko Lake

The Cathedral Escarpment is also exposed on the lower southwest slopes of Mt. Odaray, and on the nearby west flank of Park Mountain (Fig. 50). In both areas, the vertical contact between the Cathedral and "basinal" Stephen formations is marked by a normal fault. Recent maps (Cook, 1975; Price *et al.*, 1980) and aerial observations by the writer indicate that the stratigraphic separation across this fault is substantial at Mt. Odaray (hundreds of metres), but minor at Park Mountain. In the latter exposure, bedding in the Cathedral Formation clearly terminates at the carbonate wall (Plate 38e). Small numbers of soft-bodied and slightly sclerotized fossils have been recovered from the "basinal" Stephen Formation at both of these localities (Collins *et al.*, 1983).

No exposures of the Cathedral Escarpment are known to occur between Park Mountain and Nataalko Lake, a distance of 42 km. The Cathedral Escarpment is not exposed at Curtis Peak (near Mt. Biddle; Plate 46), as reported by Collins *et al.* (1983).² Aerial observations by the author indicate that the escarpment is similarly not exposed at Hawk Creek (Fig. 4), as was suggested by Aitken (in press, a).

7.2.3 Configuration of the Cathedral margin at Nataalko Lake

Previously undescribed exposures of the Cathedral Escarpment occur in the Nataalko Lake/Monarch area (Fig. 51; Plates 38d, 40, 41, 42). The Nataalko Lake example is

² The fossils recovered from that locality by Collins *et al.* (1983) probably came from the McArthur unit.

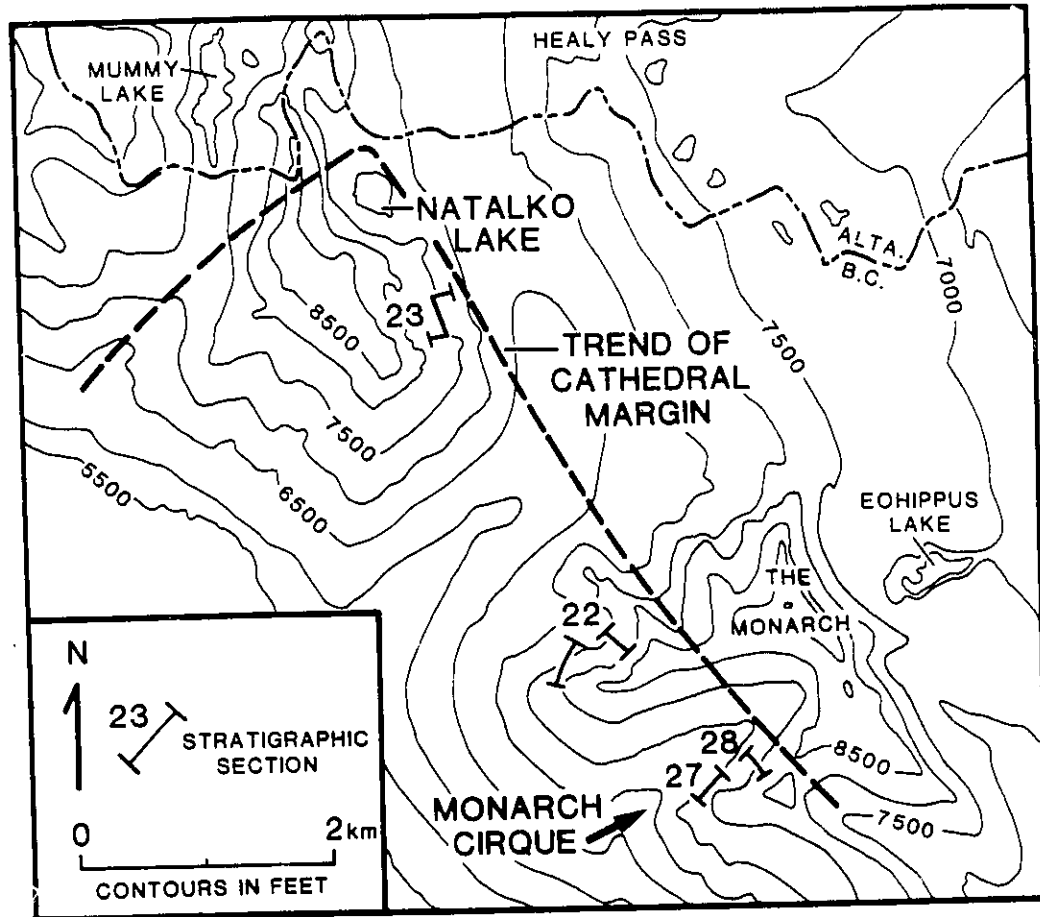


Figure 51. Detailed map of the Cathedral Escarpment and Nataalko Embayment in the Nataalko Lake/Monarch area.

inaccessible, but is so spectacularly exposed that a wealth of information could be gleaned from close aerial observation and the examination of enlarged photographs. A stratigraphic section was measured through the Takakkaw Tongue (excluding the Cathedral megabreccia) and the overlying "basinal" Stephen Formation about 1.2 km southeast of this exposure (section 23, Fig. 51; Plate 43b). Additional stratigraphic sections have been measured a short distance basinward of the Cathedral Escarpment on the north face of The Monarch and in Monarch cirque (sections 22, 27, 28, Fig. 51; Plates 41, 42, 43a).

In the exposures overlooking Nataoko Lake, visibly bedded, light buff to reddish dolostone of the Cathedral Formation terminates abruptly at a wall with an average inclination of about 65° (Plate 40). Three major rock units abut this wall from the southeast: (1) reddish-weathering dolostone of the **Cathedral megabreccia** (Section 5.3.3); (2) grey-weathering ribbon limestone, limestone conglomerate, and scattered periplatform talus blocks (up to 25 m in diameter) of the **upper Takakkaw Tongue**; and (3) brown-weathering argillite of the "**basinal**" **Stephen Formation**. The sequence is capped by dark grey-weathering, thin-bedded limestones of the **lower Tokumm sub-unit**. Massive dolostone of the Cathedral Formation projects southeastward beneath these units for about 500 m before plunging from view.

The total relief of the escarpment is estimated to be about 250 m, as measured from the base of the Cathedral megabreccia to the top of the exposure. A prominent, outward bulge occurs in the lower 75 m of the profile. The remainder of the profile is essentially straight (Plate 40). Bedding is clearly truncated at the carbonate wall.

The base of the Cathedral Formation is covered at Natałko Lake. Several hundred metres to the north, the formation rests directly on the Gog Group. The estimated thickness of the Cathedral Formation at this locality is 360 m.

The basal Tokumm sub-unit occurs at the same level as the uppermost Cathedral Formation. This contrasts with the configuration of the classical exposures near Field, where the "thin" Stephen Formation is physically continuous with the upper "basinal" Stephen. Three factors may have acted singly or in combination to create the configuration visible at Natałko Lake:

1. **Differential compaction:** the argillite section would have compacted more than the early-cemented carbonate rocks composing the platform margin. Differential compaction is also known to occur across the Cathedral Escarpment on Mt. Field (McIlreath, 1977a, p. 206).
2. **Minor faulting:** minor, undetected faults may run along the escarpment face. If present, however, they do not visibly offset rocks beneath the Cathedral megabreccia.
3. **Insufficient slope aggradation:** the upper slope may not have aggraded sufficiently to bury the escarpment completely by the end of Stephen time. Thus, a minor marginal escarpment may have persisted during deposition of the lowermost Tokumm sub-unit.

7.2.4 Configuration of the Cathedral margin at The Monarch

About the lower half of the Cathedral Escarpment is preserved on the southern wall of Monarch cirque (sections 27, 28; Fig. 51; Plate 41). Only the base of this feature is preserved on the north face of the mountain (Fig. 51; Plate 42). At both localities, the stratigraphic units abutting the escarpment are easily accessible.

The exposure on the south wall of Monarch cirque is cut by three, minor, west-side-down normal faults with stratigraphic separations on the order of several tens of metres (Plate 41). These are late stage structural features, and do not affect facies. One of the faults coincides with the face of the Cathedral Escarpment.

Despite these minor structural complications, the Monarch cirque and Nataiko Lake exposures are virtually identical. The sub-Cathedral angular unconformity is well exposed on the north wall of Monarch cirque (Plate 37c). Peritidal strata of the **lower Cathedral Formation** are directly overlain by the **Cathedral megabreccia**. Although fabrics have been largely obliterated by destructive dolomitization in this deposit, "ghost" blocks and better-preserved megablocks (up to 90 m in maximum dimension) are nevertheless recognizable. Some of these had considerable sea floor relief (Plate 26d), and were onlapped and draped by ribbon limestones of the **upper Takakkaw Tongue**. The ribbon limestone sequence also contains limestone conglomerate, megaconglomerate, and periplatform talus blocks up to 50 m in maximum dimension. The overlying "**basinal**" **Stephen Formation** contains a few periplatform talus blocks (up to about 9 x 11 m in size) at its base, but the remainder of the unit is composed almost exclusively of argillites and dolomitic argillites.

The thicknesses of these stratigraphic units vary with distance from the Cathedral Escarpment. The **Cathedral megabreccia** (lower Takakkaw Tongue) has a thickness of 51.5 m adjacent to the escarpment in Monarch cirque (section 28; Appendix 2). At Nataoko Lake, it appears to pinch out about 500 m from the escarpment (Plate 40), but this has not been confirmed on the ground. The overlying units all thicken basinward. The **upper Takakkaw Tongue** is only 37.5 m thick near the escarpment on the north face of The Monarch (section 22), but thickens to more than 81.8 m in an incomplete section, 1.2 km from the escarpment in section 23. The "**basinal**" **Stephen Formation** is only 84.1 m thick in Monarch cirque (section 27), but thickens markedly to 177.8 m farther from the escarpment on the north face of The Monarch (section 22).

7.2.5 Comparison of "new" and "classical" Cathedral margin examples

Of the eight main exposures of the Cathedral Escarpment, the Mt. Field, Mt. Stephen, Nataoko Lake and Monarch cirque examples are the best documented. While there are striking similarities between the new and classical exposures, there are also significant differences. These are important to consider if a common origin is being proposed for the Cathedral Escarpment in both areas.

The Field and Nataoko Lake/Monarch exposures of the Cathedral Escarpment are similar in the following respects:

1. Both are situated in major embayments in the regional trend of the Cathedral margin (see below).

2. In both areas, the escarpment is a steep carbonate wall on the order of 200 m high, and is abutted by non-bioturbated sediments of deep-water aspect (Takakkaw Tongue and "basinal" Stephen Formation).
3. At Nataiko Lake, as on Mt. Field and at Park Mountain, sub-horizontal bedding in the Cathedral Formation visibly terminates at the carbonate wall, and there is no evidence of an intervening massive ("reefal") zone.
4. Bedded peritidal strata project beneath the inferred deep-water strata in both areas, although this is more pronounced at the latter locality. Where primary sedimentary textures and components have been preserved, these strata are composed of interbedded and intercalated oolitic-pisolitic dolograins, fenestral dolostone, and layers of "Yoholaminites".

There are several important differences between the Field and Nataiko Lake/Monarch area exposures:

1. Stratigraphic units in the Field area are thicker by about a factor of two. This disparity is inferred to be the result of depositional factors (i.e. higher subsidence and/or sedimentation rates), as there is no reason to suspect that the age range of the Cathedral Formation is shorter in the Nataiko Lake/Monarch area than at other localities in and adjacent to the study area. Notably, the thickness of the Cathedral Formation near Nataiko Lake (360 m) is typical of most westerly, complete sections

of the formation along the Kicking Horse Rim (365 m; Aitken, 1989).³ The anomalous thicknesses in the Field area imply that it was an important depocentre.

2. The Cathedral Escarpment at Field is near-vertical, but is inclined at about 65° near Natalko Lake. The lower part of the escarpment profile in the latter area also has a prominent "bump" or bulge (Plate 40), which has no counterpart in the Field exposures.
3. No unit comparable to the Cathedral megabreccia was deposited at the foot of the escarpment near Field.
4. A few periplatform talus blocks occur at the base of the "basinal" Stephen Formation in Monarch cirque, but not near Field.

7.3 REGIONAL CHARACTERISTICS OF THE CATHEDRAL MARGIN

7.3.1 Regional trends

The **upper** Cathedral margin can be traced fairly accurately through most of the study area (Fig. 52). Control points are provided by the eight known exposures of the Cathedral Escarpment.⁴ In the intervening areas, the margin trend can be closely approximated from available stratigraphic and reconnaissance data.

³ The closest localities where measured thicknesses are available are at Wedgewood Peak (360 m), 21 km to the southeast, and Vermilion Pass (343 m), 26 km to the northwest (Aitken, in press, a).

⁴ The eight known exposures are: Fossil Ridge, Mt. Field, Mt. Stephen, Odaray Mountain, Park Mountain, Natalko Lake, The Monarch (north face), and Monarch cirque.

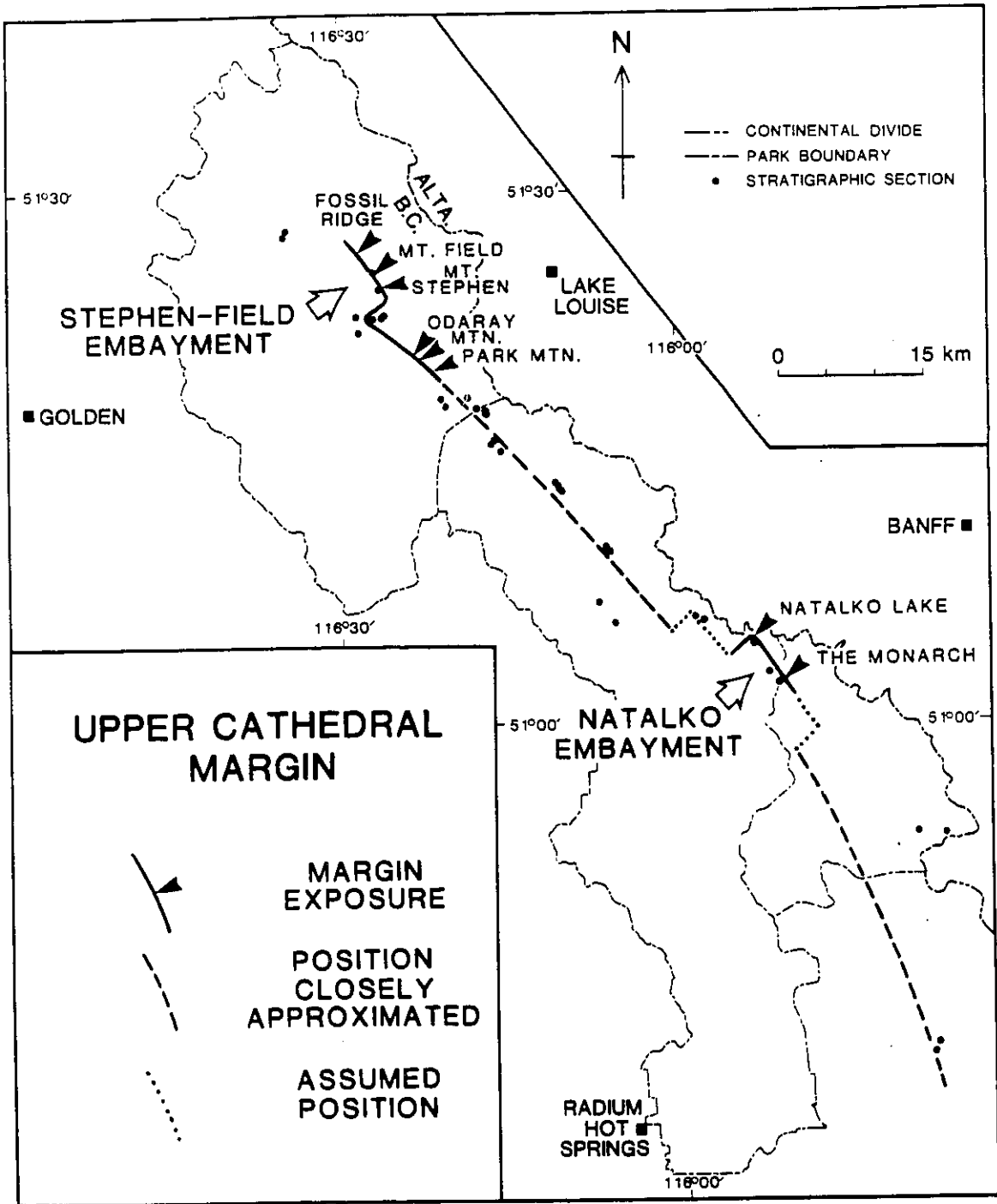


Figure 52. Regional trend of the upper Cathedral margin.

The **earliest** Cathedral margin trend can also be traced through much of the study area. Carbonate shoals originally nucleated along the proto-Kicking Horse Rim (Aitken, 1989), which is recognizable today as a NW-SE-trending zone, in which Gog Group quartzites are unconformably overlain by the Cathedral Formation.⁵ This unconformable relationship is exposed at Odaray Mountain (Hockley, 1973), and along a nearly continuous belt, up to 9 km wide, between the Mt. Biddle area and The Monarch (Fig. 53). The belt appears to continue as far southeast as Ferro Pass, where the Naiset Formation reappears and thickens southward (Aitken, in press, a; Leech, 1979). Near Field, visible facies changes in the Naiset Formation suggest that it probably dies out beneath the eastern flank of Mt. Field. The zone of non-deposition must be very narrow at that locality, as Mt. Whyte sediments appear about 1.8 km farther east (Price *et al.*, 1980).

7.3.2 Margin embayments

Three major embayments affect the Cathedral margin, which is otherwise remarkably straight. Only one of these affects the entire Cathedral margin: the Stephen-Field Embayment (McIlreath, 1977a; Figs. 52, 53). The Nataiko Embayment (new name) affects only the upper Cathedral margin (Fig. 52), and the less well-defined Assiniboine Embayment (new name) indents only the lower Cathedral margin (Fig. 53).

The **Stephen-Field Embayment** contains the classic Cathedral margin exposures near Field (McIlreath, 1977a, p. 128 and his Fig. 6-7). Its southeastern boundary is well defined on the ridge linking Mt. Stephen and Mt. Dennis, and is marked by two near-right-angle bends (Fig. 50). The northwestern boundary of the embayment is poorly defined due

⁵ This linear zone corresponds to an area of non-deposition between the zero-edges of the Naiset and Mt. Whyte formations.

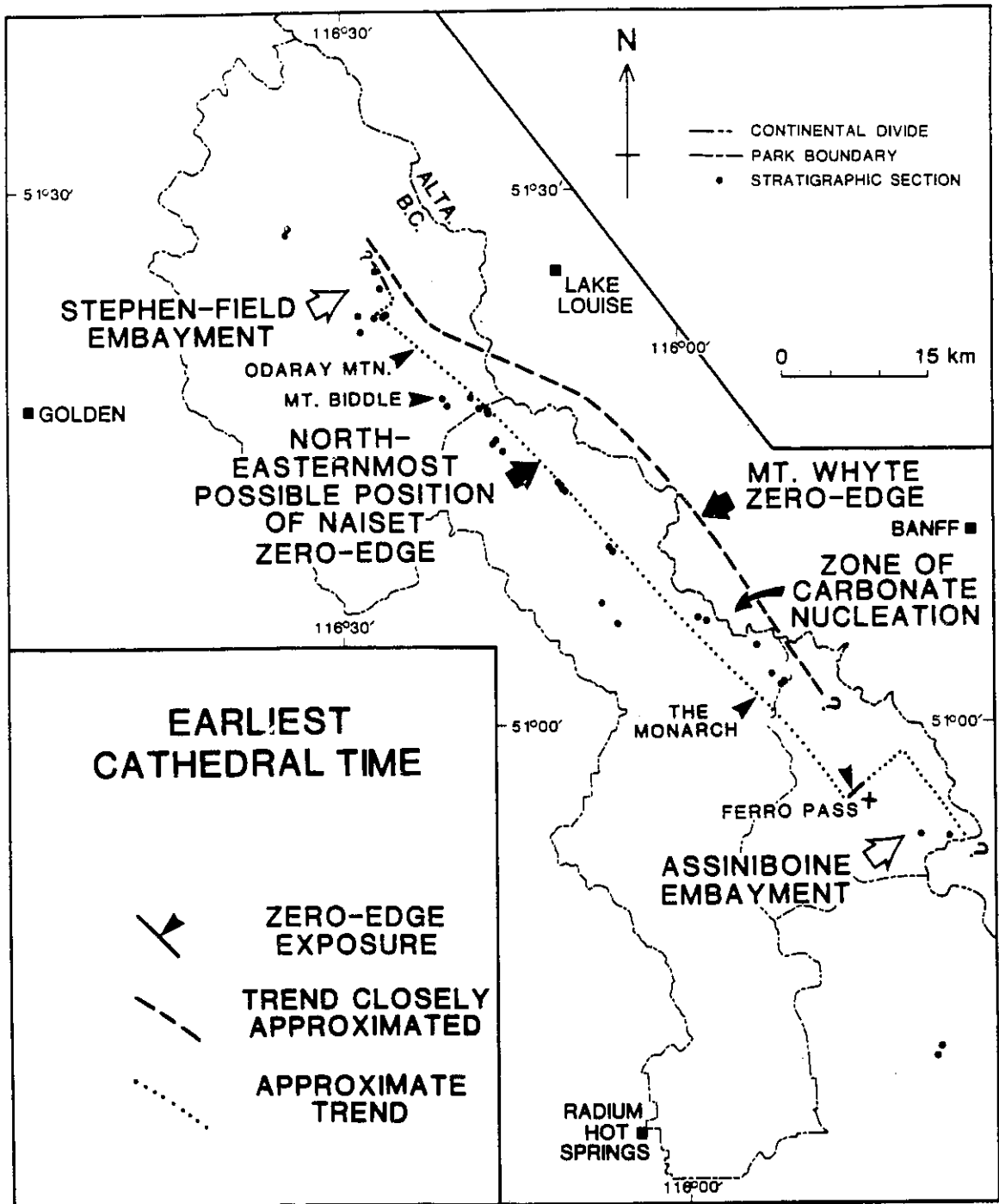


Figure 53. Regional trend of the zone of carbonate nucleation along the Kicking Horse Rim in earliest Cathedral time.

to faulting and a lack of exposure. The Stephen-Field Embayment has a cross-strike width of about 4.5 km, and a minimum along-strike length of 9.5 km.

Near Field, the Cathedral margin nucleated about 5 km inboard of the **regional** upper Cathedral margin trend (Fig. 52), and managed to prograde less than a kilometre basinward beneath the level of the Cathedral Escarpment. The Stephen-Field Embayment also continued to affect sedimentation patterns in post-Cathedral time.

It is unclear whether the anomalous stratigraphic thicknesses in this area are confined to the Stephen-Field Embayment, or whether the depocentre had a wider extent. Measured stratigraphic thicknesses are not available immediately northwest or southeast of the embayment. On the northeastern side of Odaray Mountain (Fig. 50), the Cathedral Formation is estimated from the geological map of the area (Price *et al.*, 1980) to have a thickness of about 350-450 m. If the true thickness is closer to the lower end of this range, the depocentre was probably confined to the embayment.

The **Natalko Embayment** is characterized by an abrupt, near-right-angle swing in the **upper** Cathedral margin trend at its northwestern end (Fig. 52). From that point, the margin trends northeastward for about 3 km through the Natalko Lake exposure (Plate 40), then abruptly turns southeastward again for at least 6 km to pass through The Monarch and Monarch cirque. The southeastern end of the embayment is not preserved, but the margin must swing about 3 km southwestward again to join up with the regional trend of the upper Cathedral margin (Fig. 52).

The northwestern end of the Natalko Embayment may be stepped, although this is conjectural. The upper Eldon/Pika margin is known to be embayed in the Verdant

headwaters area (Section 6.4.2.3; Fig. 48). This may reflect control by antecedent topography, and thus a minor embayment is tentatively inferred to be present in the underlying Cathedral margin.

The **Assiniboine Embayment** is the only area outside of the Stephen-Field Embayment where the Naiset Formation is known to penetrate well platformward of its projected **regional** zero-edge (Fig. 53). The configuration of this embayment is poorly understood. Its southeastern margin is not exposed due to a southeasterly structural plunge. The northwestward disappearance of the Naiset Formation near Ferro Pass (Aitken, in press, a; Leech, 1979) is inferred to reflect onlap and facies change against the northwestern boundary of the embayment (Fig. 53). This boundary is assumed to trend northeastward, like the other embayment boundaries in the region.

In the Assiniboine Embayment, the Cathedral margin nucleated at least 10 km inboard of the regional upper Cathedral margin trend. The fact that the **upper** Cathedral margin is not embayed at this locality (Fig. 52) indicates that the Assiniboine Embayment had completely healed over prior to Stephen deposition.

7.3.3 Origin of embayments

Local, northeastward penetration of the Naiset Formation in the **Stephen-Field and Assiniboine embayments** indicates that both of these features **predate** Cathedral and Mount Whyte/Naiset deposition. The northeastward-trending margin of the former embayment is orthogonal to the regional trend of the Middle Cambrian margin, and is parallel to faults with known Proterozoic and younger movements in the southwest (Lis and Price, 1976; Section 2.3.5.1). These characteristics suggest antecedent or synsedimentary fault control.

The suggestion of underlying tectonic control is supported indirectly by other lines of evidence. Aitken (in press, a) reported significant, northeasterly deflections in isopachs of certain Middle Cambrian units. He suggested that reactivation of old northeasterly fault trends was the most likely cause. Although these deflections are much larger in scale than the Stephen-Field Embayment, they appear to confirm that Mount Whyte and Naiset sedimentation patterns were affected by older structural features. A similar conclusion was reached by Hockley (1973).

In the study area, pre-Middle Cambrian block faulting could have created local paleotopographic lows, which subsequently became depocentres. Alternatively, some of the faults could have remained active throughout the Middle Cambrian, creating local depocentres with higher subsidence rates than adjoining parts of the margin. Either mechanism could explain the anomalously thick sediments found within the Stephen-Field Embayment.⁶

The Assiniboine Embayment presumably originated from pre-Middle Cambrian block faulting. The thickness of the Cathedral Formation there is comparable to regional values, suggesting that this part of the margin subsided at the regional rate. Thus, the inferred fault activity must have ceased immediately after the embayment was formed.

The Nataalko Embayment is unlike the other two embayments in that it indents only the upper Cathedral margin. Thus, the Naiset zero-edge and lower Cathedral platform margin lie **basinward** of the Cathedral Escarpment. These relationships indicate that the

⁶ This assumes that the anomalously thick sediments are confined to the Stephen-Field Embayment, which cannot be proven on the basis of available data.

embayment formed during Cathedral deposition, and was not a pre-existing bathymetric depression.

The origins of the Nataalko Embayment and the Cathedral Escarpment in the Nataalko Lake/Monarch area are one and the same problem. These features will thus be interpreted together later in this chapter.

7.4 INTERPRETATION OF THE CATHEDRAL ESCARPMENT

7.4.1 Introduction

The Cathedral Escarpment has received world-wide attention as the backdrop for the Burgess Shale, and is thought to have played a critical role in localizing and preserving the soft-bodied Burgess fauna (Aitken and McIlreath, 1984). The classic interpretation of this feature is based on detailed stratigraphic, structural, sedimentological and paleontological studies, and has been widely accepted by the scientific community (Aitken and Fritz, 1968; Fritz, 1971; McIlreath, 1977a, b; Aitken and McIlreath, 1984; Aitken, 1989 and in press, a). This interpretation has, however, recently engendered considerable controversy (Beales *et al.*, 1986; Ludvigsen, 1989, 1990).

Ludvigsen's (1989) reinterpretation of the Cathedral Escarpment is crucial to the present discussion, as it denies the very existence of a Cambrian submarine cliff. Moreover, it has attacked the biostratigraphic evidence cited in support of the classic interpretation (Fritz, 1971). Ludvigsen's reinterpretation has been discussed in the rebuttals by Fritz (1990) and Aitken and McIlreath (1990), and is evaluated further in Appendix 3. In the opinion of the writer, Ludvigsen's (1989, 1990) reinterpretation is invalid, and it will not be discussed further.

The Cathedral Escarpment has classically been interpreted as the product of rapid, vertical aggradation of the Cathedral platform in response to accelerated relative sea level rise (McIlreath, 1977a; Aitken and McIlreath, 1990). However, conclusive proof of this origin remains elusive. One particular problem is that the full height of the escarpment is not backed by a massive zone, analogous to the "prograding reef" in the pre-escarpment Cathedral (Section 7.2.1). The visible truncation of bedding on Mt. Field, Park Mountain, and near Nataoko Lake (Plates 39a, b; 38e; 40) calls into question the concept of a vertically aggrading reef, as classically presented by Aitken and McIlreath (1984, 1990).

The truncation of platform bedding is compatible with an erosional origin for the Cathedral Escarpment. In view of the overwhelming evidence for outer platform collapse in the overlying Eldon-Pika sequence, there is every reason to suspect that similar events probably occurred at other times in the history of the Cambrian margin. The Nataoko Lake/Monarch exposures are crucial in this regard, as they contain the strongest evidence that this process also occurred during Cathedral time.

7.4.2 Summary interpretation of the Nataoko Lake-Monarch exposures

The exposures of the Cathedral Escarpment at Nataoko Lake and in Monarch cirque are essentially identical in terms of facies configuration (Sections 7.2.3, 7.2.4). The former is undeformed and spectacularly exposed, but it is the latter, faulted exposure that is accessible for study. The techniques used to unravel the sedimentological history of these exposures included the measurement of stratigraphic sections, lateral traversing, close helicopter reconnaissance, and the careful examination of enlarged colour photographs.

The stratigraphic and sedimentological relationships observed in the Nataalko Lake/Monarch area are compatible with large-scale collapse of the outer Cathedral platform. These relationships can successfully be accounted for in a local model for the origin of the Nataalko Embayment and the Cathedral Escarpment in that area (Fig. 54). The basic elements of this model are summarized below:

1. **Initial offlapping depositional margin:** after platform growth was initiated on a Gog Group substrate along the crest of the Kicking Horse Rim, the platform prograded substantially basinward (Plate 54a). The style of margin at that time is assumed to have been similar to the rimmed depositional margin seen in the pre-escarpment Cathedral on Mt. Field.
2. **Major outer platform collapse:** collapse of the outer platform during late Cathedral time left behind a broad zone of removal that was essentially free of debris. The allochthonous material generated by the collapse was presumably transported tens of kilometres downslope.
3. **Minor collapse of the upper truncated margin:** the upper part of the truncated margin suffered minor collapse immediately after the main event, and the Cathedral megabreccia was deposited by rockfall at the foot of the escarpment (Fig. 54b).
4. **Deposition of the upper Takakkaw Tongue:** the truncated platform continued to aggrade and export copious quantities of lime mud, which blanketed the upper slope (Fig. 54c). Debris flows and periplatform talus blocks were also shed periodically from the active margin.

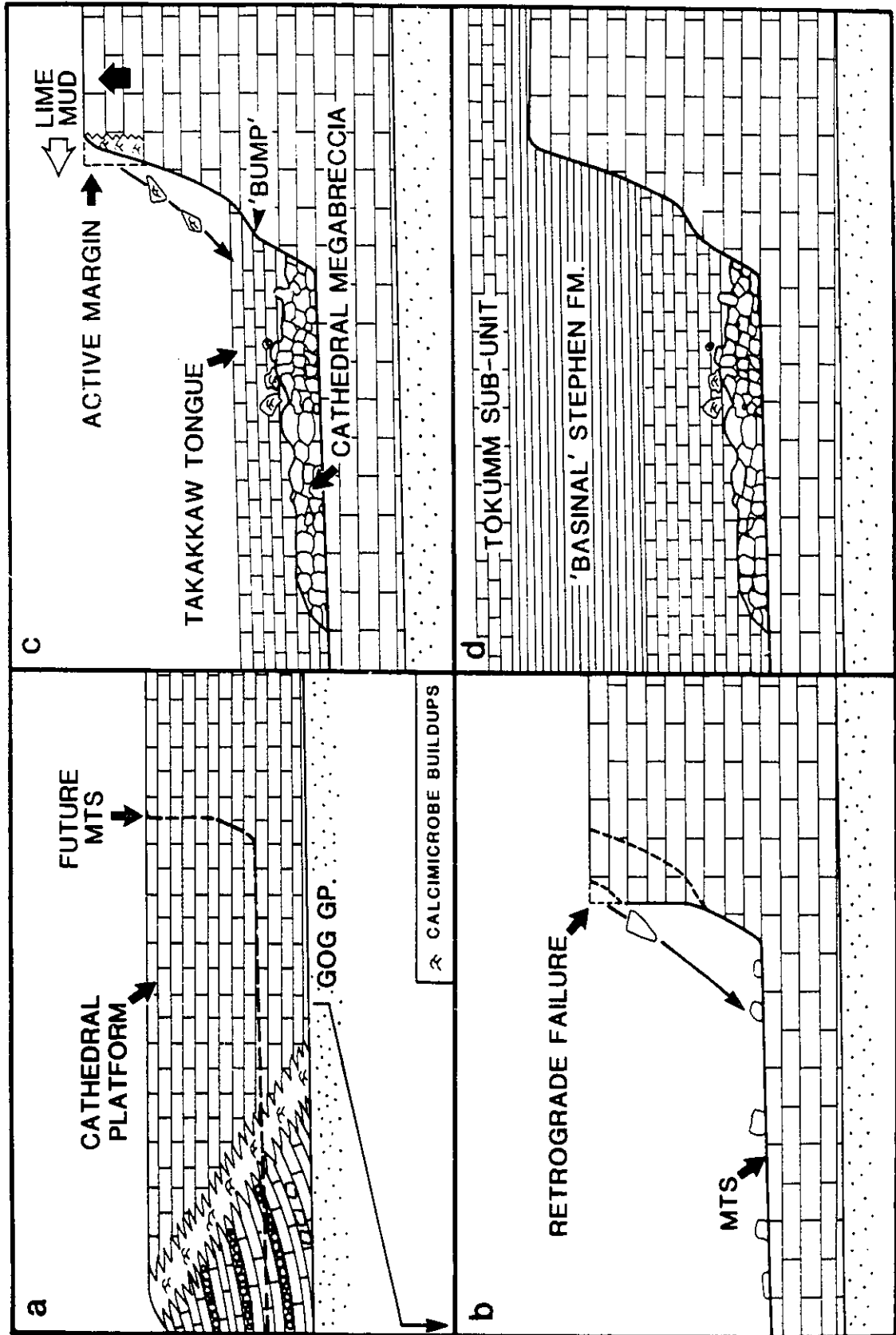


Figure 54. Model for the development of the Cathedral Escarpment in the Natalko Lake/Monarch area. Details are given in the text.

5. **Termination of platform growth and entombment of the escarpment:** a subsequent influx of fine-grained siliciclastic sediments smothered the platform, and rapidly entombed the remaining escarpment (Fig. 54d). Widespread carbonate platform sedimentation was eventually re-established (Eldon Fm.), and deep-water carbonate sedimentation resumed on the adjoining slope (Tokumm sub-unit).

7.4.3 Discussion of model components

7.4.3.1 Stage 1: Initial offlapping depositional margin

The pre-escarpment Cathedral margin is not exposed anywhere in the Nataiko Lake/Monarch area, and thus the style of platform-to-basin transition is unknown at that level. In the absence of evidence to the contrary, the lower Cathedral platform is assumed to have been bounded by a prograding, reef-dominated depositional margin like that exposed on Mt. Field (Plate 39; Fig. 54a). Extensive platform progradation over unstable slope sediments would have made the outer platform vulnerable to subsequent, large-scale collapse.

7.4.3.2 Stage 2: Major outer platform collapse

Large-scale collapse of the outer platform created the Nataiko Embayment, and resulted in the removal of a 200 m thick section of platform margin and bedded peritidal strata. The initial slide scar is postulated to have had a near-vertical headwall, but rapidly flattened basinward to become sub-horizontal. This configuration is very similar to that of the intra-Vermilion megatruncation surface in Verdant cirque (Plate 54), and to the Grayburg megatruncation surface in the Permian Basin (Fig. 42). The allochthonous debris generated by this event was presumably transported tens of kilometres downslope beyond the current

limits of exposure, and little or no material remained behind to veneer the zone of removal at the foot of the headwall.

The collapse occurred during late Cathedral time. The accumulation of upper Takakkaw Tongue lime mudstones above the megatruncation surface implies the existence of a healthy carbonate platform that continued to export copious quantities of lime mud and periplatform debris basinward after the collapse event.

7.4.3.3 Stage 3: Minor collapse of the upper truncated margin

The collapse of the outer platform was followed almost immediately by a minor collapse of the upper headwall region (Fig. 54b). A "bump" was created in the margin profile where the new detachment surface intersected the headwall of the original slide scar. The upper part of this detachment surface formed a steeply-dipping headwall with an inclination of about 65°.

Under this interpretation, the Cathedral megabreccia was deposited when the detached slide block degenerated into smaller blocks at the foot of the escarpment.⁷ The chaotic fabric and angular clasts observed in the megabreccia are typical of such rockfall deposits (Nardin *et al.*, 1979). This deposit is also unique in that wherever sedimentary fabrics could be recognized, blocks of all sizes are composed of bedded, peritidal strata identical to those truncated at the escarpment face.⁸

⁷ The secondary collapse need not have been a single event. The present margin profile could also have also resulted from a closely spaced succession of small failures.

⁸ This differentiates the Cathedral megabreccia from the Vermilion sub-unit megaconglomerates, which contain mostly Epiphyton boundstone megaclasts. The composition of the megabreccia clasts is compatible with the notion of minor collapse of an already truncated margin, along which the zone of Epiphyton buildups had already been removed.

The Cathedral megabreccia plays a pivotal role in dating the time of escarpment formation, and is crucial to the collapse model advocated here. Clearly, the platform margin must have had appreciable relief to shed a megabreccia containing a 90 m high megaclast **standing on end** (Plates 26d; 41). Had the Cathedral Escarpment been formed by depositional means (*i.e.* rapid platform aggradation in response to a sustained, rapid relative sea level rise), deep-water carbonate sediments would have accumulated at the foot of the growing carbonate wall until this relief was attained. It is notable in this regard that the Cathedral megabreccia directly overlies bedded peritidal strata of the lowermost Cathedral Formation, and no such deep-water strata intervene (section 28, Appendix 2; Plates 40, 41). Thus, the formation of the escarpment and the deposition of the megabreccia were closely linked in time, a relationship that strongly favours a collapse origin for the Cathedral Escarpment in the Natalko Lake/Monarch area. Notably, had the megabreccia been absent, it would have been difficult or impossible to differentiate between a depositional or collapse origin for this feature.

7.4.3.4 Stage 4: Deposition of the upper Takakkaw Tongue

Following deposition of the Cathedral megabreccia, the carbonate platform continued to aggrade vertically and export significant quantities of lime mud basinward. These events were manifested on the adjoining slope by the deposition of a carbonate mud apron. Sufficient lime mud was exported to deposit more than 80 m of ribbon limestone against the escarpment in section 23 (Fig. 51). Rarely occurring graded beds of intraclastic-peloidal grainstone in the slope sequence indicate that carbonate sand was also being generated on the platform. Periplatform talus blocks and megaconglomerate clasts up to 13.5 m in maximum dimension testify to the re-establishment of calcimicrobe buildups along the outer fringe of the truncated margin. Some of the periplatform talus blocks project upward

into the "basinal" Stephen Formation, and a few are wholly incorporated in the basal part of that unit. This suggests that minor margin failures continued up to the end and even slightly after the demise of carbonate sedimentation on the platform.

7.4.3.5 Stage 5: Termination of platform growth and entombment of the escarpment

The Takakkaw Tongue is abruptly succeeded by a monotonous sequence of fine-grained, siliciclastic sediments belonging to the "basinal" Stephen Formation. This succession is broken only by a few, thin intraclast beds containing various quantities of trilobite, mollusc and pelmatozoan debris. The composition of the "basinal" Stephen Formation implies that carbonate sedimentation had effectively ceased on the adjoining platform, which had been transformed into a subtidal siliciclastic shelf. Vast quantities of terrigenous muds were transported across the shelf to settle out as graded laminae on the rapidly aggrading slope at the foot of the inactive escarpment. A minor marginal escarpment may have persisted after the siliciclastic influx ceased. With the return of widespread carbonate sedimentation on the platform, the escarpment became fully entombed, and the slope was transformed into a carbonate ramp (Tokumm sub-unit).

7.5 PROPOSED REVISIONS TO THE GEOLOGICAL HISTORY OF THE CATHEDRAL ESCARPMENT NEAR FIELD

If the Cathedral Escarpment in the Natalko Lake/Monarch area can plausibly be interpreted as the headwall of a large-scale slide scar, it must be questioned whether the morphologically similar exposures near Field had a similar origin. To illustrate this possibility, a proposed geological history of the Cathedral margin near Field is outlined below. It accounts for all of the observed structural, stratigraphic and sedimentological

relationships documented on Mt. Field and Mt. Stephen by previous workers and by the writer.

Cathedral carbonate sedimentation commenced in the Field area with the nucleation and basinward progradation of a reef-dominated depositional margin (McIlreath, 1977a; Aitken, 1989). In contrast to previous interpretations, it is proposed here that progradation did not terminate at the level of the apparent "backstep", as suggested by Aitken and McIlreath (1990, p. 113). Rather, the depositional margin probably continued to prograde rapidly outward over the adjoining slope sequence until late Cathedral time. This process probably accelerated in post-Trinity Lakes Member time, when high carbonate accretion rates are indicated by pronounced, eastward progradation of peritidal sediments into former subtidal areas of the Cathedral platform (Aitken, 1989). It is conceivable that, as in the case of the Assiniboine Embayment, margin progradation was sufficient to completely heal over the Stephen-Field Embayment. Such extensive, lateral margin progradation over relatively unstable slope sediments would have produced an outer platform prone to large-scale collapse.

During late Cathedral time, a 200 m thick section of the outer Cathedral platform detached and collapsed into the basin, leaving behind a near-vertical headwall scarp. The declivity of the headwall was presumably structurally controlled, although evidence for pre-existing fractures, such as neptunian dikes (Playford, 1984; Playford *et al.*, 1989), has not yet been recognized. The remainder of the slide scar is inferred to level out and continue basinward as a sub-horizontal surface. Under this interpretation, the apparent "back-step" surface visible on Mt. Field is a segment of the megatruncation surface floor (Plate 39).

At present, the basinward extension of the inferred megatruncation surface cannot be located with confidence, despite the fact that the Takakkaw Tongue is completely exposed (though somewhat deformed) on Mt. Field and Mt. Stephen. Notably, the surface should have been traversed by at least four stratigraphic sections (MJA-723, 725 and 726 on Mt. Field, and MJA-733/AC-114 on Mt. Stephen; Fig. 3).

That an erosion surface of this magnitude could have gone undetected is not necessarily surprising, in view of previous experience with the megatruncation surface in the overlying Eldon-Pika sequences. The intra-Vermilion megatruncation surface in Verdant cirque is instructive in this regard. It passes basinward over a short distance from a near-vertical headwall to a sub-horizontal feature (Plate 54). The lower segment of the surface is difficult to detect, because it is parallel to bedding and free of allochthonous debris (Section 6.2.3.2).

These characteristics are crucial to the argument that the Takakkaw Tongue contains a major, previously undetected megatruncation surface. First, the surface itself may be very subtle, because it is bounded above and below by monotonous, thin-bedded limestones of the Takakkaw Tongue. The lower segments of the intra-Vermilion megatruncation surfaces in both Stephen and Verdant cirques are equally subtle and difficult to recognize in stratigraphic sections, despite extensive, cross-strike exposure (Plates 50, 54). Second, studies of modern and ancient slide scars indicate that the zones of removal on these features often extend several kilometres or even tens of kilometres downslope. This would explain the lack of collapse-related debris over the full length of the available cross-strike exposure in the Stephen-Field Embayment (about 3.5 km).

Near Field, the collapse of the outer Cathedral margin was not immediately followed by further retrograde failure, as was the case in the Nataoko Lake/Monarch area. This explains why the escarpment near Field is almost vertical, as opposed to the average of 65° recorded in the latter area. Presumably, the post-collapse stability of the vertical headwall near Field reflects a lack of additional, suitably oriented fractures and/or the absence of subsequent strong seismic events.

Following the collapse, the Cathedral platform continued to produce carbonate sediment and aggrade vertically. Copious quantities of lime mud were exported basinward, together with minor oolites, peloids, oncoids, bioclasts, and periplatform talus blocks. These sediments now make up about the upper 138 m of the Takakkaw Tongue, as measured immediately west of the escarpment on Mt. Field (McIlreath, 1977a, section MJA-726; Fig. 3).

An increase in the rate of relative sea level rise initiated a general deepening across the platform, which was accompanied by minor influxes of fine-grained siliciclastic sediment (Narao Member). Two areally extensive, shale-based cycles were deposited as subtidal lime mud deposition continued to predominate on the platform proper (Aitken, in press, a). A narrow peritidal shoal area was maintained along the Kicking Horse Rim throughout this period (Aitken, 1989, his Fig. 12).

Carbonate mud production was temporarily inhibited by the initial relative sea level rise and accompanying terrigenous influx. Siliciclastic mud bypassed the margin, and was deposited as a thin blanket on the slope at that time (unit 1 of Fritz, 1990). Carbonate sediment production then escalated as the narrow margin continued to aggrade during Narao Member time. Carbonate mud and sand were once again exported basinward, and were

incorporated in a minor successor carbonate apron, the Boundary Limestone (Fritz, 1971; McIlreath, 1977a, b). However, the quantity of sediment was much diminished from the period of Takakkaw Tongue deposition, suggesting that the platform had already started to die.

Initially, ooliths, peloids, and bioclasts were exported in large quantities to the proximal part of the slope. Small blocks also broke off a narrow band of Epiphyton buildups that had become re-established along the outer edge of the truncated margin. These were incorporated in the Boundary Limestone as submarine talus. Biostratigraphic evidence suggests that the apron expanded basinward with time (McIlreath, 1977b, p. 116-117), implying a concomitant modest increase in the rate of carbonate production on the adjoining platform. Carbonate particles continued to be supplied intermittently, but carbonate mud deposition dominated the later stages of apron accretion.⁹ Locally, however, large (up to 10 x 3 m) blocks of peloidal-intraclastic-oolitic grainstone were shed from the reactivated margin during the terminal stages of Boundary Limestone deposition.¹⁰

Two events subsequently combined to transform the carbonate platform into a siliciclastic shelf: (1) a major influx of siliciclastic mud, which encroached upon and eventually buried the entire platform (Waputik Member of the platformal Stephen; Aitken, in press, a); and (2) a rapid relative rise in sea level, which submerged the peritidal zone on the outer platform. In this interpretation, the end of Boundary Limestone deposition coincided with the final smothering of the outermost Cathedral platform by siliciclastic mud (Section 5.4.6.3).

⁹ This vertical change in lithofacies is recorded in McIlreath's (1977a) Stephen Glacier section (MJA-731), immediately adjacent to the escarpment on Mt. Stephen.

¹⁰ These are now exposed at the top of a 20.5 m thick section of the Boundary Limestone in section AC-161/162, near Fossil Gully on Mt. Field (Fig. 3).

An outstanding problem with this interpretation concerns the disappearance of the Glossopleura Zone fauna on both the platform and slope. Glossopleura and its affiliates were eliminated from the slope after only about a third of the Boundary Limestone "bench" had been deposited. On Mt. Stephen, for example, approximately 66 m of mainly carbonate mud accumulated on the proximal slope between the deposition of the last Glossopleura-bearing strata and the onset of siliciclastic mud deposition (McIlreath, 1977a). This section contains the Kootenia sp. 1 and Ogygopsis klotzi faunules (Fig. 24; McIlreath, 1977a, his Appendix I), and demonstrates that carbonate mud was still being produced in abundance on the platform after the disappearance of Glossopleura. However, Glossopleura persists virtually to the top of the outer platform sequence (Fritz, 1971), and thus the source of the post-Glossopleura carbonate mud is problematical.

As a possible solution to this impasse, it is proposed that smothering of the entire platform by siliciclastic mud was preceded by submergence of the outer platform shoal area to water depths of, perhaps, a few tens of metres. Carbonate mud continued to be produced and exported from the platform to accumulate as the upper Boundary Limestone. Prolific carbonate mud production and export is reported to occur under similar incipient drowning conditions (20-30 m or more water depth) on carbonate banks along the Nicaraguan Rise (Droxler and Glaser, 1990). On these small, isolated banks, the sediment is almost totally exported to flanking periplatform wedges, where sedimentation rates are on the order of 1300-2000 mm/k.y. Under these conditions, a wedge the thickness of the upper Boundary Limestone could accumulate in as little as 33,000 years. Incipient drowning of the margin would also explain why carbonate mud, rather than sand, predominated in the later phases of Boundary Limestone deposition.

There is no depositional record of this postulated deeper phase of carbonate sedimentation on the outer platform. Energy conditions over the site of the former peritidal barrier may have been high enough to inhibit carbonate mud deposition on the outer platform, resulting in a hiatus. The adjoining carbonate-producing area continued to shrink due to the progressive, westward encroachment of fine-grained siliciclastic sediment. Carbonate production and export eventually ceased with further deepening and the eventual spread of siliciclastic mud over the carbonate margin.¹¹

It should be noted that there is, at present, no specific evidence for a non-depositional episode near the edge of the Cathedral platform during the accumulation of the upper Boundary Limestone. Evidence for this hiatus should include, for example, hardgrounds or phosphate horizons (Shanmugam, 1988, p. 85). This evidence may, however, have been erased by subsequent destructive dolomitization.

The remainder of the proposed depositional history parallels earlier interpretations by McIlreath (1977a) and Aitken (in press, a). Rapid entombment of the Cathedral Escarpment followed, as most of the siliciclastic mud bypassed the shelf and was deposited on the slope. The substantial thickness difference between the shelf and slope successions presumably reflects the limited accommodation space available on the shelf, as opposed to the favorable environment for mud accumulation offered by the slope. Aggradation of the slope ultimately led to the establishment of a gently-dipping siliciclastic ramp. A break in slope probably developed over the site of the former escarpment due to differential compaction (see McIlreath, 1977a, p. 204, 206).

¹¹ The disappearance of *Glossopleura* and its affiliates at a lithological boundary (between limestone and shale) is troubling, as it could reflect environmental, rather than temporal control. If this is correct, *Glossopleura* and its affiliates could have disappeared progressively from the platform interior as deepening continued and the siliciclastic sediments encroached southwestward.

7.6 SUMMARY

The Cathedral margin is a relatively straight feature that is interrupted by three major embayments in the study area. The **Stephen-Field** and **Assiniboine** embayments predate Mount Whyte/Naiset and Cathedral deposition, and probably originated from antecedent or synsedimentary faulting along the Kicking Horse Rim. Both of these features probably healed over by late Cathedral time due to rapid margin progradation. In contrast, the **Nataloko Embayment** affects only the upper Cathedral Formation. It is considered to be a local notch (local, structurally controlled collapse feature) in a regionally extensive slide scar that formed during late Cathedral time. The **present-day** Stephen-Field Embayment also probably originated in this manner.

Cross-strike exposures of the entire Cathedral margin are found only in the Field and Nataloko Lake/Monarch areas. In the classic exposures near Field, the lower Cathedral platform is bounded by a depositional margin. This feature was formerly rimmed by a zone of Epiphyton buildups, now represented by a narrow dolomitized zone separating bedded peritidal strata to the east from slope sediments of the Takakkaw Tongue to the west. The upper Cathedral platform terminates westward at the 200 m high Cathedral Escarpment, which is abutted by the upper Takakkaw Tongue and "basinal" Stephen Formation. In the Nataloko Lake/Monarch area, the seaward margin of the lower Cathedral platform is not exposed. There, the Cathedral Escarpment is also about 200 m high, and has an average inclination of about 65°. The base of this wall is abutted by the Cathedral megabreccia, which overlies bedded peritidal strata of the Cathedral Formation, and is overlain by the upper Takakkaw Tongue and "basinal" Stephen Formation.

The truncation of platform bedding at the Cathedral Escarpment near Field, on Park Mountain, and in the Nataoko Lake/Monarch area provides the first indication that the Cathedral Escarpment is an erosional, rather than a depositional feature. The most explicit evidence favouring a collapse origin for this feature is the Cathedral megabreccia, which could only have been deposited at the foot of a platform margin with appreciable relief. The formation of the escarpment and the deposition of the megabreccia were closely linked in time, and thus the megabreccia is most plausibly interpreted as the product of a minor, secondary failure of a platform that had previously suffered large-scale collapse.

The stratigraphic and sedimentological relationships in the Field area suggest that the Cathedral Escarpment there probably had a similar origin. Large-scale collapse of the outer Cathedral platform created a slide scar with a near-vertical headwall. Like the morphologically similar intra-Vermilion megatruncation surface in Verdant cirque, the lower, sub-horizontal segment of the slide scar is subtly expressed in outcrop, despite extensive, cross-strike exposure. A talus wedge comparable to the Cathedral megabreccia is missing, implying that the truncated margin remained stable after the initial collapse. Otherwise, the post-collapse sedimentation histories in the Field and Nataoko Lake/Monarch areas are rather similar.

CHAPTER 8

DEPOSITIONAL HISTORY AND CONCLUSIONS

8.1 INTRODUCTION

The primary goal of this study was to establish the stratigraphic and sedimentological relationships across the zone of facies change between a Middle and Upper Cambrian shelf assemblage and its slope and basin equivalent, the Chancellor succession. This goal was achieved by documenting the style of facies change in key parts of the stratigraphy at a series of crucial cross-strike exposures, and integrating this information with regional stratigraphic and sedimentological data (Fig. 55). A generalized depositional history of the platform and slope succession is summarized below, drawing upon the stratigraphic, sedimentological and structural relationships outlined in the preceding chapters.

8.2 DEPOSITIONAL HISTORY

8.2.1 Naiset/Mount Whyte deposition

The Naiset and Mount Whyte formations were the first strata to be laid down during marine transgression over the sub-Middle Cambrian unconformity at the top of the Gog Group. A siliciclastic shelf and slope quickly became differentiated on either side of the proto-Kicking Horse Rim (Aitken, in press, a). Local block faulting along this trend created

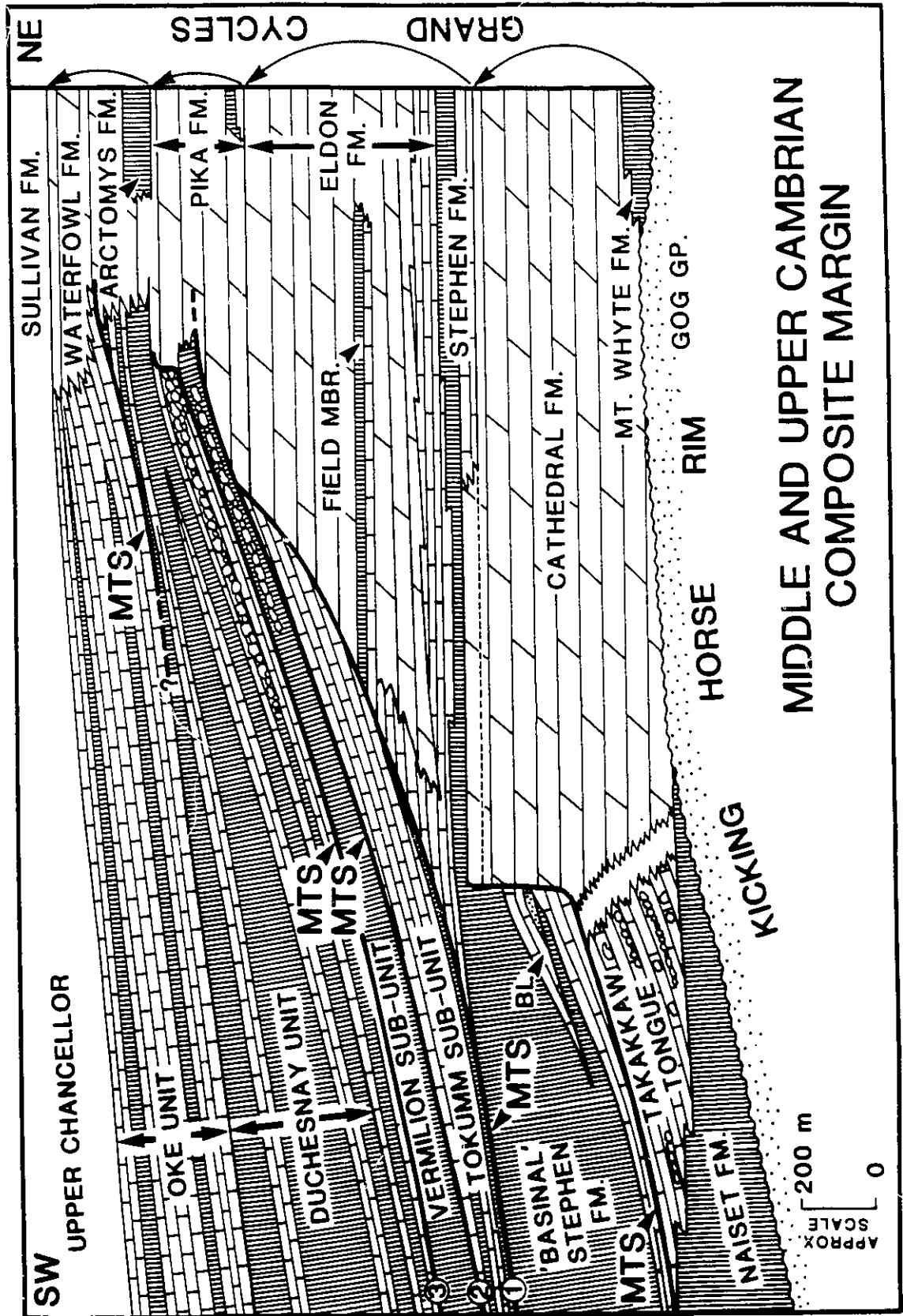


Figure 55. Regional model (schematic) for the Middle and Upper Cambrian composite margin.

the Stephen-Field and Assiniboine embayments prior to, and perhaps partly during the deposition of these two units (Section 7.3.2; Fig. 53).

In the type area of the Naiset Formation, the shelf margin was probably occupied by a largely emergent paleotopographic high. Definite evidence of coeval carbonate sedimentation does not appear until near the top of that formation. An emergent rim would have been a ready source for the fine-grained quartz sands found in the upper Naiset, and would explain the paucity of carbonate material in that sequence.

The nature of the shelf margin probably varied considerably along depositional strike. Significant units of lime mudstone in the Naiset Formation at Ferro Pass (Aitken, in press, a), and in the Field area (sections 2, 3; Appendix 2), may reflect the local establishment of carbonate shoals between emergent areas northwest of the type area. A similar depositional scenario was also advocated for the Field area by McIlreath (1977a, p. 161).

In the Stephen-Field and Assiniboine embayments, initial Naiset sedimentation took place in a quiescent, probably oxygen-deficient environment below maximum storm wave base (Section 5.2.7). Most sediments were deposited by a combination of dilute, muddy turbidity currents and hemipelagic settling (argillite lithofacies; Section 4.3.3). Slope aggradation and a consequent shallowing of the depositional environment are recorded by the upward appearance of biogenic structures and the disappearance of syndepositional deformation structures in the sequence. A really extensive carbonate shoals eventually became established over the full length of the shelf margin by the close of Naiset time.

8.2.2 Takakkaw Tongue/Cathedral deposition

The initial carbonate deposits to accumulate along the Kicking Horse Rim were oolite sand shoals (McIlreath, 1977a).¹ They formed the nucleus of a subsequent, more areally extensive peritidal shoal complex ("Yoholaminites" and related sediments; Section 4.8.4), which was rimmed on the seaward side by a zone of Epiphyton buildups. East of this peritidal rim was an extensive, subtidal inshore basin, into which carbonate sediments progressively expanded (with minor interruptions) until the end of Cathedral time (Aitken, 1989).

Prolific carbonate sediment production and export from the Cathedral platform led to the establishment of a large carbonate apron (Takakkaw Tongue) along its flank. Slope sedimentation was dominated by a combination of hemipelagic fallout and turbidite deposition of platform-derived lime mud. Minor failures along the actively accreting margin also shed periplatform talus blocks and megaconglomerate into this regime. As the rate of carbonate accretion outpaced the rate of relative sea level rise, the margin prograded rapidly outward over the adjoining slope sediments. During this stage, the Assiniboine Embayment, and possibly the Stephen-Field Embayment, completely healed over. Such extensive lateral progradation of the outer Cathedral platform over unstable slope sediments made it vulnerable to large-scale collapse.

During late Cathedral time, a 200 m thick section of the outer Cathedral platform and part of the adjoining slope collapsed along a broad, slightly arcuate front, probably greater in length than the entire study area. Allochthonous material of all sizes was carried

¹ These oolite shoals are best documented near Field (McIlreath, 1977a), but have also been observed by the writer and by Aitken (in press, a) at Wedgewood Peak (section 15).

tens of kilometres downslope to be deposited as an immense olistostrome. Pre-existing lines of weakness orthogonal to the trend of the collapse led to the re-establishment of the Stephen-Field Embayment, and probably created the Natalko Embayment as well (Fig. 52). In the latter embayment, a prominent talus wedge (Cathedral megabreccia) was deposited immediately afterward in response to small-scale, retrograde failure of the slide scar headwall. In the Stephen-Field Embayment, the headwall remained stable, and maintained a near-vertical profile.

In the aftermath of the collapse, the truncated platform continued to aggrade and export lime mud, and the Takakkaw Tongue resumed its basinward expansion at the foot of the escarpment. Thereafter, incipient drowning of the platform and the subsequent, westward progradation of siliciclastic muds precipitated the decline and eventual demise of the Cathedral platform.

Incipient drowning of the Cathedral platform led to the establishment of deeper water conditions in the inshore basin, and the influx of minor amounts of fine-grained siliciclastic sediment (Narao Member of the Stephen Formation). Although the peritidal rim itself was not drowned, the export of carbonate mud was severely curtailed. In the Stephen-Field Embayment, this period was marked by the deposition of a minor successor carbonate apron, the Boundary Limestone.

The subsequent, rapid encroachment of siliciclastic muds over the Cathedral platform (Waputik Member of the Stephen Formation) presumably reflects a major paleoclimatic change that led to intensive weathering and erosion of the craton, and the release of large volumes of siliciclastic sediment. When the outer platform was finally

smothered by these muds, all carbonate sedimentation ceased on the slope, and deposition of the remaining "basinal" Stephen Formation ensued.

8.2.3 Remainder of Stephen deposition

The remainder of Stephen time witnessed the establishment of a broad, siliciclastic shelf bounded on the west by the inactive Cathedral Escarpment. The slope at the foot of the escarpment aggraded rapidly in response to efficient, off-shelf transport of siliciclastic mud. In the Stephen-Field Embayment, the shelf prograded westward over the site of the former escarpment, creating a broad area of relatively shallow-water deposition (Wapta Member; Aitken, in press, a). In the Natalko Embayment, deep-water conditions were maintained throughout this period. As the supply of terrigenous muds began to diminish, subtidal carbonate sediments again began to accumulate throughout the region, marking the commencement of a new phase of carbonate platform and slope sedimentation.

8.2.4 Tokumm sub-unit/Eldon-Pika deposition

With the return of shallow-water carbonate deposition on the platform, the siliciclastic shelf and adjoining, gently-dipping slope were transformed into a subtidal carbonate ramp. A ramp configuration is evident in the lower Eldon Formation in Biddle cirque, where burrow-mottled limestone passes gradually westward into limestone of deeper-water origin without a visible shelf-slope break (Plate 46). Initially, deep subtidal conditions prevailed on the ramp, as indicated by trilobites of deep-water affiliation in the "basal black limestone band" of the Eldon Formation (Fritz, 1990, p. 109).

Eventually, sediments built up to peritidal levels along the Kicking Horse Rim (Aitken, in press, a). Once established, peritidal deposition continued virtually unabated along this trend until the end of Waterfowl time (Fig. 16). The rim was breached only once in mid-Eldon time, when the Field Member was deposited during an incipient drowning event on the outer platform. Otherwise, the configuration of the Eldon-Pika platform was probably quite similar to the lower Cathedral margin. The platform had a peritidal rim, which was bounded on the east by an inshore basin dominated by subtidal carbonate sedimentation. A major carbonate apron, now known as the Tokumm sub-unit, accumulated southwest of the margin during this period.

Large volumes of periplatform lime mud were deposited on the slope by hemipelagic fallout and dilute turbidity currents in response to carbonate sediment overproduction and export from the adjoining Eldon-Pika platform. The scarcity of allochthonous calcarenites in this sequence suggests a strong shelfward component of sediment transport, typical of windward margins. Mass flows that did reach the upper slope apparently bypassed it to deposit most sand and coarser material beyond the limits of current exposure. Small-scale margin failures were also uncommon during this time, as indicated by the general rarity of periplatform talus blocks and megaconglomerate in the Tokumm sub-unit.

The precise platform-to-basin relationships during Eldon time will never be known, as much of the outer Eldon platform was removed by large-scale collapse along the intra-Tokumm megatruncation surface. As a result, the Tokumm sub-unit is composed of at least two discrete ribbon limestone packages separated by a significant, internal unconformity (Figs. 16, 46, 55). The lower package accumulated partly on a carbonate ramp, and partly

downslope from a peritidal margin during early Eldon time. The upper package accumulated in a large-scale slide scar, and is coeval with part of the lower Pika Formation (Fig. 16).

8.2.5 Vermilion sub-unit/Pika deposition

Sedimentation was abruptly interrupted by outer platform collapse along the sub-Vermilion megatruncation surface during mid-Pika time. The collapse front was at least 56 km wide, indicating that many cubic kilometres of debris must have hurtled down the slope to deposit an enormous olistostrome in the basin (Fig. 47).

The Vermilion sub-unit above the slide scar records a marked change in the style of slope sedimentation. In contrast to the extensive carbonate aprons that accumulated during earlier times, an argillite-dominated sequence was deposited. This succession is punctuated by some of the most spectacular features in the Chancellor: calcarenite-filled slide scars, periplatform talus blocks, and megaconglomerate. Collectively, these features imply a large degree of margin instability.

The abundance of argillite, particularly in the lower Vermilion sub-unit, is not easily explained. These sediments were deposited by dilute turbidity currents, and must have been derived from the adjoining platform (Section 4.3.3.1). At the time, the Pika shelf was the site of moderately deep subtidal carbonate sedimentation, and fine-grained siliciclastic sediments were largely confined to an inner detrital belt bordering the remote craton. The abundance of siliciclastic mud in the upper slope sequence implies the operation of an efficient bypassing mechanism, the exact nature of which remains to be determined.

Following outer platform collapse, a peritidal margin was re-established well back of its former position. Two parallel facies belts emerged at the seaward edge of the truncated margin: an outer belt of Epiphyton buildups, and an inner belt of carbonate sand shoals (Fig. 47). Once established, the margin began to prograde outward over the upper part of the slide scar. Minor gravity sliding affecting the outermost part of the margin contributed periplatform talus blocks and spectacular megaconglomerates to the adjoining slope (Plates 52-54). A few of these failures cut far enough back into the margin to tap the inner belt of carbonate sand shoals. The resultant slide scars were subsequently infilled by carbonate sand transported by high-concentration turbidity currents (Section 4.5.3).

The third, and final, outer platform collapse occurred during latest Pika time. It left behind a slide scar which, in the Verdant cirque area at least, had a near-vertical headwall. Subsequent small-scale failures of the rejuvenated margin at the crest of the escarpment contributed blocks to a prominent talus wedge, as well as to a series of major debris flows extending well downslope (Plates 52-54). The areally extensive megaconglomerate bodies and other allochthonous carbonate sediments at the top of the Vermilion sub-unit imply repeated margin failure near the end of Pika time. This may reflect a short-lived period of intense seismic activity.

8.2.6 Duchesnay unit/Arctomys deposition

Carbonate deposition ended over almost the entire platform area due to a sudden, regressive shift in the position of the cratonal shoreline some 600 km to the southwest of its former position (Fig. 12). A narrow shelf was established behind a carbonate barrier along

the Kicking Horse Rim, and became the site of very shallow, evaporitic, dominantly siliciclastic sedimentation (Aitken, 1978).

The precise platform-to-basin relationships during this period are not preserved. Clearly, the upper slope was no longer being bypassed by most sediment gravity flows, as indicated by the abundance of siliciclastic and carbonate turbidites in the Duchesnay unit. Instead, the slope aggraded due to the input of sediment gravity flows along a broad front. Once again, this implies the operation of efficient, off-shelf sediment transport processes. The relative scarcity of sedimentary features indicative of slope instability suggests that the slope was gentle. Thus, a low-angle depositional margin, on which sediment gravity flow deposits extended up to the shelf-slope break, is the most probable configuration.²

During Duchesnay unit time, the carbonate margin was probably dominated by carbonate sand shoals intermingled with a few Epiphyton buildups. This is suggested by the abundance of carbonate sand and silt turbidites in the Duchesnay unit, and by the fact that calcarenite clasts are usually much more abundant than Epiphyton boundstone clasts in debris flow deposits.

The outer platform drowning event that apparently preceded deposition of the Duchesnay unit in the Hamilton Lake and possibly Miller Pass areas (Section 6.5) is seemingly antithetical to the marked, regional regression indicated for the beginning of Arctomys/Duchesnay time. For this reason, the drowning event is best explained by local synsedimentary tectonism in the outer shelf region. As obvious evidence for synsedimentary tectonism is lacking (e.g. talus accumulations associated with fault scarps; abundant

² This would correspond in general form to the lime sand shoal-dominated depositional margin model of McIlreath and James (1984), and the slope apron model of Mullins and Cook (1986).

sediment failures related to seismicity), this postulated event may have occurred in response to variations in subsidence patterns, rather than by active surface faulting. Perhaps deep-seated faulting along old lines of weakness locally caused parts of the outer platform to subside faster than the regional rate.

8.2.7 Oke unit/Waterfowl deposition

At the beginning of Waterfowl time, widespread shallow-water carbonate deposition returned to the platform. Sedimentation alternated between repeated, tidal flat progradation over a shallow, aggraded platform, and subtidal deposition in a platform lagoon about 50-80 km wide (Waters, 1986).

The style of sedimentation that was introduced at the beginning of Duchesnay unit time continued during Oke unit deposition. Efficient, off-shelf sediment transport continued, and the deposition of carbonate silt and sand turbidites caused the slope to aggrade (Section 4.4.3). The abundance of allochthonous calcisiltite and calcarenite in this sequence suggests that the margin continued to be dominated by carbonate sand shoals. Meanwhile, the continued proximity of the cratonal shoreline ensured that siliciclastic silt and minor sand continued to reach the slope, presumably through a combination of marine and aeolian processes.

During Waterfowl time, part of the Waterfowl platform collapsed in the Hamilton Lake area. The areal extent of the postulated slide scar cannot be determined due to the vagaries of exposure. Following the collapse, the margin re-established itself at the top of a temporary bypass zone created by the upper part of the slide scar. The calcarenite and

subordinate Epiphyton boundstone blocks in the megaconglomerate a short distance above this surface confirm that the margin continued to be dominated by carbonate sand shoals and associated Epiphyton buildups. While the bypass zone continued to receive mainly siliciclastic muds, carbonate turbidite deposition caused the slope to aggrade until a low-angle depositional profile was re-established. This shelf-slope configuration persisted until the end of Waterfowl-Oke time.

8.2.8 Upper Chancellor/Sullivan deposition

Incipient platform drowning near the end of Waterfowl time (Waters, 1986) was followed by a rapid increase in the rate of relative sea level rise, and an accompanying influx of fine-grained siliciclastic sediment. The initial shelf-slope break of the newly formed Sullivan siliciclastic shelf presumably followed the edge of the former Waterfowl platform.

Off-shelf sediment transport was overwhelmingly predominant during Upper Chancellor/Sullivan time, causing the shelf to prograde rapidly basinward. Persistent tracts of carbonate sand shoals in high energy zones contributed enormous quantities of carbonate sand to the slope via high-concentration turbidity currents. The siliciclastic influx did not diminish until the deep-water trough was infilled to relatively shallow depths. As the siliciclastic influx began to diminish, the Lyell/Ottertail carbonate platform commenced its remarkable, westward progradation over the full width of the trough, marking the end of Chancellor deposition.

8.3 CONCLUSIONS

8.3.1 Stratigraphy

1. The Chancellor is a stratigraphic unit of Middle to Late Cambrian age that unconformably overlies the Gog Group, and is conformably overlain by the Ottertail Formation. It is coeval with an eastern shelf succession comprising eight carbonate and siliciclastic formations.
2. In and near the zone of facies change, the Chancellor is divisible into seven major stratigraphic units. Two have already been designated as formations (Naiset and "basinal" Stephen formations), and the remainder are deserving of that rank (Takakkaw Tongue, McArthur unit, Duchesnay unit, Oke unit, and upper Chancellor). As a consequence, the Chancellor succession must eventually be elevated to Group status.
3. The McArthur unit is divisible into the Tokumm and Vermilion sub-units. Both merit the rank of member in any subsequent formalization of Chancellor nomenclature.

8.3.2 Sedimentology

1. The Chancellor succession was deposited in a deep-water trough bounded by the Kicking Horse Rim to the northeast, Montania to the southeast, the Peace-Athabasca Arch to the northwest, and the Windermere High to the southwest.

2. In the study area, the Chancellor sequence accumulated in an upper slope environment bordering a series of carbonate and siliciclastic shelves. The deep-water sediments were deposited primarily by sediment gravity flows and hemipelagic fallout, and were derived almost exclusively from the shelf region.
3. Five basic lithofacies are present: argillite, ribbon calcilutite, ribbon calcisiltite, calcarenite, and conglomerate (including megaconglomerate). Due to the influence of depositional and diagenetic factors, each lithofacies is represented by a range of rock-types.
4. The **argillite lithofacies** encompasses finely laminated argillaceous argillite, laminated silty argillite, and laminated/crosslaminated argillaceous siltstone that were deposited largely by muddy and silty turbidity currents.
5. The sediments now incorporated in the **ribbon calcilutite lithofacies** were probably deposited by a combination of dilute turbidity currents and hemipelagic fallout, but owe their final appearance to diagenetic enhancement of one or more primary sedimentary rhythms.
6. The **ribbon calcisiltite lithofacies** is characterized by interbedded centimetre- to decimetre-scale carbonate silt turbidites and millimetre-scale terrigenous mud turbidites. The latter are identical to those in the argillite lithofacies.
7. The **calcarenite lithofacies** is represented by calcarenite beds and lenses that occur throughout the Chancellor succession, and by calcarenite-filled megachannels that occur mainly in the Vermilion sub-unit. These sediments were deposited by sandy,

high-concentration turbidity currents. The calcarenite-filled megachannels originated as slide scars, which acted as conduits for sand transport from the inner platform margin to the slope.

8. The **conglomerate lithofacies** encompasses four major categories of conglomerates. Three are classified on the basis of dominant clast type (limestone plates, limestone chips, or exotic blocks), and have predominantly muddy or dolomitic matrices. The fourth has a grainy matrix. The limestone plate conglomerate, limestone chip conglomerate, and megaconglomerate all show evidence of high matrix strength, and were thus deposited by debris flows. The grainy matrix conglomerate units were deposited by density-modified grain flows, or gravelly, high-concentration turbidity flows.

8.3.3 Evidence for large-scale outer platform collapse during Eldon/Pika time

1. The outer Eldon-Pika platform region is traversed by the intra-Tokumm, sub-Vermilion and intra-Vermilion megatruncation surfaces, all of which probably have areal extents greater than that of the entire study area. These features are inferred to be the upper parts of major slide scars formed by large-scale outer platform collapse, and are directly analogous to the collapse structures recently described from carbonate platforms in the Gulf of Mexico and Caribbean regions.
2. The megatruncation surfaces are generally listric in longitudinal profile, and visibly truncate up to 215 m of outer platform strata. At least one example is inferred from indirect evidence to have a relief of at least 360 m over its traceable extent.

Comparisons with slide scars of similar scale (in two dimensional profile) in modern carbonate and siliciclastic settings indicate that the megatruncation surfaces could extend 100 km or more along depositional strike, and several tens of kilometres across depositional strike.

3. Where preserved, the platformward ends of the megatruncation surfaces either level out and disappear imperceptibly into horizontally bedded platform strata, or form near-vertical headwalls. The lower parts of these surfaces are generally inclined at angles of less than 20°. Suitably oriented, pre-existing fractures or joints were probably the primary control on headwall declivity.
4. The megatruncation surfaces are directly overlain and onlapped by sediments of deep-water origin. Like the "zones of removal" found in the upper parts of modern slide scars, the surfaces are generally free of allochthonous debris.
5. The presence of these large-scale submarine unconformities has obvious implications for the regional stratigraphy, as different stratigraphic sections would be encountered at various points along the cross-sectional profiles of the megatruncation surfaces. Despite these complications, all of the key stratigraphic relationships observed in the study area can be distilled into a simple model.
6. Platform margin collapse on the scale indicated implies the presence of major olistostromes downslope. Although these are not exposed, they potentially have volumes of several tens of cubic kilometres, and probably contain allochthonous blocks from outer platform, platform margin, and upper slope settings.

7. The concept of outer platform collapse is also probably applicable to the Arctomys-Waterfowl margin near Hamilton Lake, where a sharp lithological contact superimposing deep-water sediments (including a laterally extensive megaconglomerate) over platform strata can plausibly be interpreted as a megatruncation surface. The regional significance of this feature is unclear due to a lack of other, strategically placed cross-strike exposures.

8.3.4 Implications for the Cathedral margin

1. The straight to slightly arcuate trace of the Cathedral margin is interrupted by three major, sharp-cornered embayments. The Stephen-Field Embayment probably originated from pre-Middle Cambrian block faulting, which may have continued during Cathedral and Stephen deposition. The Assiniboine Embayment probably had a similar origin. Both embayments probably healed over prior to late Cathedral time. The Nataiko Embayment affects only the upper Cathedral margin.
2. The Stephen-Field Embayment was probably re-established as a result of regional outer platform collapse during late Cathedral time. The Nataiko Embayment also formed during this regional collapse event. Both embayments are considered to be local notches in a regionally extensive slide scar.
3. The "new" and "classical" exposures of the Cathedral Escarpment are similar in that both are steep, dolostone walls about 200 m high that visibly truncate peritidal platform strata on one side, and are abutted by the upper Takakkaw Tongue and "basinal" Stephen Formation on the other.

4. In the Nataalko Lake/Monarch area, the Cathedral Escarpment is the headwall of a major slide scar formed by regional collapse of the Cathedral margin during late Cathedral time. The Cathedral megabreccia was deposited by a minor rockfall immediately after the main event. Upper Takakkaw Tongue sedimentation coincided with a short period of continued platform aggradation. Stephen siliciclastic muds eventually smothered the platform and entombed the escarpment.

5. The "classical" Cathedral Escarpment near Field is similarly interpreted as the headwall of a large-scale slide scar. It differs from the Nataalko Lake/Monarch exposure in that the truncated margin did not suffer a secondary collapse, and consequently maintained a near-vertical profile. Otherwise, the history of the Cathedral margin is rather similar to that inferred for the Nataalko Lake/Monarch area.

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PLATES

PLATE 1: ARGILLITE LITHOFACIES

NAISET FORMATION

- a: Vaguely laminated argillaceous argillite. Wedgewood Peak, section 15, 75.1-91.6 m; hammer 34 cm long.
- b: Chloritic spots and layers in argillaceous argillite. Wedgewood Peak, section 15, 23.1-67.1 m; scale in centimetres.
- c: Laminated argillaceous argillite with interlaminated, fine-grained quartz sand (light brown) commonly exhibiting low amplitude ripple crosslaminae. Wedgewood Peak, section 15, 23.1-67.1 m; scale in centimetres.
- d: Very thinly interbedded argillite (relatively resistant) and very fine- to fine-grained, burrowed sandstone (relatively recessive). The sandstone occurs as thin, irregular interbeds, stringers, and isolated burrow fills. The intensity of bioturbation was insufficient to disrupt the even, regular bedding. Upper Naiset Formation, Naiset Point, section 14, 89.2-145.9 m; hammer 34 cm long.

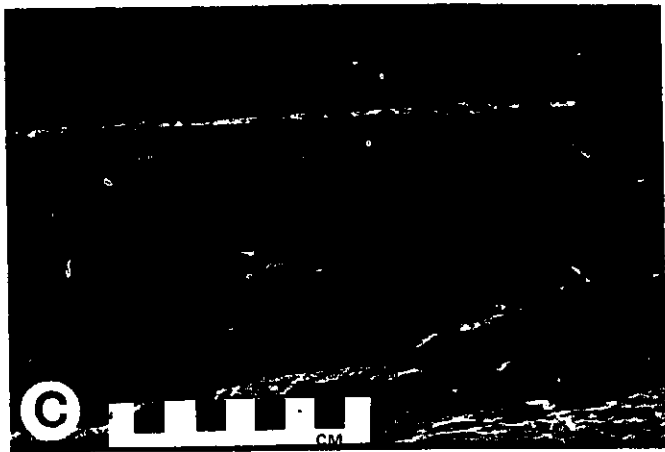


PLATE 2: ARGILLITE LITHOFACIES

NAISET FORMATION (CONTINUED)

- a: Closeup of argillite (dark grey) with irregular interbeds, stringers, irregular blobs and slightly compacted burrow fills of very fine- to fine-grained sandstone (brown). The irregular sandstone distribution is attributed to burrowing. Upper Naiset Formation, Naiset Point, section 14, 89.2-145.9 m; white card at lower right is 5.5 cm high.
- b: Horizontal Palaeophycus and vertical Skolithos burrows on bedding surface. Upper Naiset Formation, Wedge Gully, section 3, 90 m; scale in centimetres.
- c: Synsedimentary deformation (convolute bedding and recumbent synsedimentary folds). Basal Naiset Formation, North Gully, section 2; figure for scale.
- d: Intrafolial recumbent folds in very thinly interbedded and interlaminated sequence of argillite and burrowed sandstone. Features such as these suggest slope instability, and occur rarely in the upper Naiset. Wedgewood Peak, section 15, 96.1-109.3 m; scale in centimetres.

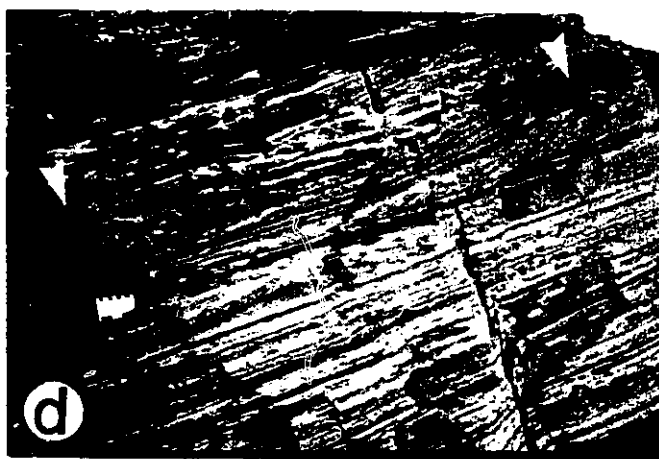


PLATE 3: ARGILLITE LITHOFACIES

"BASINAL" STEPHEN FORMATION

- a: Finely laminated dolomitic shale. In thin section, this rock type is composed of a series of graded laminae up to 5 mm thick. Fossil Gully, Mount Stephen, section AC-161/162, unit 2 of Aitken (in press, a); scale in centimetres.
- b: Laminated dolomitic argillite. In thin section, this rock type is composed of a series of graded laminae generally less than a centimetre thick. Each consists of a lower, dolomitic portion (orange brown-weathering), in which silt-sized carbonate grains have been completely replaced by phyllosilicates, and an upper, homogeneous clay portion (grey-weathering) containing abundant organic matter. Burgess Quarry, Fossil Ridge; scale in centimetres.
- c: Laminated dolomitic argillite in a polished, water-washed, natural outcrop. The dark laminae contain silt-sized, former carbonate peloids (now replaced by phyllosilicates), local quartz silt, organic matter, and disseminated dolomite crystals. They grade upward into lighter coloured, homogeneous clay with disseminated dolomite crystals. Lowermost "basinal" Stephen Formation, Big Fly Gully, Burgess Pass area, section MJA-727; scale in centimetres.
- d: Monotonous, massive argillite typical of the "basinal" Stephen Formation in the Natalko Lake/Monarch area. The Monarch (north face), section 22; figure for scale.

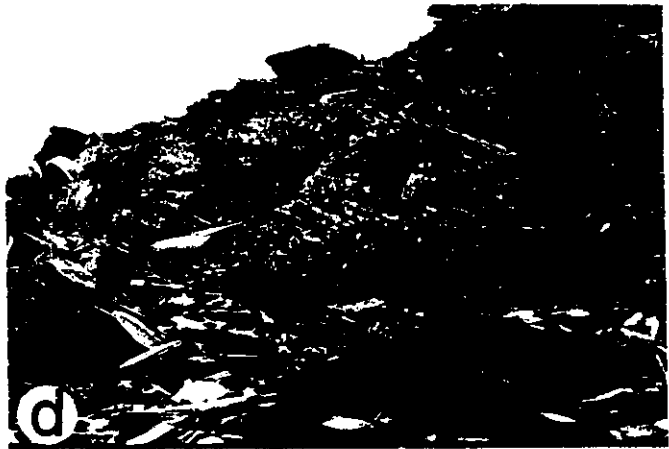


PLATE 4: ARGILLITE LITHOFACIES

"BASINAL" STEPHEN FORMATION (CONTINUED)

- a: Vaguely laminated to unlaminated dolomitic argillite. Remnant laminae in this and surrounding outcrops suggests that the original sediment was homogenized while still soft. Nataiko Lake, section 23, 140.5-163 m; scale in centimetres.
- b: Small-scale, recumbent folded zone overlying small-scale truncation surface. Host lithology is finely laminated argillite. Nataiko Lake, section 23, 81.8-115.2 m; scale in centimetres.

DISTAL EQUIVALENT OF THE NAISSET FM., TAKAKKAW TONGUE, AND "BASINAL" STEPHEN FM.

- c: Large-scale recumbent fold (horizontal axis shown by white line) in finely laminated slate. Roadside outcrop, 900 m north of Vermilion Crossing on Highway 93; pogo divisions each 0.5 m.
- d: Small-scale, intrafolial recumbent fold in finely laminated slate. Roadside outcrop adjacent to Vermilion Crossing bridge, Highway 93; scale in centimetres.
- e: Debris flow conglomerate overlain by synsedimentary deformed slate. Crack infilled by matrix in large clast (arrow) indicates sediment was partially lithified prior to transport. Roadside outcrop, 900 m north of Vermilion Crossing on Highway 93; scale in centimetres.

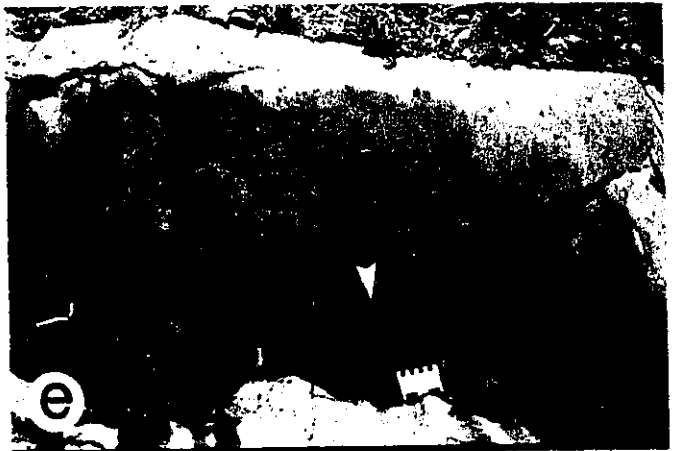
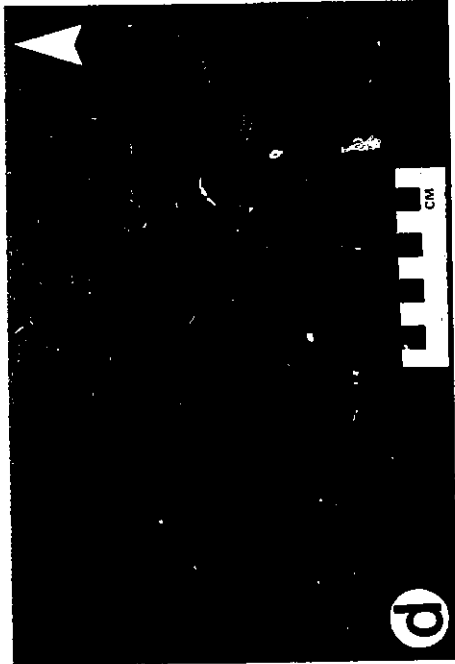
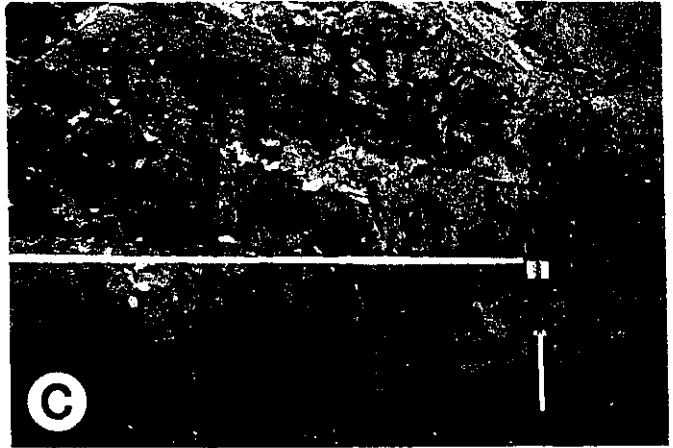


PLATE 5: ARGILLITE LITHOFACIES

TOKUMM SUB-UNIT

- a: Finely laminated argillite, composed of millimetre-scale Bouma $E_{\text{turbidite}}$ - Bouma $E_{\text{hemipelagite}}$ divisions. Microscopic horizontal burrows are also rarely present in this outcrop. Upper siliciclastic marker, Haffner Creek North, section 4, 45.7-62.9 m; scale in centimetres.
- b: Ribbon argillite. Recessive interbeds are composed of laterally continuous, structureless lime mudstone. Resistant argillite interbeds are identical to (e) below. Upper siliciclastic marker, Prospectors Valley 1, section 9, 188.1-221.5; hammer 34 cm long.
- c: Small-scale, hummocky cross-stratified dolosiltite. Low angle truncation of laminae is indicated by arrows. This is the only known example of HCS in the Chancellor. The Monarch (north face), section 22, 228-237.6 m; scale in centimetres.

VERMILION SUB-UNIT

- d: Dolomitic ribbon to nodular argillite. The nodules are composed of structureless lime mudstone. The relatively resistant argillite interbeds are identical in composition to (e) below. Verdant Headwaters North, section 34, 85.7-89.9 m; hammer 34 cm long.
- e: Finely laminated dolomitic argillite. The dark laminae contain quartz and dolomite silt in a matrix composed of clay with abundant streaks of organic matter, and grade upward into homogeneous clay with disseminated dolomite. As in (a) above, these millimetre-scale cycles are composed of the Bouma $E_{\text{turbidite}}$ and Bouma $E_{\text{hemipelagite}}$ divisions. Prospectors Valley 1, section 9, 368.8-374.7 m; scale in centimetres.

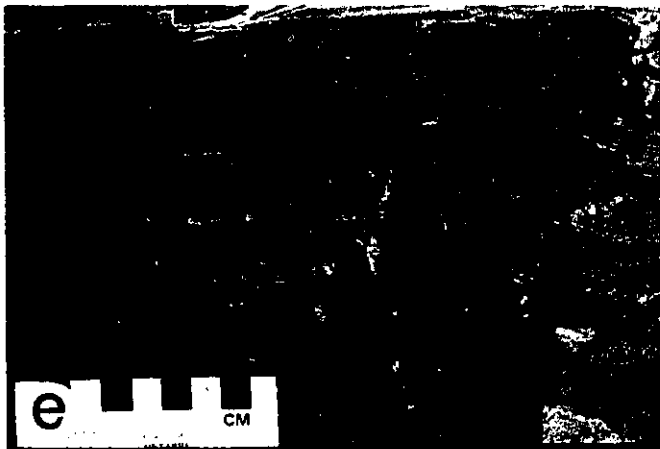


PLATE 6: ARGILLITE LITHOFACIES

VERMILION SUB-UNIT (CONTINUED)

- a: Finely laminated, dolomitic argillaceous siltstone/silty argillite (lower orange-brown weathering unit), identical to (b) below. Note sharp contact with overlying irregular ribbon limestone. Haffner Creek North, section 4, 275.3-276.9 m; pogo divisions each 0.5 m.
- b: Finely laminated dolomitic argillaceous siltstone/silty argillite, composed of silt-sized quartz and ferroan dolomite in a clay matrix. Also present are relatively thin clay interlaminae containing disseminated ferroan dolomite. Haffner Creek South, section 29, 261.2-262 m; scale in centimetres.
- c: Irregular to nodular ribbon argillite in an internally deformed, probable slide mass. The deformed zone overlies undisturbed sediment, and has a sharp, flat base (arrow at lower left). The most intensely deformed part is a chaotic mixture of limestone nodules in a homogenized argillite matrix (immediately above pogo head). The top of the slide mass is not exposed. Haffner Creek North, section 4, 223.7-229.6 m; pogo divisions each 0.5 m.
- d: Recumbent folded zone (hinge zone indicated by arrow) in laminated dolomitic argillite overlying massive limestone conglomerate (C). The lower limb of the fold is truncated. Laterally, the same stratigraphic interval passes into chaotic, small-scale folds. Haffner Creek North, section 4, 219-221.5 m; pogo divisions each 0.5 m.
- e: Intrafolial recumbent fold in dolomitic ribbon argillite. In this example, there is no obvious truncation surface, and the fold may have formed in response to subsurficial shear, rather than from surface sliding. Prospectors Valley 1, section 9, 387.8-393.6 m; scale in centimetres.



PLATE 7: ARGILLITE LITHOFACIES

DUCHESNAY UNIT

- a: Massive dolomitic argillite. Laminae and convolute laminae occur rarely, but for the most part this rock type is homogeneous. Mt. Dennis North, 391.1-428.6 m; figure for scale.
- b: Strongly cleaved dolomitic argillite, with pod of limestone conglomerate containing granule- to pebble-sized, tabular lime mudstone clasts. Mt. Dennis South, section 8, 367.2-380 m; scale in centimetres.
- c: Laminated/crosslaminated argillaceous siltstone, composed of interlaminated ripple crosslaminated, horizontal laminated, and structureless zones. These can be shown to be organized into incomplete Bouma sequences, most commonly Bouma CDE. Mt. Oke 2, section 7, 183.5-189.2; scale in centimetres.
- d: Laminated/crosslaminated argillaceous siltstone, similar to (c) above. Arrows indicate relatively large-scale starved ripples, consistently oriented to the left. They are draped by the overlying sediments. Mt. Oke 2, section 7, 136.5-139.6 m; scale in centimetres.



PLATE 8: ARGILLITE LITHOFACIES

DUCHESNAY UNIT (CONTINUED)

- a: Dark grey shale, with nodules and interbeds of partly silicified, intraclast grainstone. Misko Mountain, section 16, 9.1-15.7 m; scale in centimetres.
- b: Finely laminated, monotonous, green silty argillite. Evidence for slope instability is almost totally lacking in this sequence. The alternating dark and light coloured laminae are inferred to be Bouma E_{turbidite} and Bouma E_{hemipelagite} divisions respectively. A photomicrograph of a sample from this outcrop is shown in Plate 10d. Hamilton Lake North, section 31, 37.8-39 m; hammer 34 cm long.
- c: Ribbon to nodular argillite, locally grading to ribbon limestone. Limestone nodules and interbeds are structureless lime mudstone. Bedding plane exposures of this outcrop exhibit vertical and horizontal burrows. Hamilton Lake North, 110-121.2 m; scale in centimetres.
- d: Finely laminated dolomitic ribbon argillite. Large quantities of trilobites, hyolithids, and the remains of soft-bodied organisms have been recovered from talus derived from this unit. Basal Duchesnay unit, Miller Pass 1, section 12; scale in centimetres.
- e: Unclassified soft-bodied arthropod from basal Duchesnay unit; Miller Pass 1, section 12. This specimen (about 5 cm long) is currently being studied at the Royal Ontario Museum.

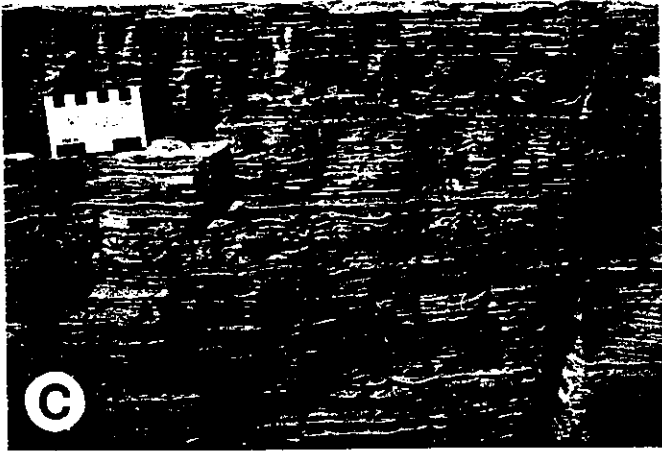


PLATE 9: ARGILLITE LITHOFACIES

UPPER CHANCELLOR

- a: Interbedded grey-weathering, laminated slate and brown-weathering, dolomitic slate. Both contain spaced, very thin interbeds of dolomitic lime mudstone. Mt. Hurd, north face; hammer (circled) 34 cm long.
- b: Laminated calcareous slate with minor, thin interbeds of lime mudstone and dolostone; Mt. Oke 2, section 7, 524.1-538.6 m; outcrop about 5 m high. In the background on the opposite (northeast) side of the valley (about 5 km distant) are grey-weathering sandstones of the Gog Group (G), which are overlain by reddish- and light grey-weathering, platform carbonates of the Cathedral Formation (C).

PHOTOMICROGRAPHS

- c: **Upper Naiset Formation:** calcite-cemented, sandy, burrowed laminae and sand-filled burrows (S) in an argillite matrix (A). Wedge Gully, section 3, 95.6-97.4 m; scale bar is 2 mm.
- d: **"Basinal" Stephen Formation:** normally graded laminae in silty argillite. Siliciclastic silt is notably rare. The grains are chiefly former carbonate peloids and skeletal fragments that have been replaced by phyllosilicates. The upper parts of the laminae contain silty clay and pervasive, probable organic matter. Abundant ferroan carbonate crystals are disseminated throughout. Nataiko Lake, section 23, 115.2-127.8 m; scale bar is 1 mm.
- e: **Vermilion sub-unit:** alternating dark and light laminae. The dark, silty laminae are pervasively lined with dark brown to black organic matter. The light laminae consist of homogeneous clay with minor streaks of organic matter. Haffner Creek North, section 4, 147.4-159.8 m; scale bar is 500 microns.

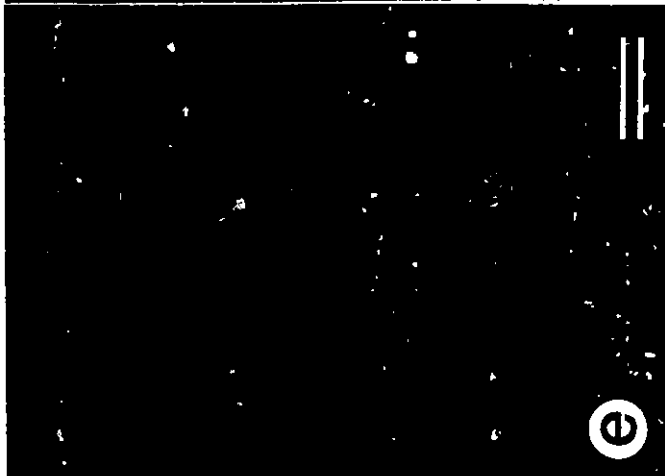
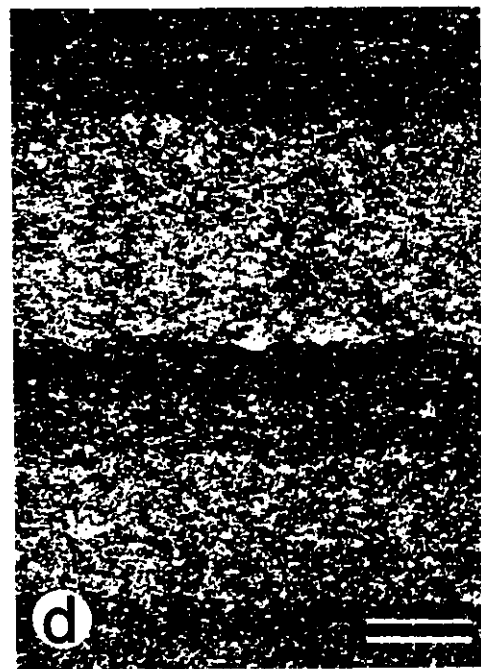
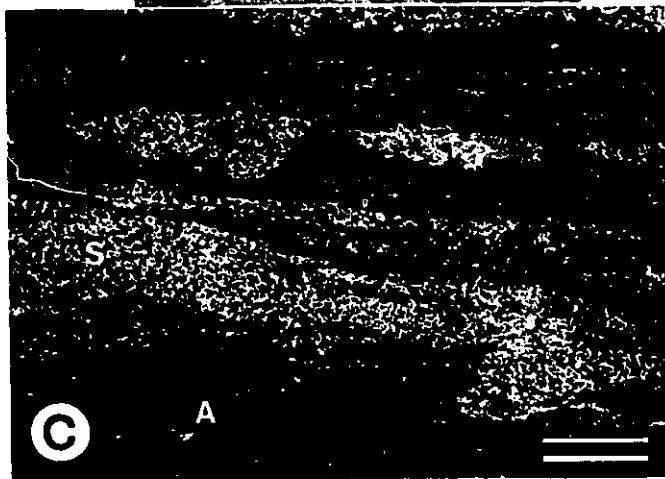


PLATE 10: ARGILLITE LITHOFACIES

PHOTOMICROGRAPHS (CONTINUED)

- a: **Vermilion sub-unit:** graded mud. Lower, darker portion (1) contains minor siliciclastic silt, chlorite grains, and scattered ferroan dolomite crystals. It passes upward via a series of vaguely to well defined laminae (2) into a lighter, homogeneous clay with scattered flakes of organic matter (3). The upper organic-rich layer (arrow) appears to mark the base of another, subtly graded layer. Haffner Creek North, section 4, 147.4-159.8 m; scale bar is 1 mm.
- b: **Vermilion sub-unit:** cloudy core, clear rim (CCCR) dolomite in a dolomitic argillaceous siltstone (arrows). The blue rims and patches are ferroan dolomite. Elsewhere, this rock contains appreciable siliciclastic silt and stringers of organic matter. Prospectors Valley 1, section 9, 383.5-386.5 m; scale bar is 50 microns.
- c: **Duchesnay unit:** laminated argillaceous siltstone. Silt to very fine sand laminae cemented by ferroan calcite alternate with darker, less silty laminae, in which clay minerals are distributed along microscopic cleavage planes. The primary layering has been obscured, but not destroyed, by incipient metamorphism. Haffner Creek North, section 4, 429.6-432.0 m; scale bar is 1 mm.
- d: **Duchesnay unit:** Laminated silty argillite, composed of millimetre- to sub-millimetre-scale silt/clay couplets. The silty laminae contain siliciclastic silt and silt-sized, ferroan dolomite crystals in a clay matrix (1). They either grade or pass fairly sharply upward into homogeneous clay laminae with scattered siliciclastic silt and minor, disseminated ferroan dolomite crystals (2). This specimen comes from the outcrop shown in Plate 8b. Hamilton Lake North, section 31, 37.8-39 m; scale bar is 1 mm.
- e: **Duchesnay unit:** vaguely laminated argillaceous siltstone. Argillaceous silty layers (1) alternate with silty argillite layers with pervasive, probable organic matter (2). Ferroan carbonate crystals are disseminated throughout. Verdant Headwaters South, section 34, 167.2-173 m; scale bar is 500 microns.

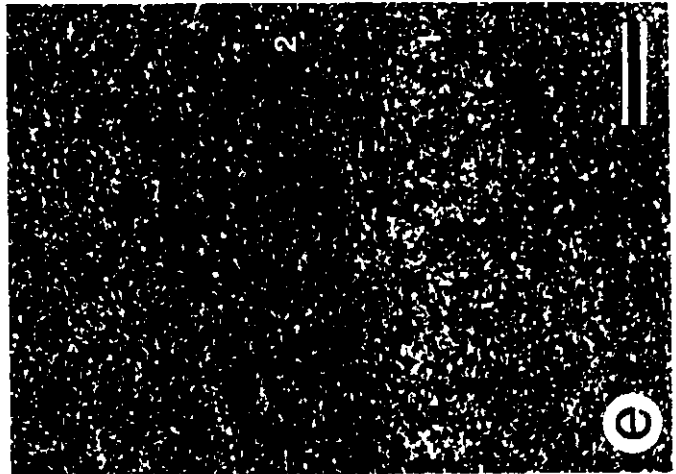
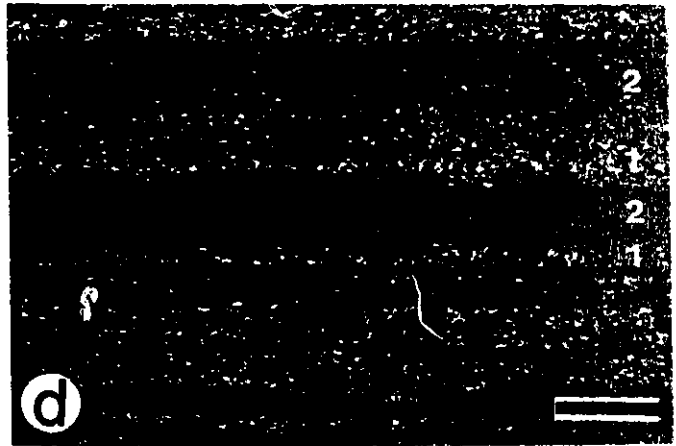
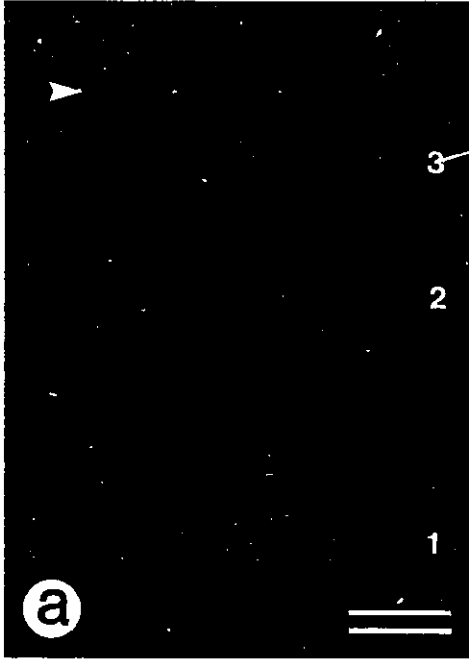


PLATE 11: RIBBON CALCILUTITE LITHOFACIES

TAKAKKAW TONGUE

- a: Monotonous, thin-bedded ribbon calcilutite. Massive bed (C) is a limestone conglomerate, which has a nearly flat base and irregular top. Fossil Gully, Mt. Stephen, near Takakkaw Tongue type section of Aitken (in press, a). Person is 1.7 m tall.
- b: Ribbon calcilutite with orange-brown-weathering dolomite interbeds and interlaminae. Faint, sometimes slightly dolomitic laminae are visible in the lime mudstone interbeds. Natalko Lake, section 23, 64.9-81.8 m; hammer 34 cm long.

TOKUMM SUB-UNIT

- c: Monotonous, thin-bedded ribbon calcilutite. Southwest side Prospectors Valley, cliffs overlooking Marble Canyon; scale card (circled) is 9 cm wide.
- d: Planar to slightly irregular bedded ribbon calcilutite with internally laminated dolostone interbeds and interlaminae. Curtis Cirque, section 21, 102.6-132.2 m; top of pogo for scale.
- e: Fitted nodular texture in ribbon calcilutite with shaly partings. Southwest side of Prospectors Valley, cliffs overlooking Marble Canyon; scale in centimetres.

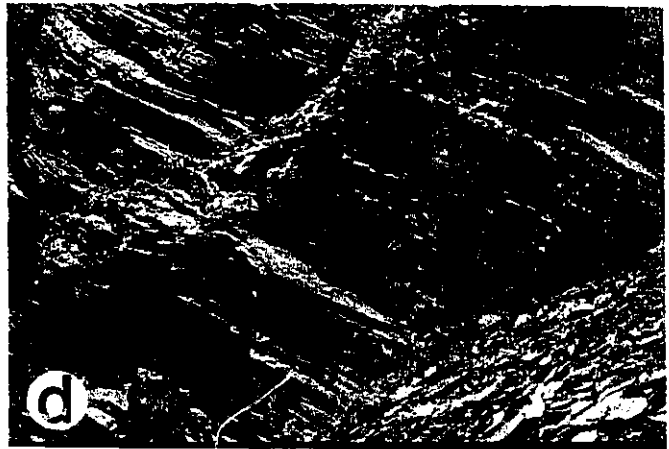


PLATE 12: RIBBON CALCILUTITE LITHOFACIES

VERMILION SUB-UNIT

- a: Ribbon calcilutite with finely laminated dolostone interbeds. Haffner Creek North, section 4, 253.5-260.4 m; scale in centimetres.
- b: Ribbon calcilutite with black, laminated argillite interbeds and interlaminae. A photomicrograph of a sample from this outcrop is shown in Plate 15c. Haffner Creek North, section 4, off line of section; scale in centimetres.
- c: Irregular ribbon calcilutite. Laminated dolomitic argillite (slightly more resistant) is irregularly interbedded with wavy to nodular lime mudstone. Haffner Creek North, section 4, 237.9-242.1 m; scale in centimetres.
- d: Stratigraphically confined, irregular ribbon calcilutite (between arrows). Dolomite (slightly more resistant) forms a highly irregular network around limestone nodules, imparting a clast-like texture. The lack of an obvious truncation surface suggests that the deformation may have been due to subsurficial shear. Southwest side Prospectors Valley, cliffs immediately upstream of Marble Canyon; scale in centimetres.
- e: Irregular ribbon calcilutite characterized by irregular to stringy dolomite layers (light colour). Synsedimentary deformed layers and intraformational truncation surfaces occur elsewhere in the same unit. Prospectors Valley 3, section 11, 69.7-83.7 m.

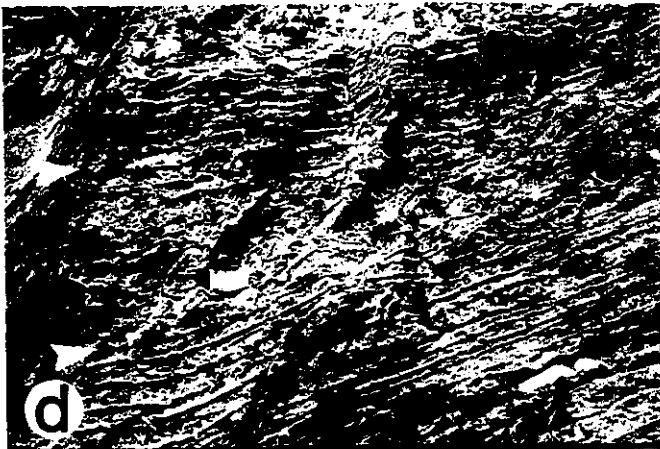
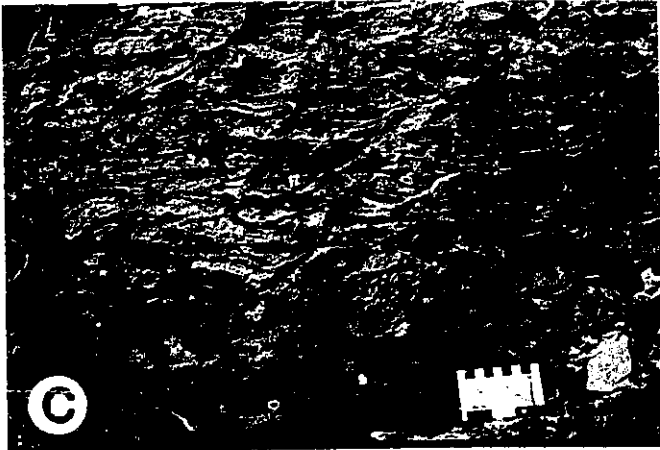
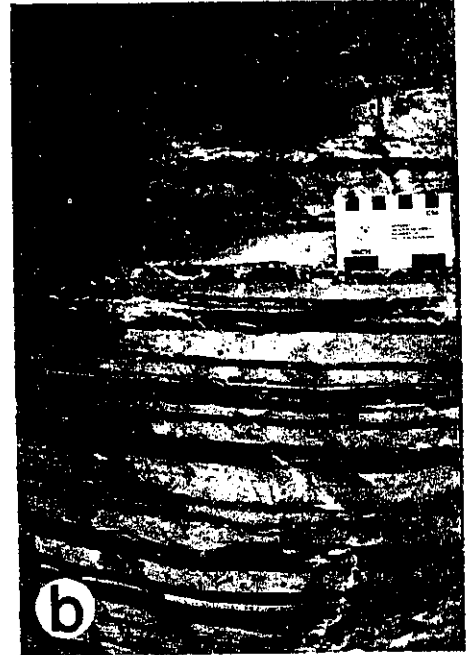


PLATE 13: RIBBON CALCILUTITE LITHOFACIES

EVIDENCE FOR SLOPE INSTABILITY: SYNSEDIMENTARY DEFORMATION

- a: Small, rotated block detached from a lime mudstone interbed in a ribbon calcilutite sequence. Convex-downward laminae in the wedge-shaped dolomitic fill at right (arrow) suggest that non-cohesive sediment infiltrated into the crack at the sediment-water interface. Brittle failure of the limestone indicates lithification at or immediately below the sea floor. Tokumm sub-unit, Prospectors Valley 3, section 11, 88.5-114.7 m; scale in centimetres.
- b: Probable pull-apart features. Slight downslope extension caused brittle failure of semi-lithified lime mudstone (grey). Gaps were infilled by dolomitic material. Fine, horizontal laminae are lost at the margin of the gap infill (arrow). Tokumm sub-unit, southwest side Prospectors Valley, cliffs overlooking Marble Canyon; scale in centimetres.
- c: Tight, double recumbent fold in ribbon calcilutite. The grey limestone beds broke brittly around the fold hinges (arrowed), and in places along the limbs. Spaces between the clasts were infilled by dolomitic material. If deformation had continued, this unit would have evolved into a debris flow, as suggested by the texture at right. Tokumm sub-unit, southwest side Prospectors Valley, cliffs overlooking Marble Canyon; scale in centimetres.
- d: Internally deformed slide mass (SM) composed of ribbon calcilutite. This body is overlain by undeformed strata of the same composition. Tokumm sub-unit, southwest side Prospectors Valley, cliffs overlooking Marble Canyon; hammer 34 cm long. Arrow indicates way up.
- e: Coherent ribbon calcilutite slide block (margins indicated by arrows), surrounded by slightly irregular sediments of the same lithofacies. Tokumm sub-unit, southwest side Prospectors Valley, cliffs overlooking Marble Canyon; scale card is 9 cm long.

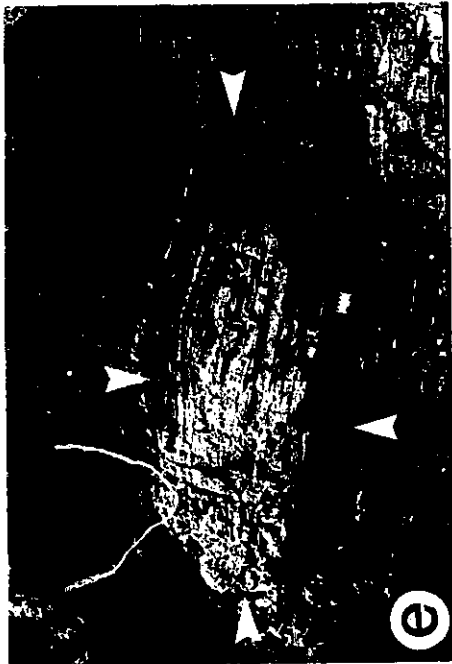
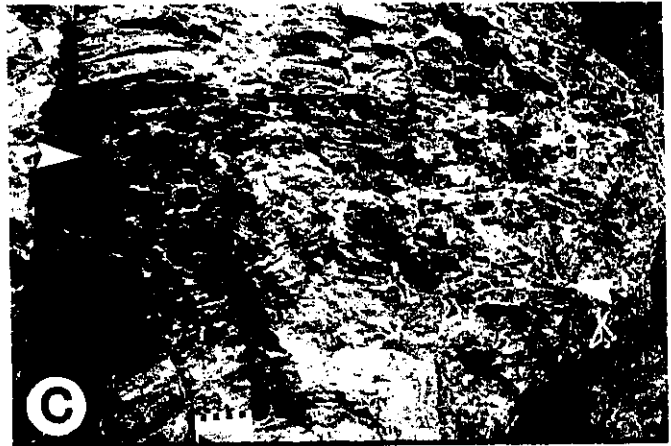
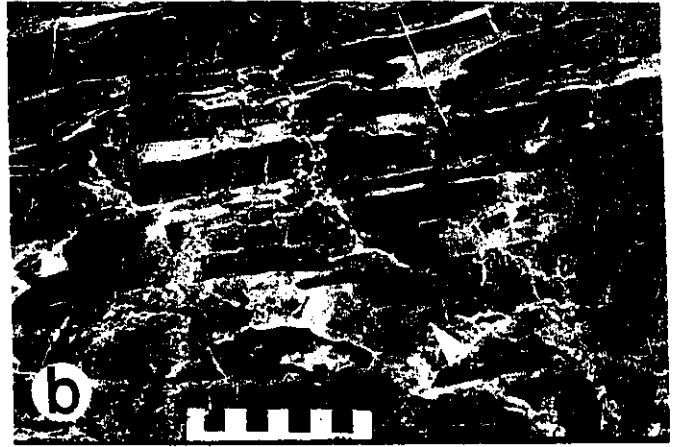
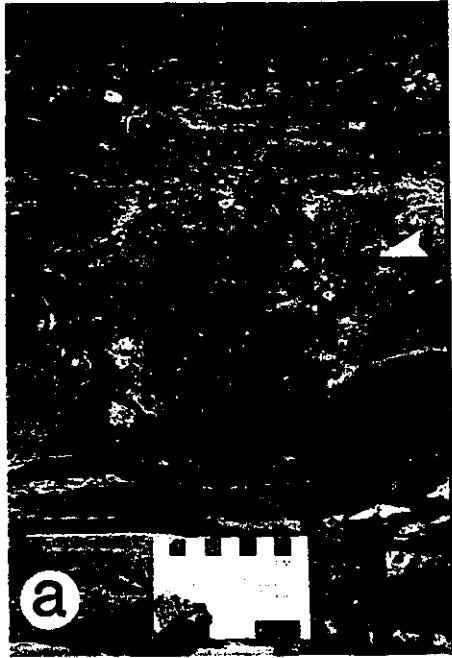


PLATE 14: RIBBON CALCILUTITE LITHOFACIES

EVIDENCE FOR SLOPE INSTABILITY: INTRAFORMATIONAL TRUNCATION SURFACES

- a: Small-scale intraformational truncation surface (arrowed). Note the smooth truncation of the underlying strata, the wedge-shaped geometry of the overlying fill, and the manner in which the surface merges with horizontal bedding at both its upper and lower ends. Tokumm sub-unit, southwest side Prospectors Valley, cliffs overlooking Marble Canyon; scale in centimetres.
- b: Medium-scale intraformational truncation surface (arrowed). Strata above and below consist of slightly irregular bedded ribbon calcilutite. The surface merges with regional horizontal bedding at both ends. Tokumm sub-unit, southwest side Prospectors Valley, cliffs overlooking Marble Canyon; hammer 34 cm long.
- c: Medium-scale intraformational truncation surfaces (two sets of arrows). The lower surface is bounded on either side by ribbon calcilutite (RL). The upper surface is overlain by massive dolomitic argillite (A). Tokumm sub-unit, Curtis cirque, section 21, 56.1-73.9 m; height of outcrop shown about 5 m.
- d: Large-scale intraformational truncation surface (arrowed), cutting downward into horizontally bedded ribbon calcilutite. The surface is overlain by broadly folded ribbon calcilutite. The deformed unit is in turn sharply overlain by horizontally bedded ribbon calcilutite (just above top of photo). Tokumm sub-unit, Haffner Creek North, section 4, 87-94.5 m; pogo divisions each 0.5 m.

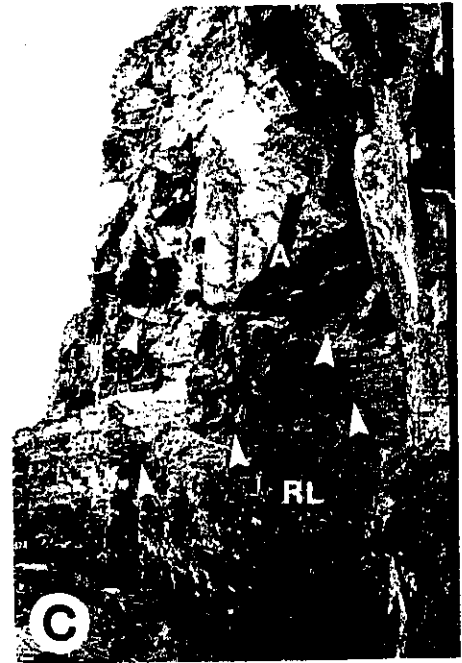
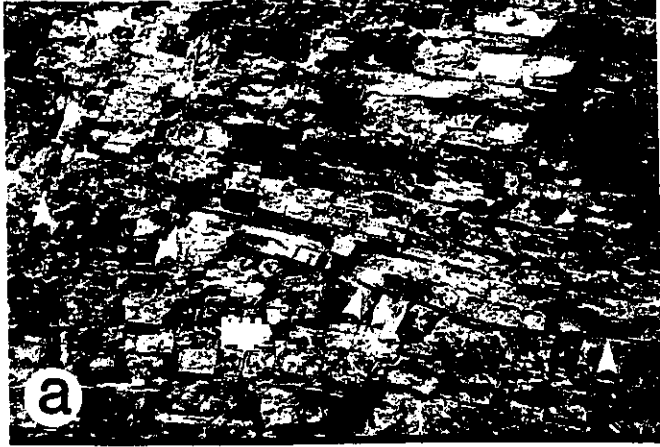


PLATE 15: RIBBON CALCILUTITE LITHOFACIES

PHOTOMICROGRAPHS

- a: Ribbon calcilutite with dolomitic interlaminae. Limestone beds (L) are non-ferroan microspar and pseudospar with disseminated, anhedral to subhedral dolomite crystals. A fine network of dolomite also follows the margins of the calcite crystals. The dolomitic layer (D) is composed of slightly ferroan dolomite crystals and non-ferroan microspar/pseudospar identical to that found in the adjoining limestone. Tokumm sub-unit, Prospectors Valley 2, section 10, 192.2-216.9 m; scale bar is 1 mm.
- b: Closeup of margin of dolomitic layer. Non-ferroan microspar (lower part of photo) contains disseminated, subhedral to euhedral, non-ferroan dolomite. The dolomite increases in proportion towards the margin of the dolomitic layer, and ferroan microspar appears (level of lower arrow). The dolomitic layer is composed of anhedral to subhedral ferroan dolomite crystals surrounded by ferroan calcite. Dark, concentrated layers of organic matter (OM) are also present. Tokumm sub-unit, Haffner Creek North, section 4, 0-33.9 m; scale bar is 500 microns.
- c: Ribbon calcilutite with argillaceous argillite layers (A) displaying graded laminae. Dark layers (arrows) contain stringers of undifferentiated organic matter. Boundary with limestone layer (L) is sharp and irregular on a microscopic scale. The outcrop from which this sample was obtained is illustrated in Plate 12b. Vermilion sub-unit, Haffner Creek North, section 4, off line of section; scale bar is 2 mm.
- d: Rapid gradation from argillaceous microspar (L) to a pervasively dolomitized argillite interbed (A) in a ribbon calcilutite. The limestone layer is composed of about 65% ferroan and non-ferroan microspar, and 35% non-ferroan dolomite. It also has a pervasive, microscopic cleavage lined with clay minerals. The dolomitized argillite layer contains about 50-60% ferroan dolomite crystals. Duchesnay unit, Mt. Dennis South, section 8, 19.8-54.2 m; scale bar is 500 microns.
- e: Poorly preserved peloids scattered throughout a limestone interbed in a ribbon calcilutite sequence. Poorly preserved internal structures suggest that some of the grains are oolites. Many of the peloids are selectively replaced by dolomite or ferroan calcite. The protolith for this rock was probably packstone or wackestone. Curtis cirque, section 21, 93.1-101.8 m; scale bar is 500 microns.

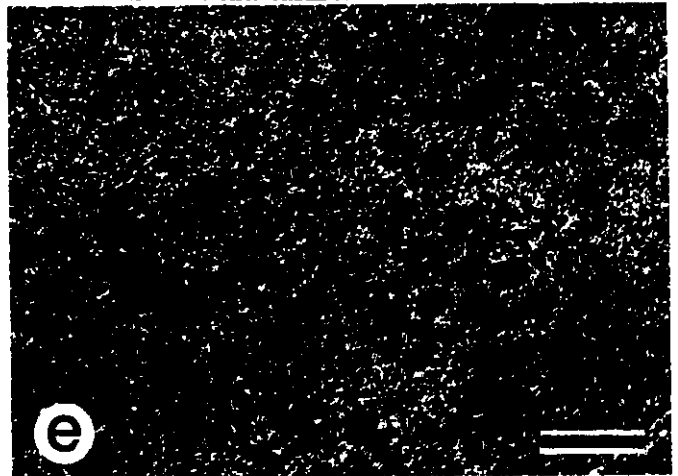
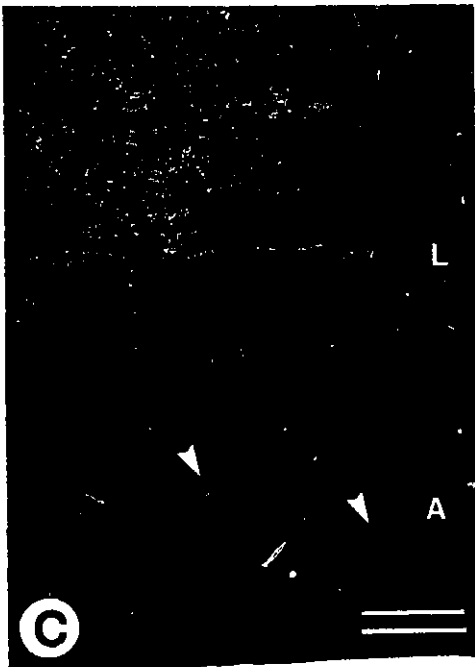
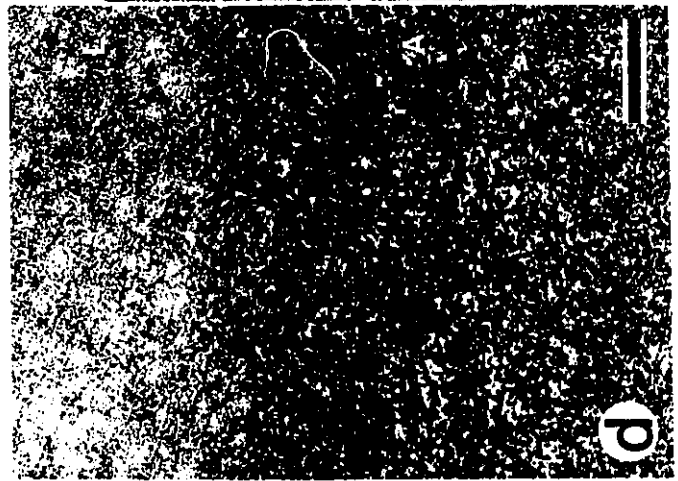
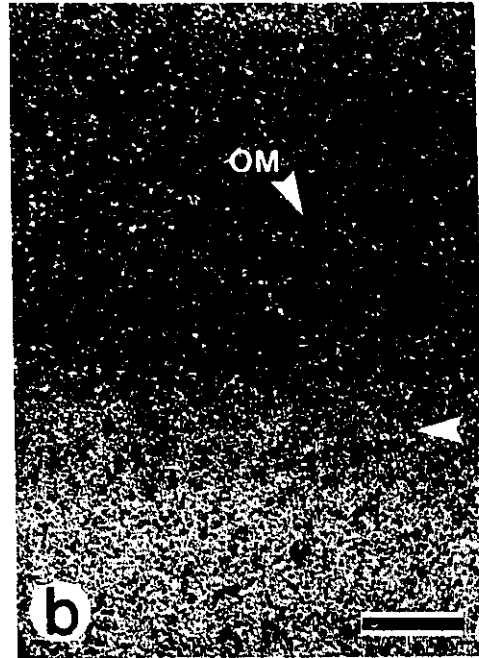
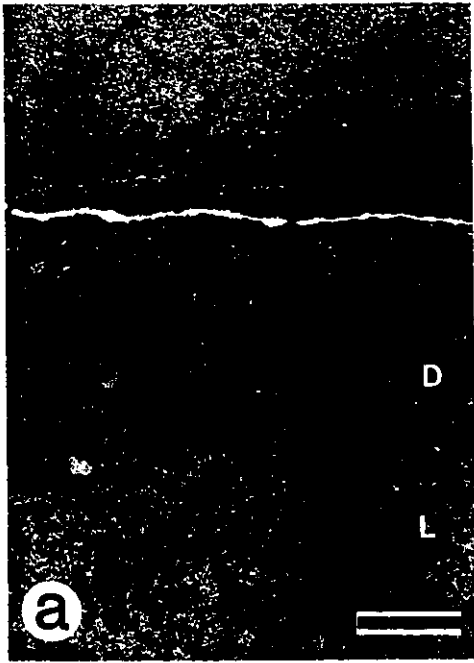


PLATE 16: RIBBON CALCISILTITE LITHOFACIES

OKE UNIT

- a: Ribbon limestone with predominantly lime mudstone interbeds. Some of these beds contain silty and dolomitic laminae at their bases. Others contain thin layers and lenses of parallel laminae or crosslaminae. The limestone is interbedded with laminated dolomitic argillite. Misko Mountain, section 16, 283.6-287.1 m; hammer 34 cm long.
- b: Closeup of outcrop similar to that illustrated in (a) above. The limestone interbeds are predominantly lime mudstone, but contain parallel laminae (L) and local isolated ripples (R). Misko Mountain, section 16, 266.6-270.4 m; scale in centimetres.
- c: General appearance of ribbon calcisiltite lithofacies in upper Oke unit. Despite the overall ribbon appearance, the dolomitic interbeds are actually quite irregular. Note the abrupt contact with brown-weathering, dolomitic slate (S). Mt. Oke 2, section 7, 328.7-349.4 m. About 6 m of ribbon calcisiltite section are shown.
- d: Closer view of ribbon calcisiltite. The limestone interbeds are composed largely of lime mudstone, but also contain parallel laminated and crosslaminated layers (not visible in this photo). Mt. Oke 2, section 7, 328.7-349.4 m; figure for scale.
- e: Ribbon calcisiltite (RL) in which the limestone component is subequal or slightly subordinate to the dolomitic argillite component. Above is a clast-supported limestone conglomerate with an argillaceous dolomite matrix. The variously shaped clasts are composed of a mixture of lime mudstone and laminated or crosslaminated calcisiltite. Maximum clast size is 70x35 cm. Misko Mountain, section 16, 314.2-321.4 m; for scale, conglomerate unit is 2.2 m thick.

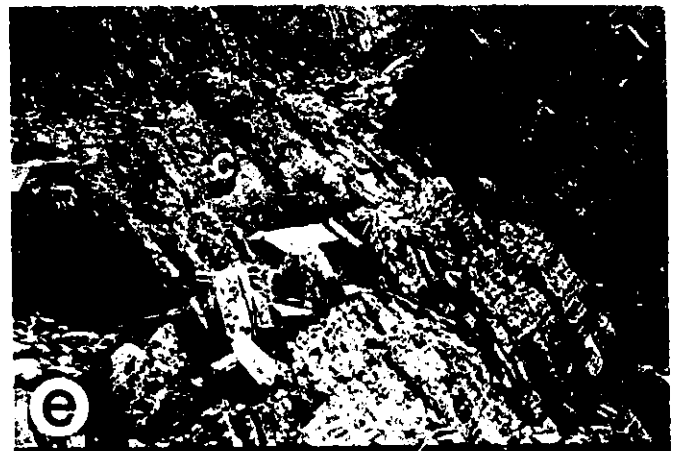
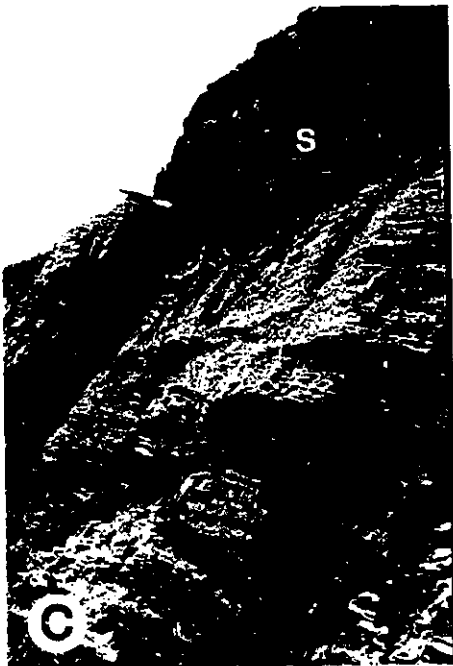
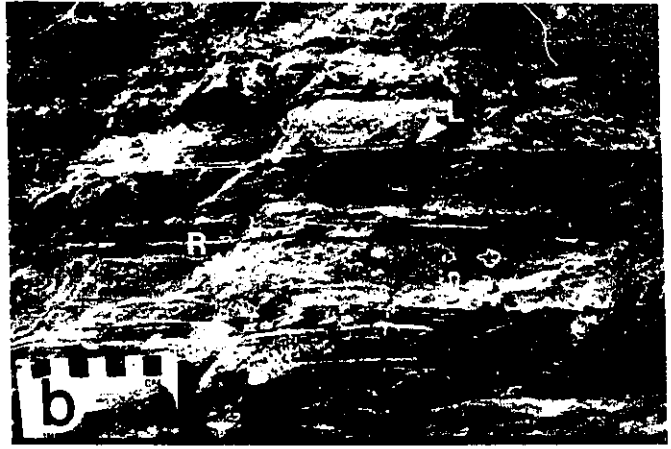


PLATE 17: RIBBON CALCISILTITE LITHOFACIES

OKE AND DUCHESNAY UNITS

- a: Detail of millimetre-scale cycles in pervasively dolomitized argillite (A). A photomicrograph of this rock is shown in Plate 20d. The limestone interbeds are composed of parallel laminated and crosslaminated calcisiltite and massive lime mudstone. The wavy bed near the top of the photo (arrow) contains ripple form sets. Oke unit, Mt. Oke 2, section 7, 458.5-494.6 m; scale in centimetres.
- b: Bouma sequences in calcisiltite. The lower part of this exposure contains sets of graded laminae (GL) which pass upward into structureless lime mudstone (M). Above are two, more complete turbidites. The lower turbidite has a relatively coarse, sandy, massive base (A division), which is followed upward by the parallel laminated (B) and ripple crosslaminated (C) divisions. The A division in the upper sequence sits in a local scour (arrow), and is succeeded by the parallel laminated (B) and ripple crosslaminated (C) divisions. The upper sequence is capped by massive, dark grey lime mudstone. Duchesnay unit, Mt. Oke 2, section 7, 105.3-117.4 m; scale in centimetres.
- c: Sedimentary structures in ribbon calcisiltite. (1) dolomitic parallel laminae (l) are truncated by ripple form set (r), which in turn is overlain by and appears to fade into lime mudstone (arrow at left); (2) dolomitic parallel laminae pass upward into massive, dolomitic lime mudstone; (3) dolomitic parallel laminae succeeded by rippled horizon and subtly laminated lime mudstone; (4) graded laminae (sensu Piper 1972b), succeeded by structureless lime mudstone. Oke unit, Mt. Oke 2, section 7, 328.7-349.4 m; scale in centimetres.
- d: Bouma ABCDE calcisiltite in dolomitic argillite sequence. Note the scoured and loaded base (arrow); normal size grading; climbing ripples in C division; and lateral dolomitization of the sequence. The thin, massive lime mudstone (E division, straddling horizontal crack) is capped by an isolate ripple form (r). Duchesnay unit, Mt. Oke 2, section 7, 105.3-117.4 m; scale in centimetres.

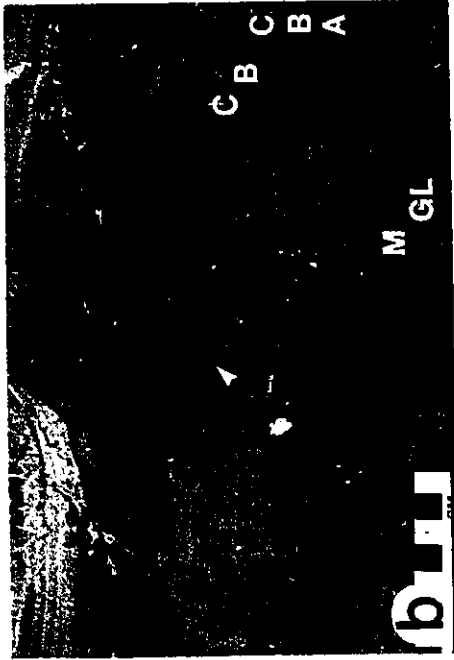


PLATE 18: RIBBON CALCISILTITE LITHOFACIES

OKE UNIT (CONTINUED)

- a: Parallel laminae (Bouma B division) overlain by climbing ripples (Bouma C division) in ribbon calcisiltite sequence. Mt. Oke 2, section 7, 410.4-417.3 m; scale card is 9 cm wide.
- b: Deformed ripple sets and other sedimentary structures in a ribbon calcisiltite sequence. 1: graded laminae succeeded upward by slightly deformed ripple crosslaminae that appear to fade laterally into lime mudstone (arrow). The crosslaminated layer is capped by lime mudstone. 2: climbing ripple form sets with deformed and oversteepened crosslaminae (r). The ripples are draped by lime mudstone with minor graded laminae. Mt. Oke 2, section 7, 328.7-349.4 m; scale in centimetres.
- c: Graded lime mudstone with superimposed ripple form sets (r). The upper rippled layer contains deformed ripple crosslaminae, and has an erosional base. Also visible in this outcrop are loaded ripples (lower arrows). Misko Mountain, section 16, 223.2-235.1 m; scale in centimetres.
- d: Closeup of limestone and dolomitic interbeds in ribbon calcisiltite. The limestone interbeds are composed of parallel laminated and crosslaminated calcisiltite and structureless lime mudstone. The pervasively dolomitized argillite interbeds contain millimetre-scale cycles identical to those in the argillite lithofacies. Misko Mountain, section 16, 363.8-375.6 m; hammer handle 30 cm long.



PLATE 19: RIBBON CALCISILTITE LITHOFACIES

OKE UNIT (CONTINUED)

- a: Closeup showing irregular interbedding common in ribbon calcisiltite lithofacies. The thin, relatively planar limestone interbeds are composed of lime mudstone (M). The wavy beds commonly contain partial Bouma sequences commencing with either the B or C divisions (upper arrow). The dolomitized argillite interbeds are identical to those in Plate 17a. Oke unit, Misko Mountain, section 16, 314.2-319.2 m; scale in centimetres.
- b: Limestone layers and crosslaminated nodules irregularly interbedded with laminated, pervasively dolomitized argillite. Oversteepened crosslaminae are present in the foreground (arrow). Misko Mountain, section 16, 360.6-363.8; scale in centimetres.

PHOTOMICROGRAPHS

- c: **Tokumm sub-unit:** graded peloidal laminae (0.7-2.5 mm thick) in ribbon calcisiltite. Peloid size is generally in the range of 40-70 microns. Many grains are selectively dolomitized. The Monarch (north face), section 22, 306.8-338.3 m; scale bar is 1 mm.
- d: **Tokumm sub-unit:** closeup of grains in a rock similar to that shown in (c) above. The grains are largely Girvanella fragments. The tubules have clear microspar cores, external diameters of about 30-50 microns, and internal diameters of about 20-28 microns. Grains with identical diameters and cores of clear neospar are probably fragmented Girvanella tubules. Some of the larger micritic grains without central canals (100-140 microns in size) are micritic peloids of uncertain origin. Others in the 40-60 micron range may be fragmented Epiphyton branches. Prospectors Valley 1, section 9, 177.6-180.5 m; scale bar is 500 microns.

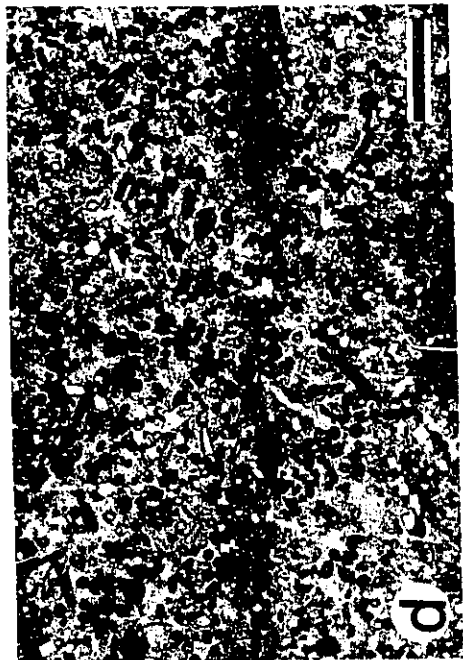


PLATE 20: RIBBON CALCISILTITE LITHOFACIES

PHOTOMICROGRAPHS (CONTINUED)

- a: **Oke unit:** closeup of vague peloidal texture in horizontally laminated, silty limestone (arrows point to a few examples of vaguely defined peloids). The peloids are spherical to oval, cloudy bodies of micrite surrounded by microspar. In cases where the grain-to-matrix transition is vague, the result is a "clotted" fabric (structure grumeleuse). Misko Mountain, section 16, 223.2-235.1 m; scale bar is 200 microns.
- b: **Oke unit:** ripple crosslaminated calcisiltite composed of siliciclastic silt and vaguely defined carbonate peloids. Mt. Dennis South, section 8, 470.6-483.7 m; scale bar is 2 mm.
- c: **Oke unit:** graded calcisiltite and argillite couplets. Peloidal grainstone with abundant siliciclastic silt and disseminated, non-ferroan dolomite (G) grades upward into dolomitic, slightly silty microspar (M) and slightly dolomitic argillite (A). Mt. Oke 2, section 7, 458.5-494.6 m; scale bar is 1 mm.
- d: **Oke unit:** millimetre-scale cycles (0.5-2 mm thick) in dolomitic argillite interbed shown in Plate 17a. Each sharp-based cycle commences with a dark layer of pervasively dolomitized argillite, which sometimes contains scattered siliciclastic silt. Grading into the overlying, lighter layers is defined by an upward dilution of ferroan dolomite crystals, and by the upward disappearance of silt. Mt. Oke 2, section 7, 458.5-494.6 m; scale bar is 1 mm.

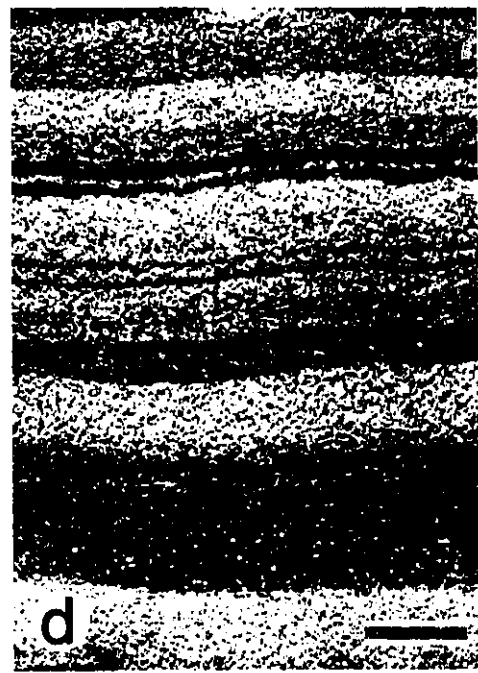
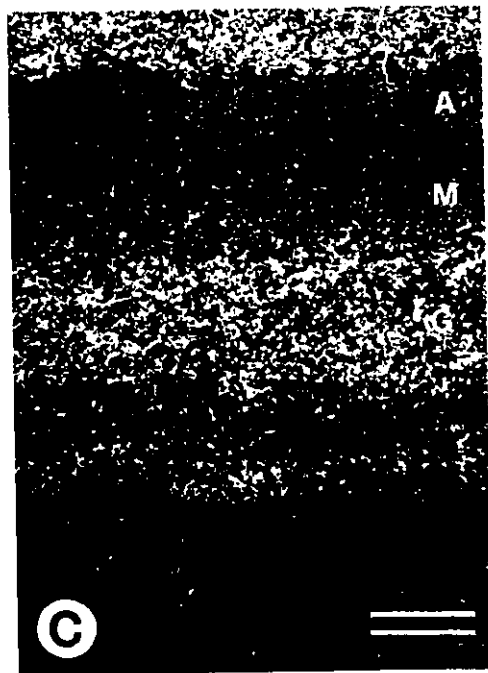
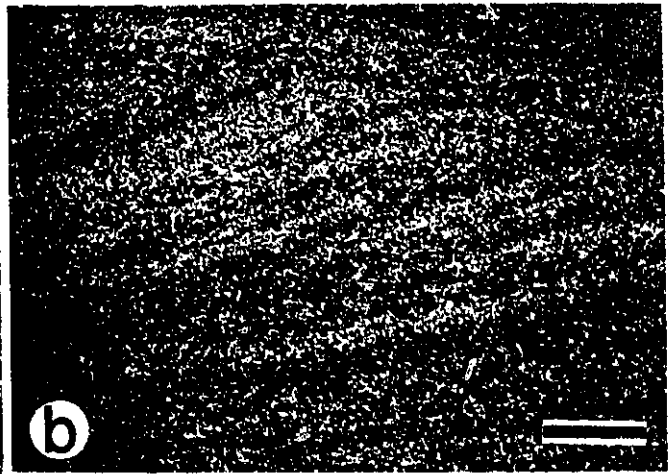


PLATE 21: CALCARENITE LITHOFACIES

MEGACHANNEL CALCARENITE: VERMILION SUB-UNIT

- a: Calcarenite-filled megachannel (outlined by arrows) encased in argillite (A). The megachannel has a lower keel (lowest arrow), and thins rapidly to an abrupt, southeasterly pinchout just to the left of the photo. Prospectors Valley 3, section 11, 180.1-203.4 m; figure (circled) for scale.
- b: Southeastern margin of megachannel shown in (a) above. The laminated dolomitic argillite (A) immediately adjacent to the calcarenite (C) is deformed (arrows). Note the detached piece of calcarenite, at left. Prospectors Valley 3, section 11, 180.1-203.4 m; scale in centimetres.
- c: Calcarenite sand bodies inside megachannel. The megachannel is composed of a complex fill of thin, elongate, tapering sand bodies separated by erosion surfaces (arrows). Most sand bodies are amalgamated, but many are locally separated by thin (<10 cm thick), laminated argillite layers that escaped erosion. The layering in this outcrop is accentuated by bedding-parallel dolomitized zones (resistant, light-coloured bands). Prospectors Valley 3, section 11, 180.1-203.4 m; hammer 34 cm long.
- d: Vaguely laminated character of massive calcarenite in megachannels. The calcarenite is composed of alternating, diffuse coarser- and finer-grained layers. The latter form a series of slightly raised ribs. The hammer head rests at the contact between two, amalgamated calcarenite bodies. In the upper body, the coarser bands thin upward from decimetre-scale to centimetre-scale. Prospectors Valley 4, section 30; 37.7-58.2 m; hammer 34 cm long.
- e: Calcarenite body with regularly spaced, dolomitic layers, disconformably overlain by a second calcarenite body (scale at contact). Prospectors Valley 4, section 30; 37.7-58.2 m; scale in centimetres.

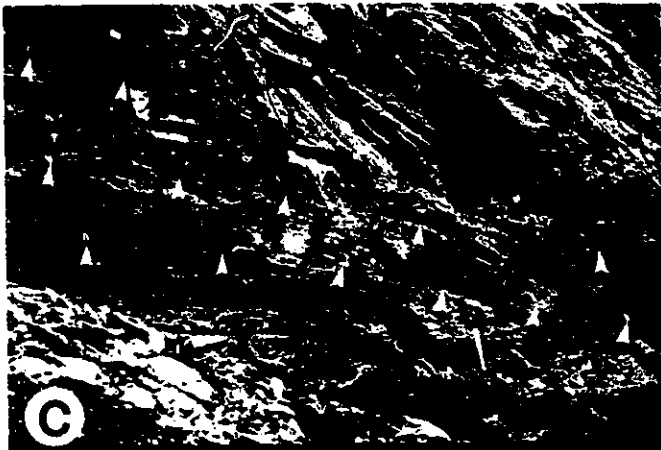
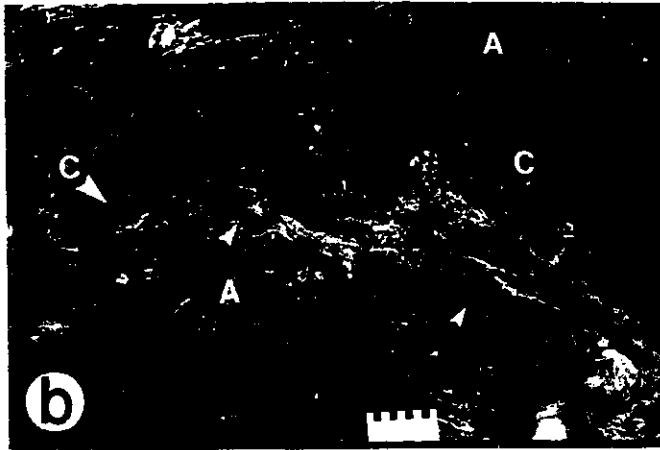
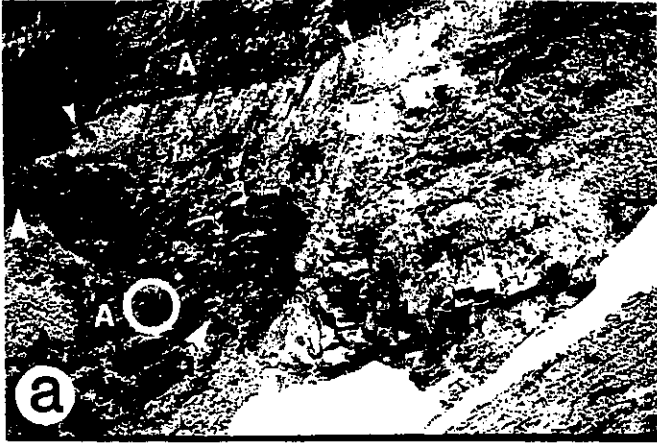


PLATE 22: CALCARENITE LITHOFACIES

MEGACHANNEL CALCARENITE: VERMILION SUB-UNIT (CONTINUED)

- a: Erosional contact (arrowed) between channellized calcarenite bodies. The lower body is characterized by thin, alternating, coarser-grained massive layers and finer-grained laminated layers. The upper body is visibly coarser, and contains thick, massive layers and minor, vaguely laminated layers. Prospectors Valley 4, section 30; 37.7-58.2 m; scale in centimetres.
- b: Closeup of massive, ungraded, coarse-grained calcarenite (m) with spaced horizons of finer-grained, horizontally laminated calcarenite (l). Note ripple trough (arrow). Prospectors Valley 4, section 30; 37.7-58.2 m; outcrop shown about 20 cm high.
- c: Closeup of massive, ungraded calcarenite (m) separated by slightly finer-grained, horizontally laminated calcarenite (l). The upper and lower contacts of the upper laminated layer are gradational, whereas the upper contacts of the lower two laminated layers are obscured by dolomitization and pressure solution. Note lateral thinning of the lower massive bed over the inclined laminated layer at the base of the photo. Haffner Creek South, section 29, 180.7-182.3 m; scale in centimetres.
- d: Closeup of dolomitized layers in calcarenite. In general, these layers are bedding-parallel, but quite irregular layers have also been observed. The cross-cutting layer at centre (arrow) probably follows the base of a small scour. A thin section of one of these dolomitic layers is illustrated in Plate 25a. Prospectors Valley 3, section 11, 180-203.4 m; outcrop shown about 50 cm high.

TAKAKKAW TONGUE

- e: Sharp-based, normally graded intraclastic-peloidal rudstone/grainstone ("flakestone"). The dolomitic, tabular intraclasts are up to 20 mm long and 2 mm thick. Natalko Lake, section 23, 67.9-81.8 m; scale in centimetres.

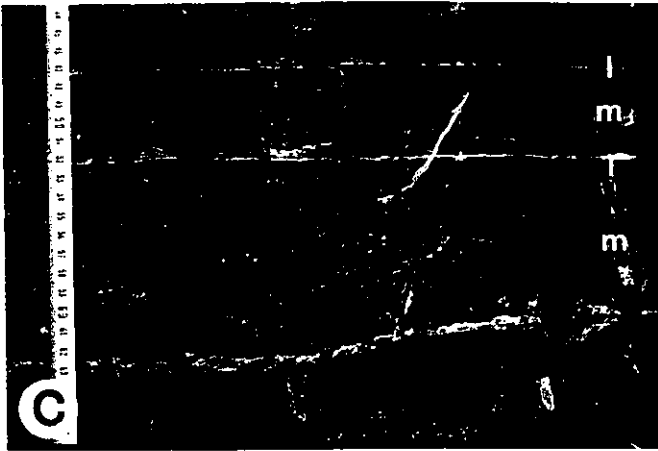
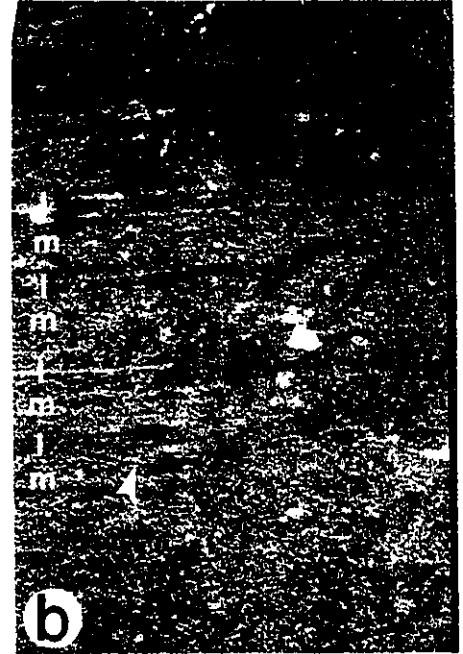


PLATE 23: CALCARENITE LITHOFACIES

TOKUMM SUB-UNIT

- a: Channellized and unchannellized calcarenite. The lower calcarenite beds are separated by thin argillite layers. The upper, more massive calcarenite is composed of at least two sand bodies. The upper body (set of inclined strata) is a broad channel fill (arrows). The lower body thins in a wedge-like fashion beneath this surface. Haffner Creek North, section 4, 78.6-80.3 m; person is 1.6 m tall.
- b: Small-scale scours in peloidal grainstone (arrows). The grainstone beds are separated by dolomitic, slightly more resistant layers. A thin section from this outcrop is illustrated in Plate 25c. Haffner Creek North, section 4, 102.8-110.6 m; scale in centimetres.

DUCHESNAY UNIT

- c: Massive calcarenites (C) interbedded with laminated, dolomitic argillite (A). Note lateral thinning of calcarenite beds at right and sharp, locally scoured bases. Mt. Oke 2, section 7, 33.7-35.3 m; scale in centimetres.
- d: Massive calcarenite (C) interbedded with dolomitic argillite (A). The calcarenite contains dolomitic intraclasts of all sizes, and visibly pinches and swells. Mt. Oke 2, section 7, 33.7-35.3 m; scale in centimetres.

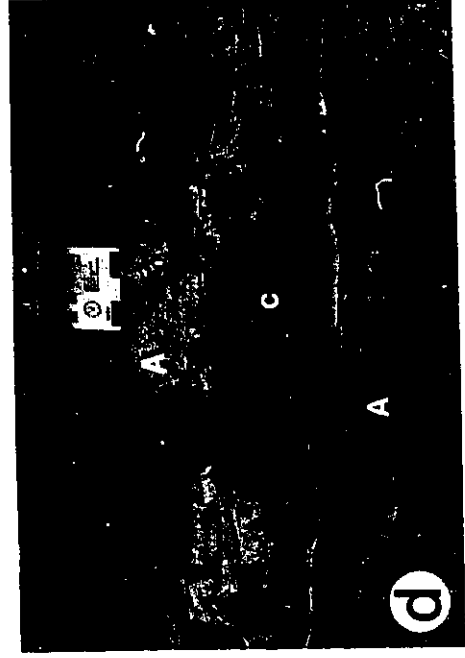


PLATE 24: CALCARENITE LITHOFACIES

DUCHESNAY UNIT (CONTINUED)

- a: Massive calcarenite (C) succeeded by laminated calcisiltite (S) and capped by laminated dolomitic argillite (A). Note basal load and flame structures containing deformed, dolomitic argillite from the underlying layer (arrows). A photomicrograph of a very similar calcarenite is shown in Plate 25d. Mt. Oke 2, section 7, 92.6-96.1 m; scale in centimetres.
- b: Complete Bouma ABCDE sequence. The A division consists of medium- to coarse-grained calcarenite, and grades upward into calcisiltite. The turbidite is interbedded with dolomitic argillite containing a few ripple crosslaminated layers. Mt. Oke 2, section 7, 9.6-15.8 m; scale in centimetres.

PHOTOMICROGRAPHS: MEGACHANNEL CALCARENITE, VERMILION SUB-UNIT

- c: Oolitic-intraclastic grainstone. Many oolith cores and intraclasts have been replaced by ferroan dolomite (blue). The grains have isopachous fringes of columnar calcite (not visible in this photo), and the remaining pore space has been infilled by a drusy mosaic of equant calcite spar. Verdant Headwaters South, section 33, 9-21 m; scale bar is 500 microns.
- d: Intraclastic-oolitic-peloidal grainstone. The large, irregularly shaped intraclast at right has a vague peloidal texture, and parts are characterized by structure grumeleuse. Vague, tubule-like bodies within it (indicated by arrows) are probably Girvanella. The other grains in this thin section are ooliths and peloids with poorly preserved internal textures. Note partial replacement of many grains by ferroan dolomite rhombs (blue). Most grains have isopachous fringes (not visible in this photo), and the remaining pore space is infilled by non-ferroan and ferroan (mauve) calcite spar. Prospectors Valley 4, section 11, 218.6-223.8 m; scale bar is 250 microns.

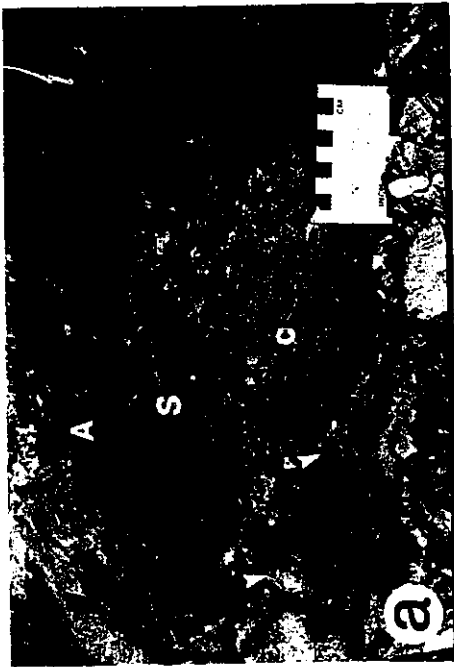
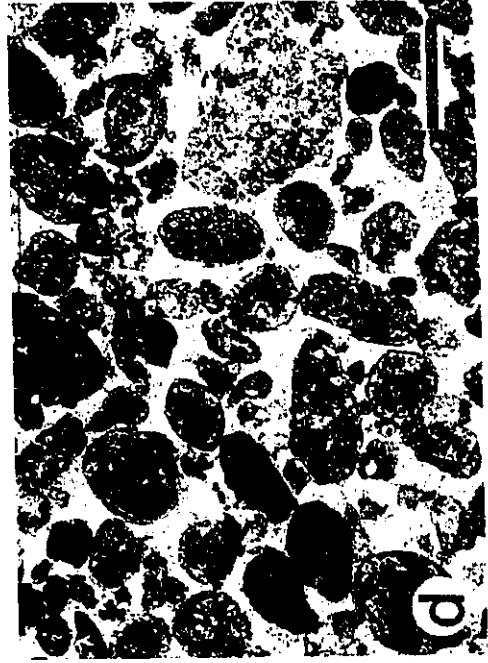
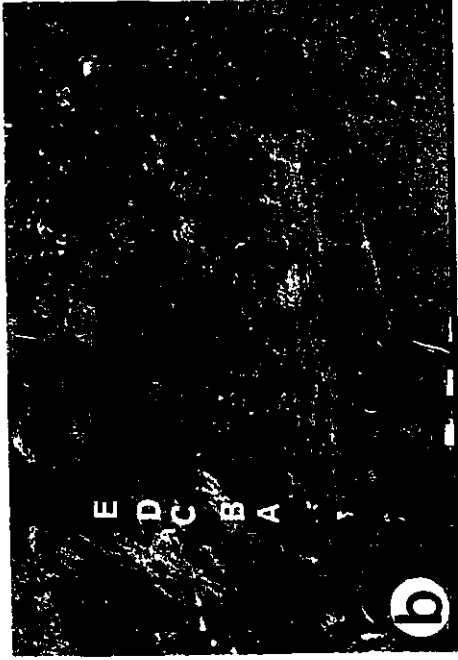


PLATE 25: CALCARENITE LITHOFACIES

PHOTOMICROGRAPHS:

MEGACHANNEL CALCARENITE, VERMILION SUB-UNIT (CONTINUED)

- a: Bedding-parallel dolomitic layer in oolitic-intraclastic-peloidal grainstone. Note truncated grains (arrows) and irregular boundaries of dolomitic zone. This zone consists mainly of CCCR dolomite with non-ferroan, cloudy, inclusion-rich cores (both rhomb- and oval-shaped) and ferroan, inclusion-free rims. Most dolomitic layers are preferentially located along sedimentological discontinuities, in this example the boundary between a finer-grained layer below and a coarser-grained layer above. Prospectors Valley 4, section 11, 180.1-203.4 m; scale bar is 2 mm.

TOKUMM SUB-UNIT

- b: Peloidal-bioclastic packstone/grainstone. The rock is composed mainly of poorly preserved peloids, 70-150 microns in diameter, together with trilobite fragments. Peloid shapes range from spherical to oval or spindle-shaped. In places, texture preservation is poor enough to be termed structure grumeleuse. Note the shelter porosity (sp) infilled by isopachous columnar and blocky calcite cement beneath the large trilobite fragment. Ferroan dolomite (blue) is disseminated throughout the rock. Prospectors Valley 4, section 11, 0-3 m; scale bar is 1 mm.
- c: Peloidal packstone/grainstone, composed of coarse silt- to very fine-sand sized peloids (40-90 micron diameter) and minor trilobite fragments (Plate 23b shows the corresponding outcrop). The peloids are variably preserved. Those in the upper part of the photo are well defined (upper arrows), whereas others in middle and lower parts of the photo are more vague (lower arrows). The light patches are non-ferroan dolomite crystals. Haffner Creek North, section 4, 102.8-110.6 m; scale bar is 200 microns.

DUCHESNAY UNIT

- d: Intraclastic-peloidal grainstone containing a wide variety of grain types. These include peloidal grainstone intraclasts (g), some of which contain Girvanella tubules; structureless, variably silicified, microspar intraclasts (m); intraclasts with vague, poorly preserved texture (structure grumeleuse, s); microdolomite intraclasts (d); variably dolomitic, structureless microspar intraclasts (i); and ooliths (o). Scattered trilobite fragments and an Epiphyton boundstone intraclast occur elsewhere in this specimen. Isopachous fringes are preserved on some grains (not visible in this photo), which are cemented by equant, non-ferroan calcite spar. Mt. Oke 2, section 7, 9.6-15.8 m; scale bar is 1 mm.

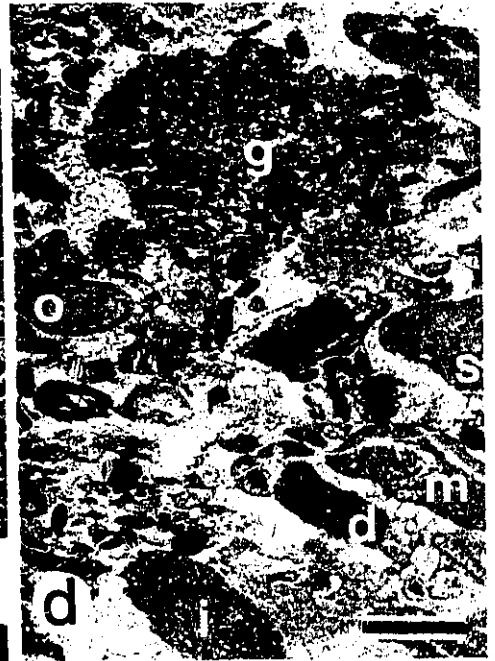
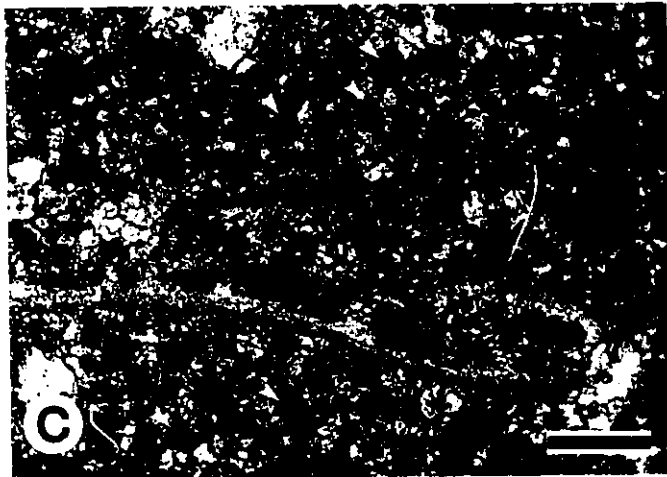
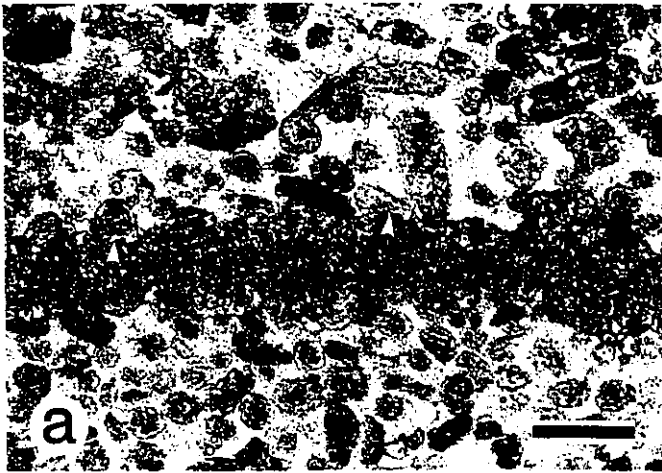


PLATE 26: CONGLOMERATE LITHOFACIES

TAKAKKAW TONGUE

- a: Megaconglomerate containing outsized, platform-derived megaclasts in a monotonous, ribbon limestone sequence. The debris flow (df) carrying the megaclasts is considerably thinner. Another, less well defined debris flow (lens-shaped massive bed) occurs slightly higher in the sequence (upper arrow). West side of Fossil Gully, Mt. Field. For scale, the largest block is estimated to be about 4-5 m thick.
- b: Debris flow (arrow) with outsized, freighted block, interbedded with monotonous ribbon limestone. The channel-shaped feature in the upper part of the exposure (ch) also contains limestone conglomerate. A wider field of view for the same exposure is shown in McIlreath and James (1984, p. 248). Wedge Gully, Mt. Field, section MJA-725; the megaclast is estimated to be about 12 m high.
- c: Two amalgamated megaconglomerate bodies (contact at level of figure's head) containing poorly-preserved, Epiphyton boundstone clasts up to 6 m in maximum dimension. Most clasts have diameters of 1-2 m. The underlying ribbon calcilutite and argillite are squeezed up into the base of this feature (arrow). Natalko Lake, section 23, off line of section (lateral extension of 16.1-28.1 m interval in section); pogo divisions each 0.5 m.

CATHEDRAL MEGABRECCIA (LOWER TAKAKKAW TONGUE)

- d: Ninety metre-high megaclast projecting from the top of the Cathedral megabreccia (base of megaclast indicated by arrows). The body of the megabreccia is the massive, reddish-weathering, destructively dolomitized interval at the base of the exposure (M). The megaclast is standing on end (steeply inclined stripes are bedding, as confirmed by remnant, internal sedimentary structures), and is overlapped and draped by thin-bedded ribbon calcilutite of the upper Takakkaw Tongue (T). The "basinal" Stephen Formation (S) caps the sequence shown. Monarch cirque 1, section 27, basal part of section.
- e: Closeup of the Cathedral megabreccia, which contains pebble- to cobble-sized clasts of ex-fenestral limestone, ex-oolitic grainstone, and grey dolomite in a brown dolomite matrix. The megabreccia is clast-supported. Monarch cirque 1, section 27, basal part of section; hammer handle 30 cm long.

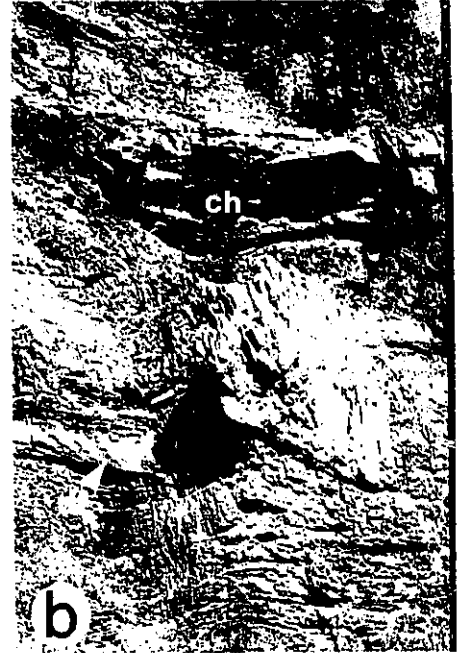


PLATE 27: CONGLOMERATE LITHOFACIES

VERMILION SUB-UNIT

- a: Mixed-clast conglomerate, composed of platy lime mudstone clasts (dark grey) and blocky calcarenite and laminated limestone clasts (light grey). The conglomerate is clast-supported, and has a dolomite matrix. The Monarch (north face), section 22, 456-458.7 m; hammer handle 30 cm long.
- b: Clast-supported limestone chip conglomerate, composed of lime mudstone, calcarenite, and argillite clasts set in a dolomite matrix containing abundant sand-sized particles. Tokumm Headwaters 2, section 18, 50.3-53.1 m; white band at upper left is part of pogo stick, and is about 5 cm long.
- c: Mixed clast conglomerate, clast-supported at the base, and becoming matrix-supported upward. The lime mudstone, laminated limestone, and calcarenite clasts are set in a matrix of dolomitic argillite. The Monarch (north face), section 22, 541-543.3 m; hammer handle 30 cm long.
- d: Megaconglomerate (M) with megaclasts up to 50 m in maximum dimension, draped (in background) by laminated argillite (A). The megablocks are composed mainly of Epiphyton boundstone. This exposure corresponds to megaconglomerate 2 in Plate 53. Verdant Headwaters North, section 34, 73.2-79.5 m; for scale, megaconglomerate is about 6 m thick in foreground.
- e: Closer view of megaclasts at northeastern end of megaconglomerate 2 (same exposure as (d) above). Megaclast behind figure (circled) is about 30 m high; Verdant Headwaters North, section 34.

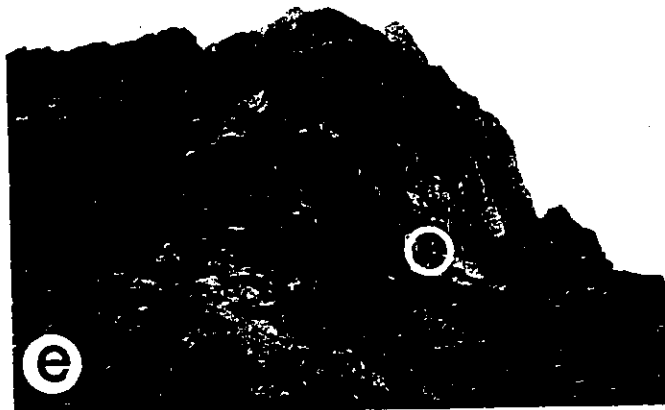


PLATE 28: CONGLOMERATE LITHOFACIES

VERMILION SUB-UNIT (CONTINUED)

- a: Outsized megaclast (11x19 m) in a debris flow near the top of the Vermilion sub-unit (megaconglomerate 5 in Plate 53). Massive argillite of the basal Duchesnay unit (D) is visible in the upper background. Verdant Headwaters North, section 34, 141.1 m; figure for scale.
- b: Megaconglomerate near the top of the Vermilion sub-unit. Megaclast near figure (circled) is about 10 m high. Note the irregular top on this feature (marked by a series of arrows). Haffner Creek North, section 4, 310.8-326.6 m.
- c: Megaconglomerate (M) near the top of the Vermilion sub-unit. The irregular top of this feature is indicated by a series of arrows. A channellized calcarenite is present at the lower left (C). Duchesnay unit argillite (D) is visible at the upper right. "SM" marks the lateral termination of a ribbon limestone slide mass. Prospectors Valley 4, above section 30; for scale, the megaclast marked "M" is about 10-15 m thick.
- d: Channellized megaconglomerate (M) near the top of the Vermilion sub-unit. The base of this feature (series of arrows) cuts down through a darker grey-weathering calcarenite unit (C) about 5 m thick (channel margin indicated by second arrow from the right). Duchesnay unit argillite is visible in the upper part of the exposure. Prospectors Valley 3, top of section 11.

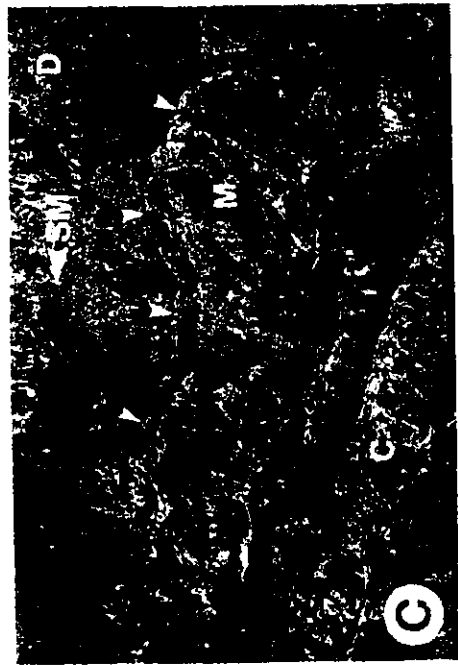


PLATE 29: CONGLOMERATE LITHOFACIES

VERMILION SUB-UNIT (CONTINUED)

- a: Lateral pinchout of channellized megaconglomerate (outlined by arrows). Note overfolded ribbon limestone (RL) beneath the lip of the channel. This syndimentary deformation probably resulted from slight lateral spreading of the conglomerate mass after its emplacement. Prospectors Valley 1, section 9, 489.7 m; hammer (circled) is 34 cm long.
- b: Deformed nodular argillite injected into the base of a channellized megaconglomerate (same exposure as Plate 28d). Prospectors Valley 3, section 11, 266.2 m; scale card (circled) is 9 cm long.
- c: Argillite deeply injected into the base of a megaconglomerate (arrow). Verdant Headwaters North, section 34, 119.1 m; figure for scale.
- d: Clast-supported fabric of a megaconglomerate. Both Epiphyton boundstone clasts (E) and calcarenite clasts (C) are visible. The matrix is dolomite with abundant, sand-sized carbonate grains. Verdant Headwaters North, section 34, 73.2 m; hammer 34 cm long.
- e: Smaller clasts in megaconglomerate. Visible are small clasts of Epiphyton boundstone (E), lime mudstone (L) and calcarenite (C). The dolomite matrix contains abundant sand-sized carbonate grains (primarily dolomitic intraclasts). Prospectors Valley 3, section 11, 266.2 m; scale in centimetres.

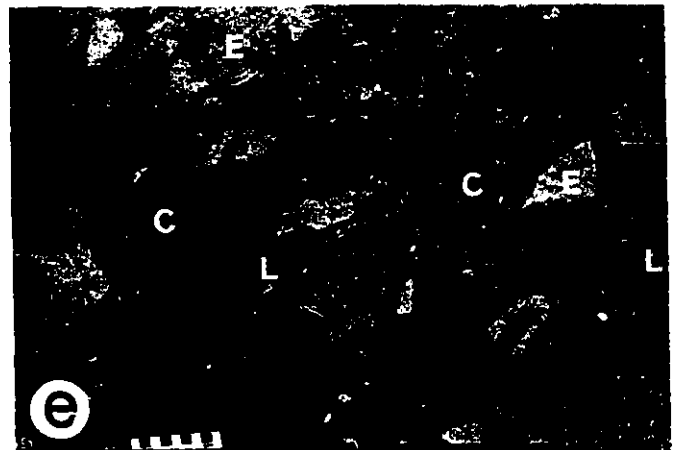
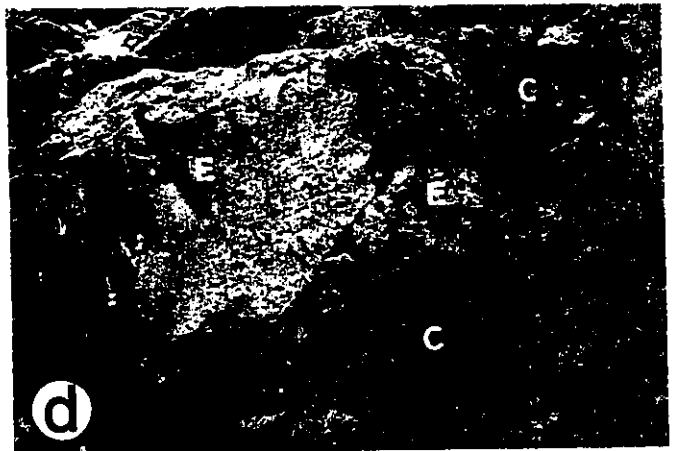
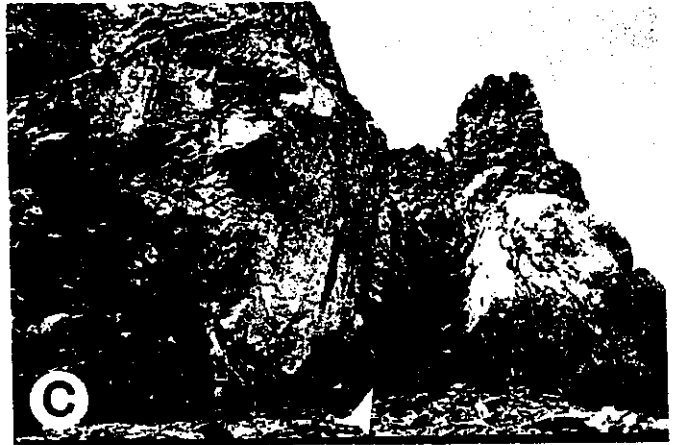


PLATE 30: CONGLOMERATE LITHOFACIES

DUCHESNAY UNIT

- a: Abrupt, tapered margin (arrow) of a limestone chip conglomerate. The conglomerate is surrounded by dolomitic argillite (A), and is succeeded by a second limestone chip conglomerate (above scale). The lower conglomerate is about 35 m wide and a maximum of 2 m thick, and is broadly channelized. Mt. Dennis North, section 1, 229.9 m; scale in centimetres.
- b: Limestone chip conglomerate containing variously shaped calcarenite and subordinate lime mudstone clasts in a grainy, dolomitic matrix. Miller Pass 2, talus block, near section 13; scale in centimetres.
- c: Clast-supported limestone chip conglomerate overlying dolomitic argillite. The conglomerate clasts are mainly lime mudstone and silty peloidal wackestone/packstone, and are set in a grainy microspar/pseudospar matrix. Note the sheared, somewhat nodular appearance of the dolomitic argillite immediately beneath this deposit. Mt. Dennis South, section 8, 153.3-154.2 m; scale in centimetres.

OKE UNIT

- d: Megaconglomerate containing Epiphyton boundstone and calcarenite megaclasts. This feature is underlain and overlain by ribbon argillite (A). Hamilton Lake South, section 32, 83.7-88.4 m; megaconglomerate is 4.7 m thick.
- e: Matrix-supported limestone conglomerate composed mainly of ovoid and subordinate tabular limestone clasts up to 10x15 cm in size in a dolomite matrix. Note the flat base and top. The conglomerate is contained in a ribbon calcisiltite sequence. Mt Oke 2, section 7, 585.9-587.7 m; figure for scale.

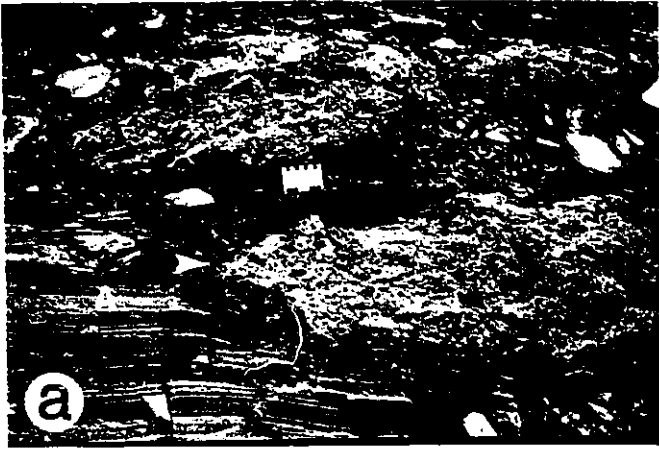


PLATE 31: CONGLOMERATE LITHOFACIES

PHOTOMICROGRAPHS

- a: Epiphyton in a megaconglomerate megaclast. The Epiphyton occurs as a series of consistently oriented bushes, and is cemented by isopachous fringes of cloudy, fibrous, non-ferroan calcite. The remaining pore space is infilled by coarse, equant, ferroan calcite (mauve). Vermilion sub-unit, Prospectors Valley 1, section 9, 487 m; scale bar is 1mm.
- b: Cross-sectional view of Epiphyton branches, giving the appearance of dense, micritic peloids 40-60 microns in diameter. Fragmented Epiphyton branches are inferred to be a major contributor of peloids to sediments downslope. Vermilion sub-unit, Haffner Creek North, section 4, 310.8-326.6 m; scale bar is 500 microns.
- c: Variously preserved Epiphyton in megaconglomerate megablock. Note the strong, preferential growth orientation, which resembles the "flat-lying growth form" of Read and Pfeil (1983). Similar vague, thread-like textures in many megablocks are inferred to be poorly preserved Epiphyton based on a comparison with examples like this where a range of preserved fabrics is visible. Vermilion sub-unit, Prospectors Valley 1, section 9, 454.5-507.3 m; scale bar is 2 mm.
- d: Closeup of well preserved, fibrous calcite in pore space between Epiphyton bushes in the same sample as (c) above (crossed nicols). Vermilion sub-unit, Prospectors Valley 1, section 9, 454.5-507.3 m; scale bar is 500 microns.
- e: Poorly preserved Renalcis (R) in growth cavity between Epiphyton clumps (E). The remainder of the cavity is filled with fibrous calcite cement. Small periplatform clast recovered from the Duchesnay unit, Miller Pass 1, immediately above section 12; scale bar is 1 mm.

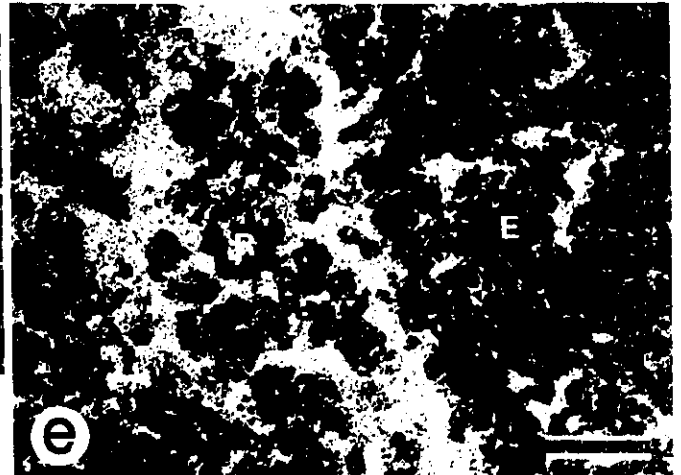
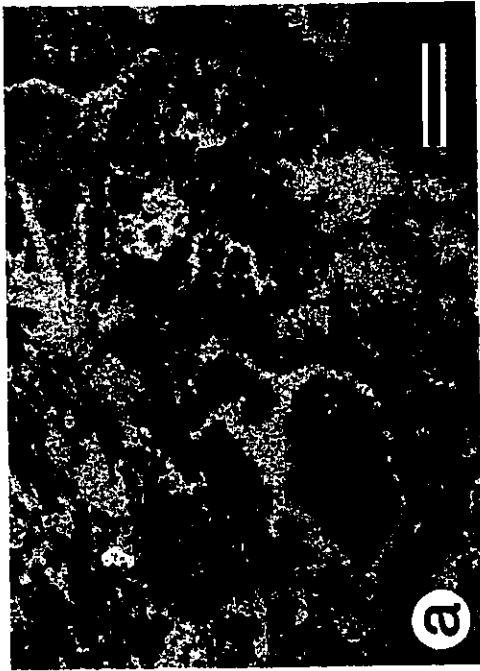
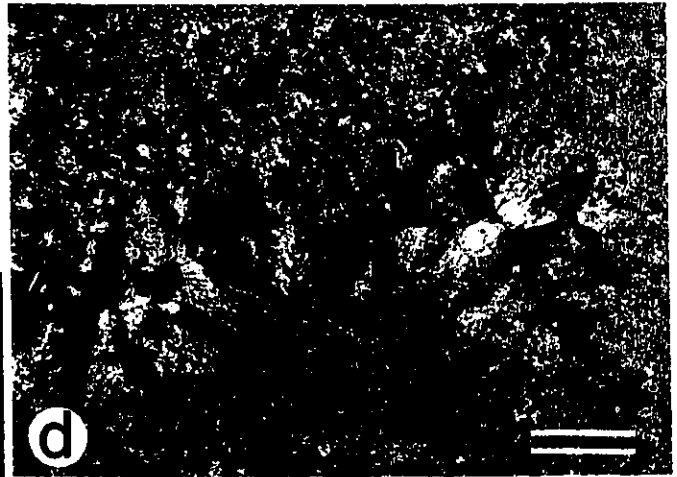


PLATE 32: CONGLOMERATE LITHOFACIES

PHOTOMICROGRAPHS (CONTINUED)

- a: Various preserved Renalcis (R) in megaconglomerate megablock, showing typical occurrence as clumps of micrite-walled lunules. Takakkaw Tongue, Fossil Gully, Mount Stephen; scale bar is 500 microns.
- b: Dolomitic matrix in limestone conglomerate. The dolomite rhombs are mainly cloudy and non-ferroan, and have ferroan rims. They are surrounded by dark grey, undifferentiated clay and organic material. Remnant patches of ferroan microspar and pseudospar are visible, suggesting that the original matrix was composed mainly of lime mud. The sand-sized and larger clasts are corroded and partly replaced by dolomite. Tokumm sub-unit, Curtis cirque, section 21, 145.7-147.9 m; scale bar is 500 microns.
- c: Grainy matrix in a limestone chip conglomerate. A variety of intraclast types are present. The inter-particle cement has been replaced by ferroan dolomite, but remnant calcite isopachous fringes can still be identified locally. Girvanella tubules (G) are rarely visible amongst peloids and peloidal intraclasts in the large clast at the upper left. Tokumm sub-unit, Haffner Creek North, section 4, 171-171.3 m; scale bar is 1 mm.
- d: Conglomerate clast composed of peloid packstone containing, variously preserved peloids (P), scattered trilobite fragments (T), oololiths (O), and intraclasts (I; >0.5 mm diameter). Scattered patches of ferroan dolomite crystals (blue) are also present. The matrix is non-ferroan pseudospar. The flattened appearance of the grains indicates pre-lithification mechanical compaction. Tokumm sub-unit, Curtis cirque, section 21, 143.8-144.5 m; scale bar is 1 mm.
- e: Conglomerate clast composed of intraclastic-oolitic-peloidal grainstone. The grains have isopachous fringes of fibrous calcite cement, and the remaining pore space is infilled by equant non-ferroan and ferroan calcite. The grains are variously dolomitic and siliceous, and include peloidal packstone intraclasts (PP), oololiths and oololith fragments (O), oolitic-peloidal grainstone intraclasts (G), micritic intraclasts (M), and peloids (P). Duchesnay unit, Mt. Dennis North, section 1, 224.1-228.4 m; scale bar is 1 mm.

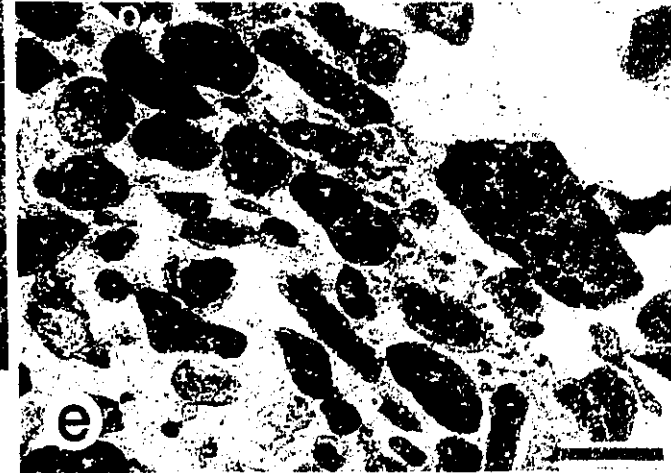
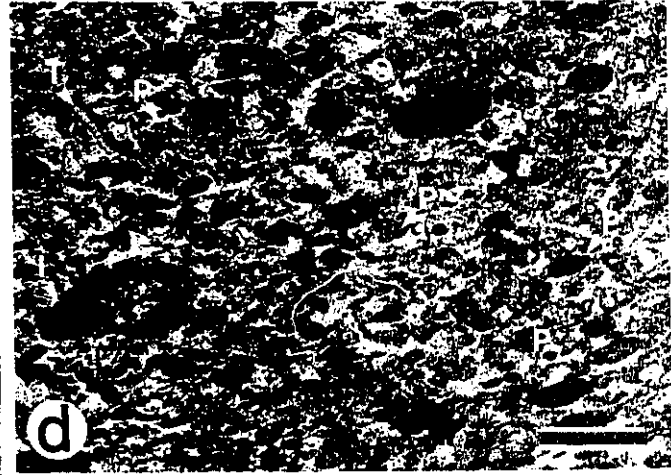
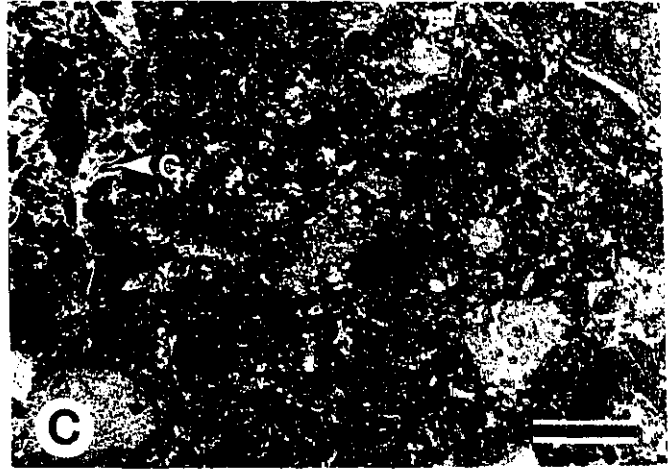
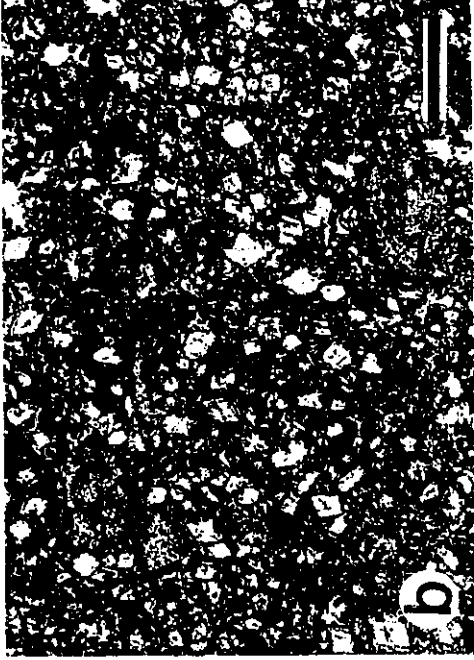


PLATE 33: PERIPLATFORM TALUS BLOCKS

- a: **Takakkaw Tongue:** periplatform talus block (T) in ribbon limestone sequence. The single, thick bed in the underlying ribbon limestone sequence is a massive limestone conglomerate (C). Note Cathedral Escarpment (CE) on Mt. Field in the background. Fossil Gully, Mt. Stephen; figure is 1.8 m tall.
- b: **Basal "basinal" Stephen Formation:** Epiphyton-bearing periplatform talus block (T) embedded in argillite sequence (A). Monarch cirque 1, section 27; pogo 1.5 m long.
- c: **Tokumm sub-unit:** Large periplatform talus block (T; estimated dimensions 6x20 m), overlying ribbon argillite (A) of the upper siliciclastic marker. Prospectors Valley 2, section 10, 229-234.9 m; pogo stick 1.5 m long.
- d: **Vermilion sub-unit:** Periplatform talus block (T) encased in brown-weathering argillaceous sediments high on the southwest wall of Prospectors Valley. Several of these blocks, measuring several tens to perhaps hundreds of metres in maximum dimension, can be seen in the walls overlooking Marble Canyon and lower Tokumm Creek.



PLATE 34: LITHOFACIES OF SHALLOW-WATER ASPECT

BURROW-MOTTLED AND BURROW-STRATIFIED LIMESTONES

- a: Burrow-mottled limestone containing numerous, cylindrical burrows, some of which are branched (arrows). Lower Eldon Formation, Prospectors Valley 1, section 9, 98.7-104.1 m; scale in centimetres.
- b: Burrow-mottled limestone, showing abundant of dark-weathering, dolomitic blobs weathering out from a light grey, limestone matrix. This texture is also easily recognizable in fully dolomitized rocks. Lower Eldon Formation, Tokumm Headwaters 1, section 17, 202.7-209.4 m; scale in centimetres.
- c: Burrow-stratified limestone with distinct, horizontally bedded, resistant-weathering dolomite mottles and stringers. The matrix is light grey lime mudstone. Lower Eldon Formation, Prospectors Valley 2, section 10, 79.8-89 m; pogo divisions each 0.5 m.
- d: Small-scale cycle in upper Duchesnay unit. The lower part consists mainly of ribbon to nodular argillite (A), which is succeeded sharply by burrow-stratified (BS) and burrow-mottled (BM) limestone (detailed fabric not visible in photo). The limestone is succeeded abruptly by nodular argillite at the base of the next cycle (top of photo). Complicating this general pattern are thin interbeds of burrow-mottled limestone in the lower part of the argillite sequence (arrows). Hamilton Lake North, section 31, 143.1-146.5 m; pogo divisions each 0.5 m.

PHOTOMICROGRAPHS

- e: **Burrow-mottled limestone:** peloidal packstone, consisting of micritic tubules (arrows) and silt-sized peloids set in equant neospar. The tubules have sparry calcite cores, and are inferred to be *Girvanella* fragments. More poorly preserved areas of the same slide have typical structure grumeleuse texture. Upper Duchesnay unit, from burrow-mottled limestone at top of a small-scale cycle, Hamilton Lake South, section 32; scale bar is 500 microns.

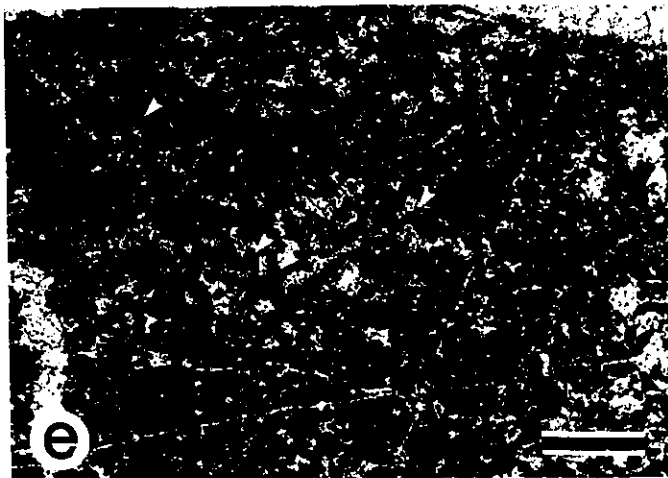
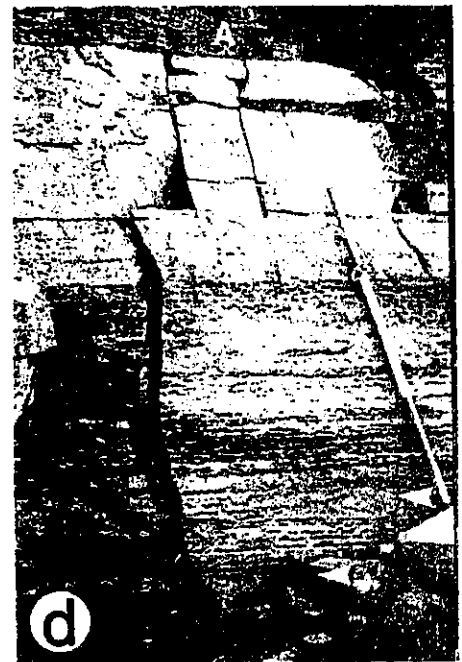
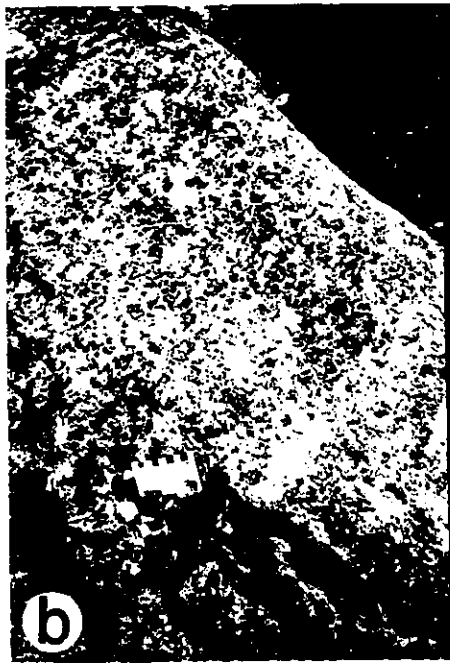
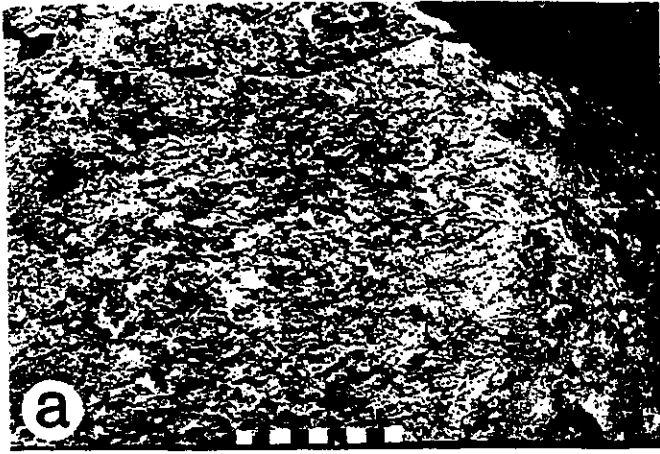


PLATE 35: LITHOFACIES OF SHALLOW-WATER ASPECT

PHOTOMICROGRAPHS (CONTINUED)

- a: **Burrow-stratified limestone:** peloidal wackestone/packstone in which vague to fairly well defined, micritic peloids are set in a microspar/pseudospar matrix. The peloidal texture (P) is obvious in parts of the slide, but becomes more poorly defined elsewhere and approaches that of structure grumeleuse (S). Elsewhere in the same slide, textures are barely visible. Tokumm sub-unit, section 10, 79.8-89 m; scale bar is 500 microns.

"YOHOLAMINITES" AND ASSOCIATED SEDIMENTS

- b: "Yoholaminites" (Y) occurring in fenestral dolomite (F). The base of the original sheet crack has an initial geopetal fill of oolitic grainstone (O), which contains small Epiphyton bushes (E). The remainder of the sheet crack is filled with white to light grey dolomite ("Yoholaminites"). It is characterized in part by dark grey laminae, and the best preserved, chevron-kinked laminae occur in the white core (details of fabric not visible in photo). Cathedral Formation, Monarch cirque 2, section 28, 81.4 m; scale in inches.
- c: "Yoholaminites" (Y) occurring in oolitic-pisolitic-intraclastic grainstone. Note bifurcation of lower "Yoholaminites" layer. Cathedral Formation, Monarch cirque, talus block; scale in cm.

FINE-GRAINED SILICICLASTIC SEDIMENTS: "PLATFORMAL" STEPHEN FORMATION

- d: Massive ribbon argillite near the base of Stephen Formation at the crest of the Kicking Horse Rim. This outcrop also contains local convolute laminae and thin sub-units of inclined strata overlying medium-scale intraformational truncation surfaces. Prospectors Valley, reconnaissance locality immediately northwest of section 10; hammer (centre left) is 34 cm long.
- e: Massive argillite (A) at the base of the Stephen Formation, overlain by dolomitic ribbon argillite (RA). The argillite contains local synsedimentary overfolds, and the ribbon argillite contains horizontal and vertical burrows. Tokumm Headwaters 2, section 17, 0-13.9 m; man is 1.8 m tall.

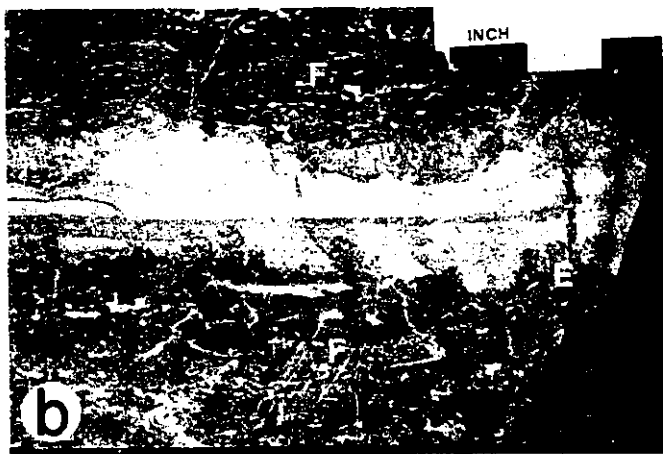
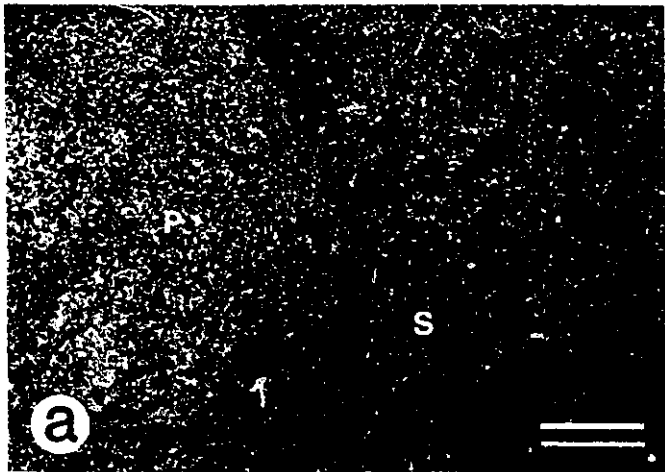


PLATE 36: LITHOFACIES OF SHALLOW-WATER ASPECT

FINE-GRAINED SILICICLASTIC SEDIMENTS: "PLATFORMAL" STEPHEN FORMATION (CONTINUED)

- a: Dolomitic argillite with thin, irregular interbeds and nodules of grey-weathering limestone. The dolomitic argillite is laminated in the lower half of the photo, but appears to be lightly bioturbated in the upper half. Burrows are visible in the centre limestone interbed (arrows). Some limestone nodules are crosslaminated (XL). Prospectors Valley 2, section 10, 14.5-31.2 m; scale in centimetres.
- b: Irregular nodular to ribbon argillite. The recessive pockets contain lime mudstone, which is encased in more resistant, dolomitic argillite. The irregular texture probably reflects bioturbation, but individual burrows are not discernable. Tokumm Headwaters 1, section 17, 17.1-22 m; scale in centimetres.

MISCELLANEOUS FEATURES

- c: **Cathedral Formation:** cryptalgal laminite in fully dolomitized platform carbonate rocks at the crest of the Kicking Horse Rim. Irregular laminae are visible in places (arrow). Prospectors valley 2, section 10, 0-1 m; scale in centimetres.
- d: **Lower Eldon Formation:** "Stromatactoid structure" (Aitken, 1966) in ex-ribbon limestone. The white, coarsely crystalline dolomite stripes are inclined at an angle to bedding, and are presumably late diagenetic features. Tokumm Headwaters, section 17; scale in centimetres.

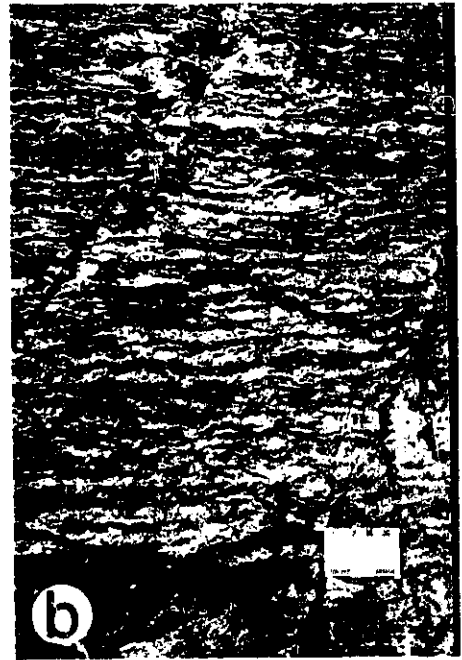
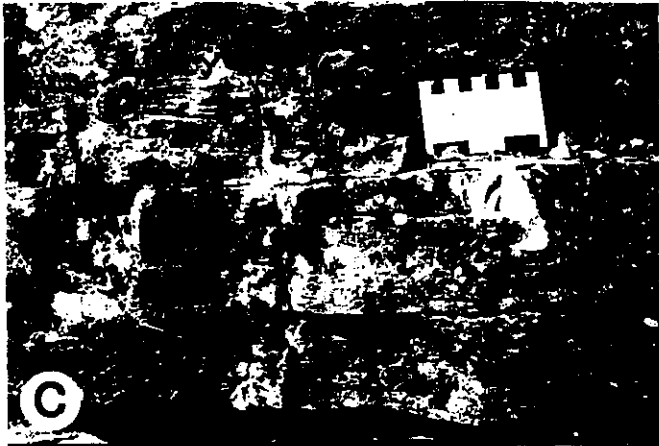
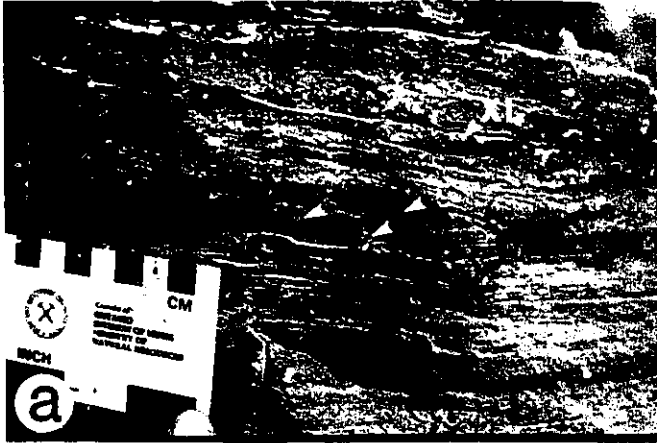


PLATE 37: OUTCROP PHOTOGRAPHS - GOG GROUP, NAISSET AND CATHEDRAL FORMATIONS

- a: Reference section for the Naiset Formation (N) at Wedgewood Peak (W) near Mt. Assiniboine. The Naiset is underlain by the Gog Group (G), and overlain by peritidal strata of the Cathedral Formation (C). View looking west, with Lake Magog in the foreground.
- b: North face of The Monarch. Gog Group (G) sandstone (lower grey cliffs) is unconformably overlain by reddish-weathering, dolomitic, peritidal strata of the Cathedral Formation (C). The contact is indicated by an arrow on the sky-line. This locality is situated at the crest of the Kicking Horse Rim, and Mount Whyte-Naiset strata are missing. View towards the southeast.
- c: North wall of Monarch cirque (opposite side of ridge shown in (b) above). The Cathedral Formation (C) and Gog Group (G) are clearly separated by a pronounced, westward-dipping, angular unconformity (arrows). View towards the north.
- d: Platform stratigraphy immediately north of Natalko Lake (Egypt Lake in the foreground). The Gog Group (G) is overlain by typical platform strata of the Cathedral (C), Stephen (S) and Eldon (E) formations. Gog Group strata can also be seen in the foreground. Again, Mount Whyte-Naiset strata are absent, as this locality is situated near the crest of the Kicking Horse Rim. Except for the dark grey band at the base of the Eldon Formation (arrow), the carbonate formations have all been pervasively dolomitized. View towards the west.

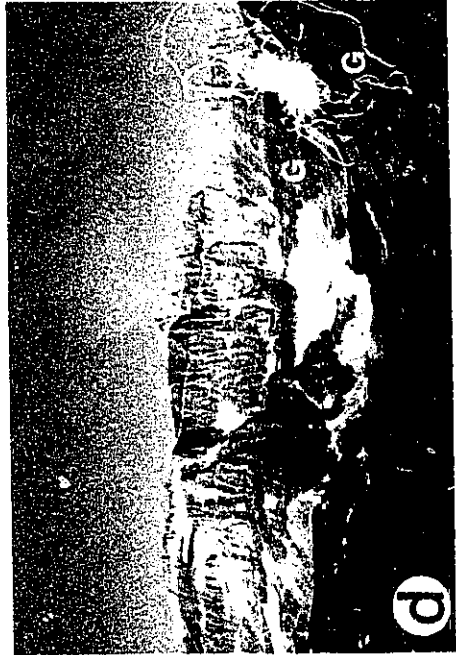


PLATE 38: THE CATHEDRAL ESCARPMENT

FIELD AREA

- a: The upper part of the Cathedral Escarpment on Mt. Field. Light brown dolostone of the Cathedral Formation (C) is overlain by the "platformal" Stephen Formation (PS), and abutted by the "basinal" Stephen Formation (BS). The upper part of Mt. Field is made up of the Eldon Formation (E).
- b: The Cathedral Escarpment on Mt. Stephen, as seen from Mt. Field. The escarpment (CE) faces obliquely outward from the mountainside. The Field Member (FM) is a prominent black band of outer detrital sediments in the middle Eldon Formation (E). BS: "basinal" Stephen Formation; T: Takakkaw Tongue. View towards the south.
- c: Fossil Ridge, connecting Mt. Field (f) and Wapta Mountain (w). The approximate location of the Burgess Quarry (bq) is marked. The Cathedral Escarpment on the south side of Mt. Field is just out of sight to the right of the photo (see Plate 39). Unit abbreviations as for (a) and (b) above. View towards the north.

NATALKO LAKE

- d: The Cathedral Escarpment at Natalko Lake. A larger photograph and line drawing of this critical exposure appear in Plate 40. CE: Cathedral Escarpment; cm: Cathedral megabreccia. Other unit abbreviations as above. View towards the west.

PARK MOUNTAIN

- e: Cathedral Escarpment on the north flank of Park Mountain. The escarpment coincides with a minor, west-side-down normal fault. Note the truncation of bedding in the Cathedral Formation at the escarpment (CE). Unit abbreviations as above. View towards the southeast.

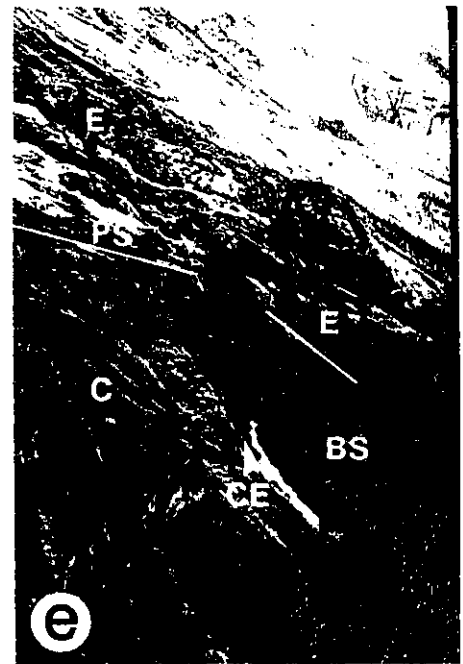
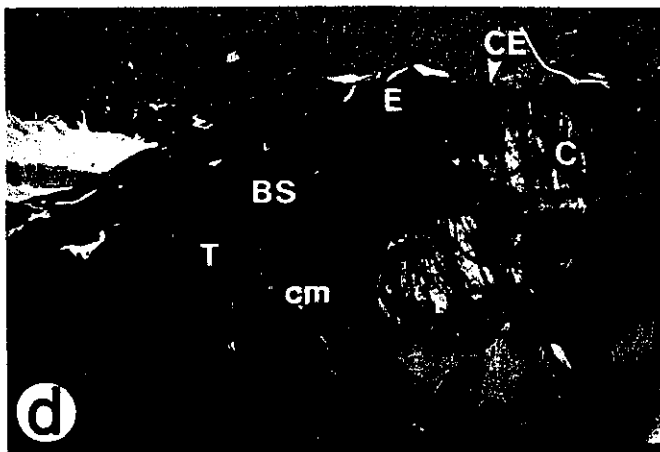
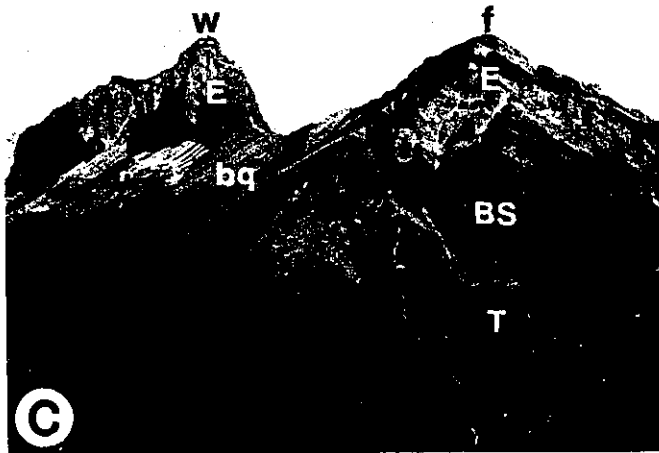
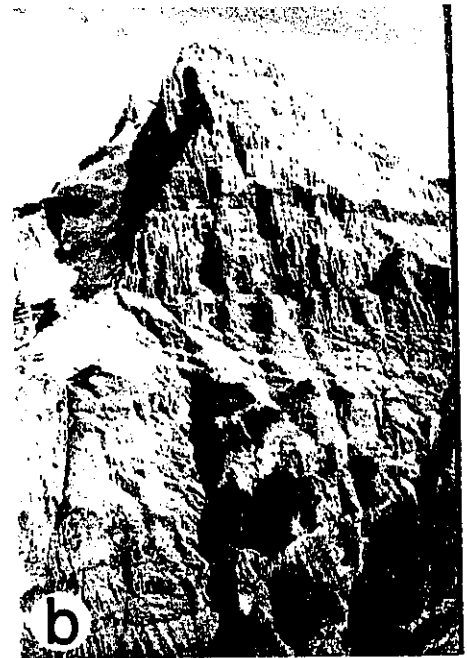
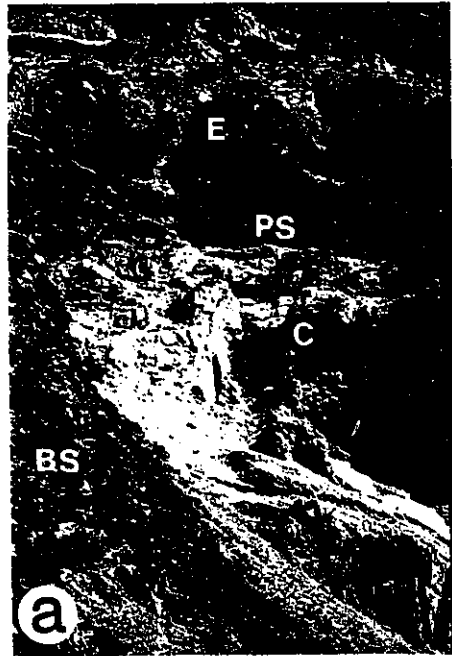
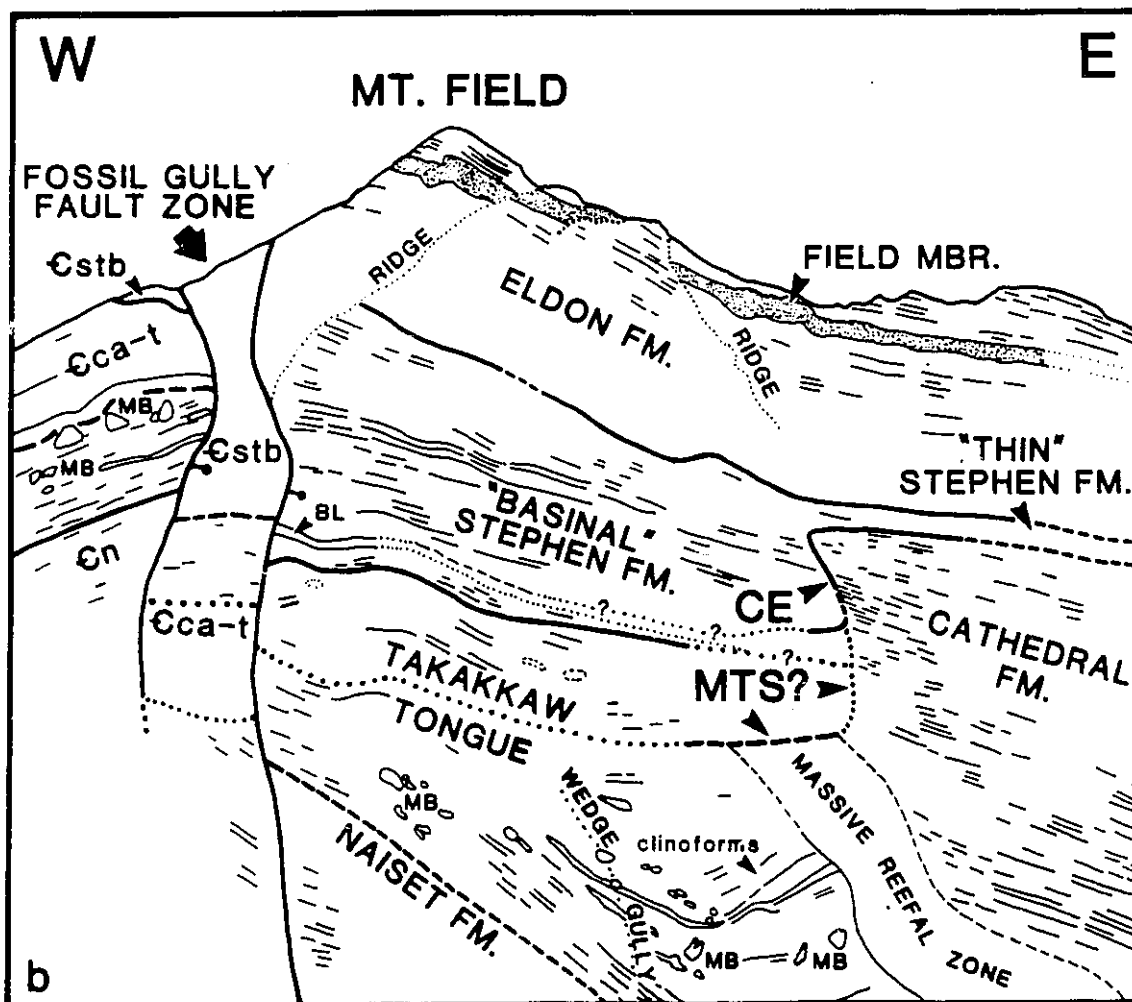


PLATE 39: THE CATHEDRAL ESCARPMENT ON MT. FIELD



- a: The Cathedral Escarpment (CE) on Mt. Field, as viewed from Fossil Gully on Mt. Stephen (original photograph courtesy of Des Collins). View towards north.
- b: Line drawing based on photograph at right. The escarpment, as defined here, is abutted by the upper Takakkaw Tongue and lower "basinal" Stephen Formation. The apparent overhang on this feature is an artifact of the viewing angle. Note the abrupt truncation of the massive "reefal" zone, and the truncated bedding behind much of the escarpment. For scale, the stratigraphic thickness of the lower Eldon Formation (beneath the Field Member) is about 250 m. CE: Cathedral Escarpment; MTS: megatruncation surface; BL: Boundary Limestone; MB: megablock(s); Cca-t: Takakkaw Tongue; Cn: Naiset Formation; Cstb: "basinal" Stephen Formation.
- c: View of progradational lower Cathedral margin on the south face of Mt. Field. Bedded peritidal strata (p) and the massive, reefal zone at the margin (m) are clearly visible. The gently inclined strata of the Takakkaw Tongue (T) pass upward into prominent clinofolds (c). The "basinal" Stephen Formation (BS) and Eldon Formation (E) are visible at the upper right. Wedge Gully (WG) is situated at the left. N: Naiset Formation. View towards the northwest.

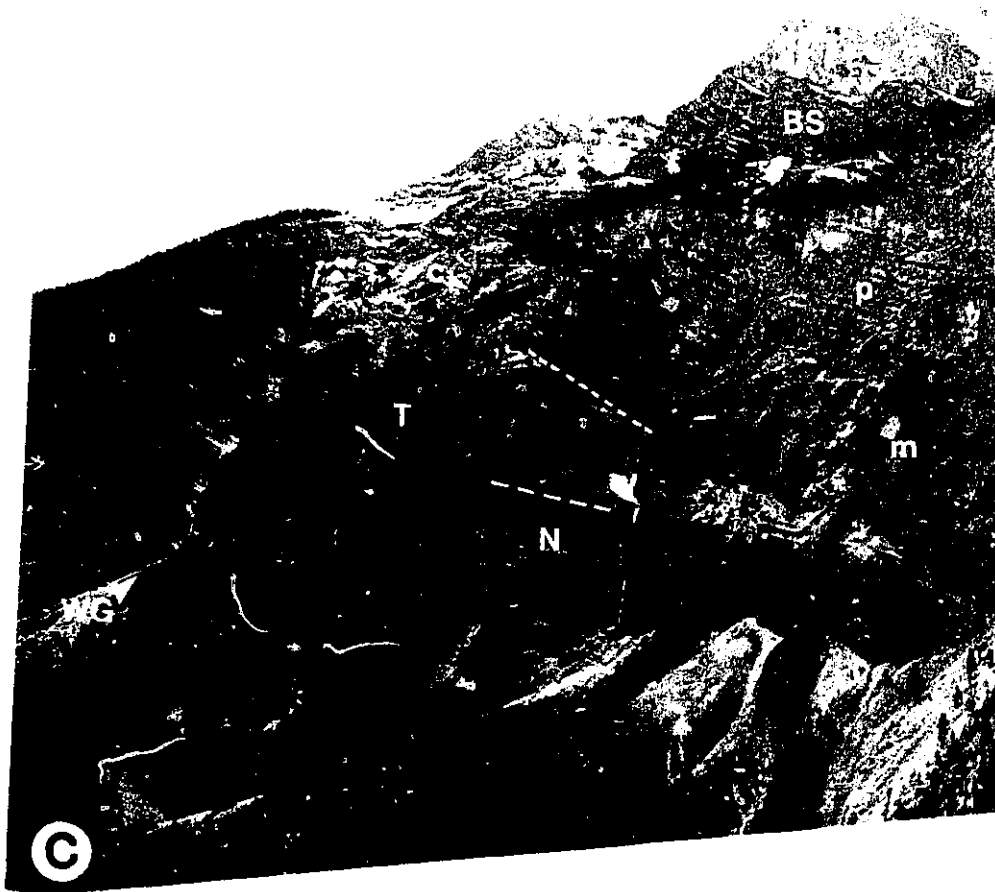
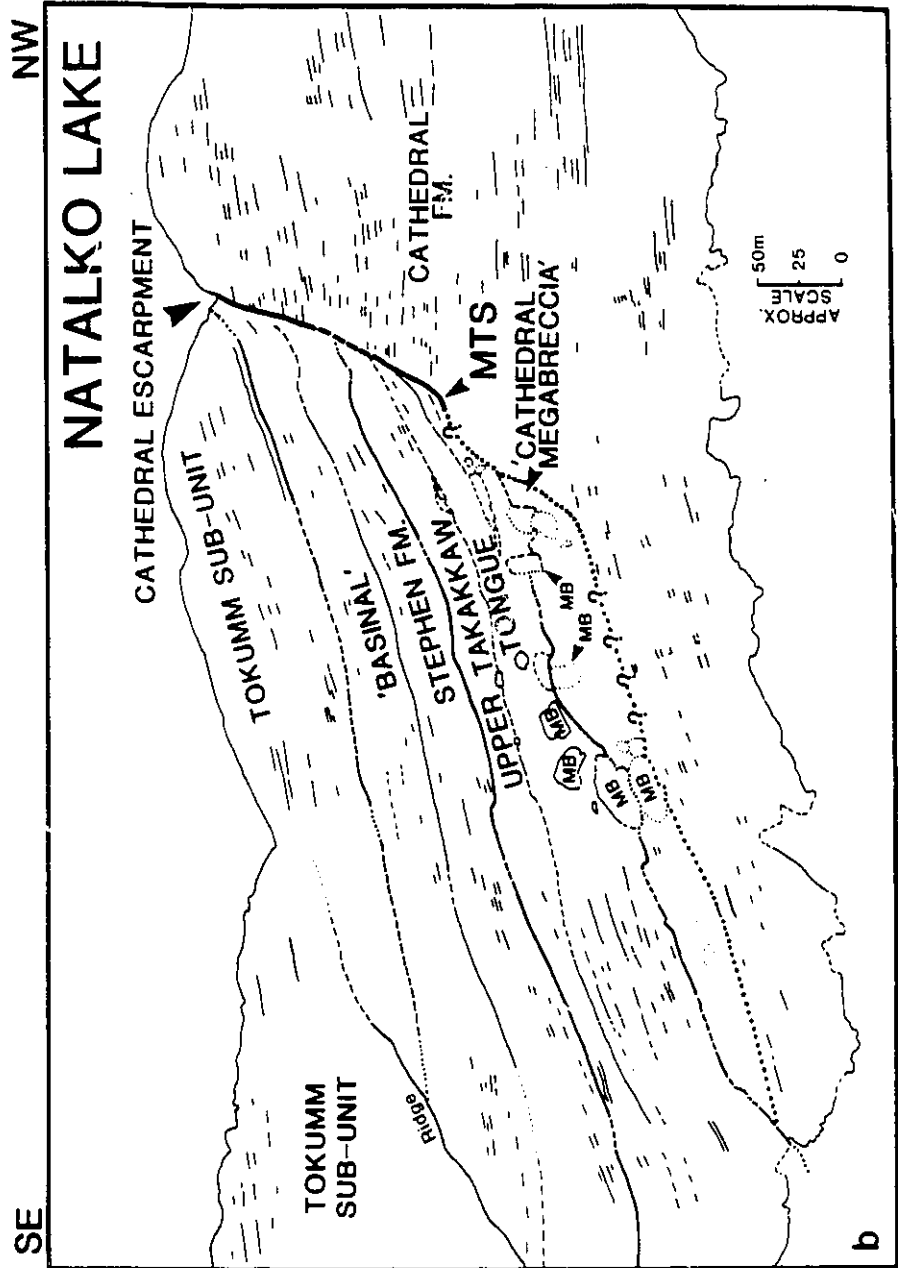


PLATE 40: THE CATHEDRAL ESCARPMENT AT NATALKO LAKE



a: The Cathedral Escarpment at Nataloko Lake. View towards the west.

b: Enlarged line drawing based on photograph, below. The Cathedral Escarpment is abutted by the Cathedral megabreccia, upper Takakkaw Tongue, and "basinal" Stephen Formation. Note the upward projection of megablocks from the top of the Cathedral megabreccia, and the occurrence of periplatform talus blocks and debris flows in the overlying upper Takakkaw Tongue. Peritidal strata of the Cathedral Formation are visibly truncated by the escarpment.

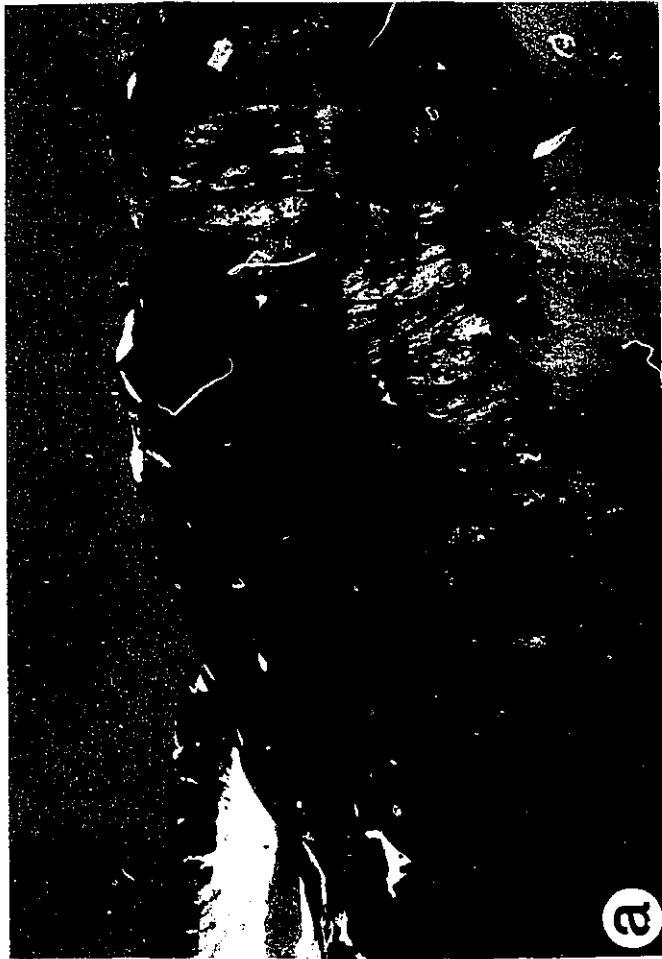
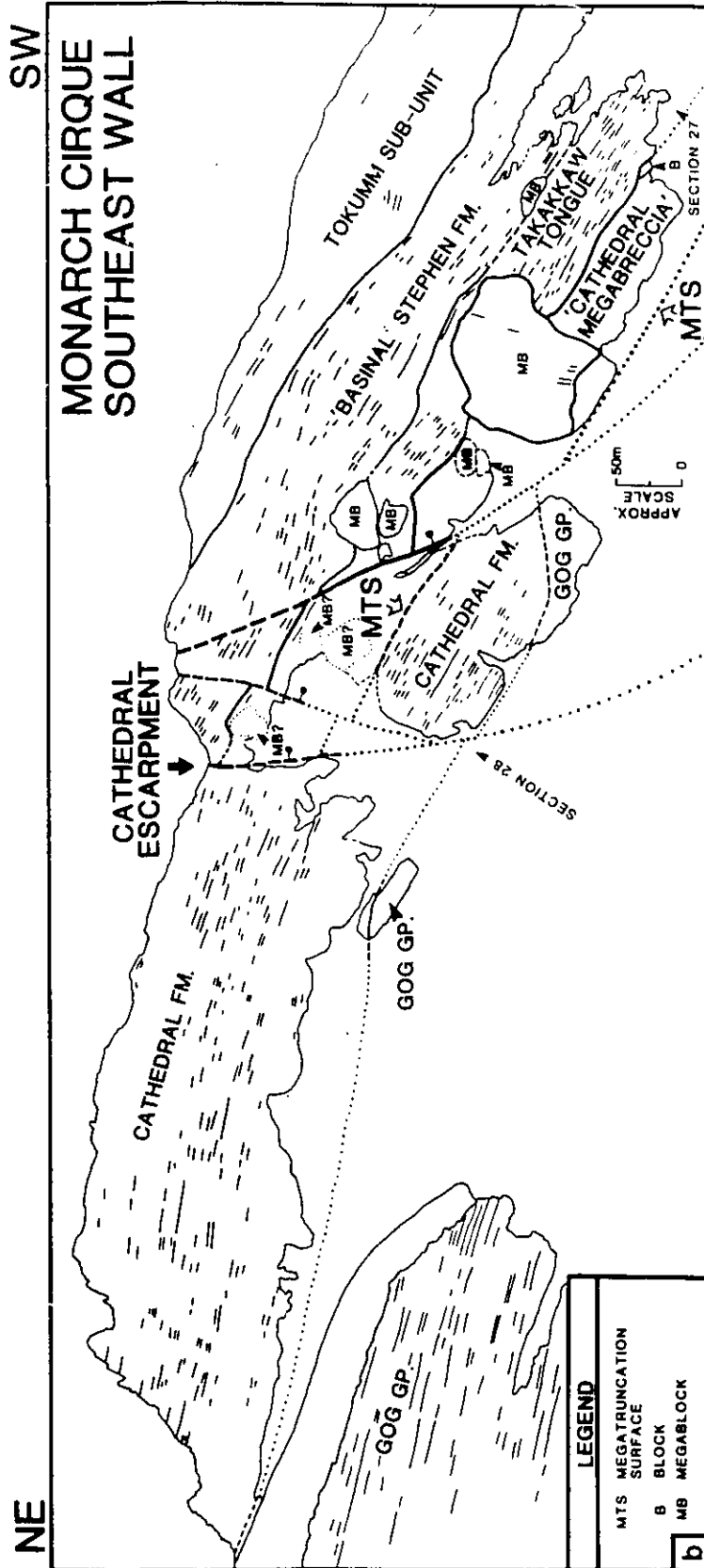


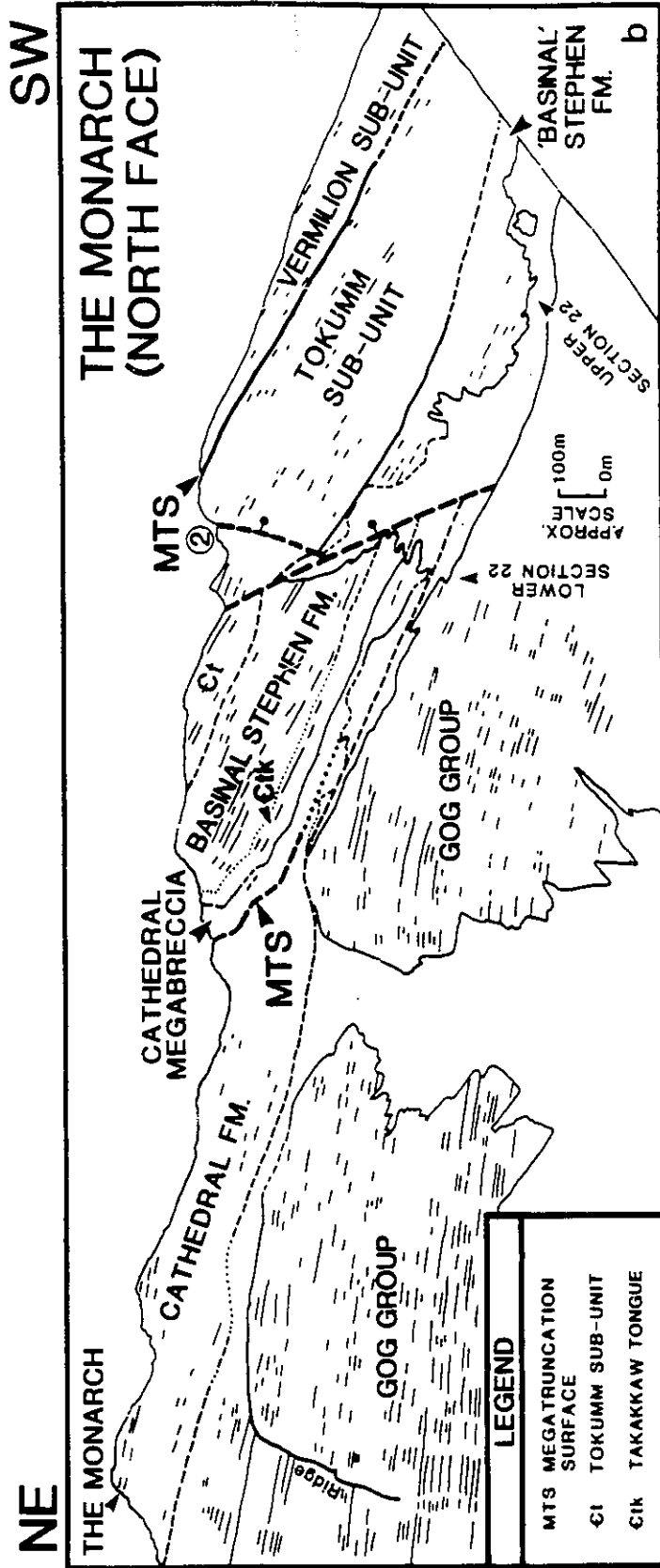
PLATE 41: THE CATHEDRAL ESCARPMENT IN MONARCH CIRQUE



- a: The Cathedral Escarpment (CE) on the south wall of Monarch cirque. View towards the south.
- b: Enlarged line drawing based on photograph, below. The lower part of the escarpment is preserved, and coincides with a minor, west-side-down normal fault. Northeast of the fault, the autochthonous platform sequence (Cathedral Formation) is composed of dolomitic, peritidal sediments. The lower part of this sequence projects southwestward beneath the escarpment, and is overlain by a reddish-weathering dolomite unit containing large "ghost" blocks of periplatform talus blocks (the Cathedral megabreccia). Note the 90 m high periplatform talus block standing on end and projecting upward into the overlying ribbon limestones of the upper Takakkaw Tongue (see also Plate 26d). The Takakkaw Tongue is overlain by the "basinal" Stephen Formation and Tokumm sub-unit at this locality.



PLATE 42: THE MONARCH (NORTH FACE)



a: Stratigraphic units exposed on the north face of The Monarch. Monarch cirque (Plate 41) is located on the opposite (south) side of this ridge. Arrows indicate the contact between the Cathedral megabreccia and the overlying Takakkaw Tongue. View towards the south.

b: Enlarged line drawing based on photograph, below. The approximate position of the now eroded Cathedral Escarpment is shown. Otherwise, the stratigraphy is the same as in Monarch cirque (Plate 41). The base of the Vermilion sub-unit is marked by a megatrust surface (MTS 2).



PLATE 43: "BASINAL" STEPHEN AND ELDON FORMATIONS

"BASINAL" STEPHEN FORMATION AND ASSOCIATED UNITS

- a: **The Monarch (North Face):** section 22, showing the Takakkaw Tongue (T) and "basinal" Stephen Formation (BS) overlying the Cathedral megabreccia (cm). Depositional fabrics have been totally obliterated in the megabreccia by dolomitization. A periplatform talus block (mb) occurs at the top of the Takakkaw Tongue on the left. G: Gog Group; E: Eldon Formation. View towards the southeast.
- b: **Natalko Lake area:** section 23, showing the Takakkaw Tongue (T) and basinal Stephen Formation (BS) overlain by the Tokumm (To) and Vermilion (V) sub-units. The Gog (G) is separated from this sequence by a minor, west-side-down normal fault. The Cathedral Escarpment (CE) at Natalko Lake itself (Plate 40) is visible in the distance at the extreme right. View towards the northwest.

ELDON FORMATION

- c: **Miller Pass area:** bedded, structureless dolomite of the undivided Eldon and Pika formations over the Kicking Horse Rim in section 12. Relict fenestrae, burrow textures and ex-oolitic grainstones are rarely visible in these rocks. Hammer is 34 cm long.
- d: **Mt. Field:** the Field Member (FM) of the Eldon Formation, composed here of 40.8 m of ribbon calcilutite (rl), overlain by 9.1 m of argillite (a; Aitken, in press, a; section AC-161/162). This unit is an eastward-pinching tongue of outer detrital sediments that interrupted peritidal carbonate deposition along the Kicking Horse Rim during mid-Eldon time.
- e: **Tokumm Creek Headwaters:** sequence exposed immediately northwest of section 17 (immediately to right of Plate 45). The east face of Mt. Biddle (B) is indicated on the right. Peritidal dolomites of the Cathedral Formation (C) and argillites of the "platformal" Stephen Formation (S; Waputik Member) make up about the lower half of the wall. The shelf margin for these units lies at least 1.5 km farther southwest. Above are limestones and dolomites of the lower Eldon Formation (E), which are succeeded sharply by the Field Member (FM) and other deep-water strata assigned here to the Tokumm sub-unit (To). View towards the northwest.

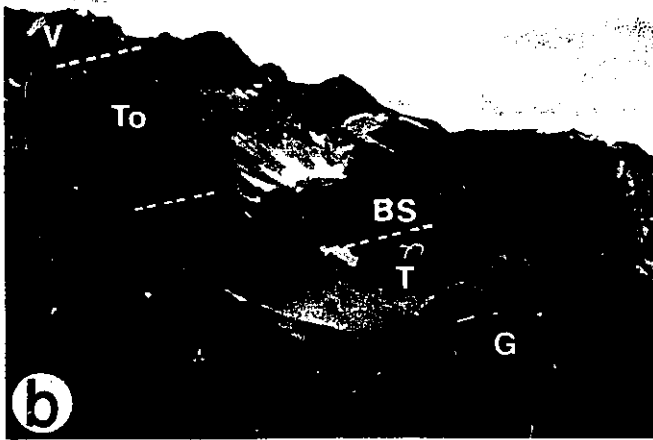
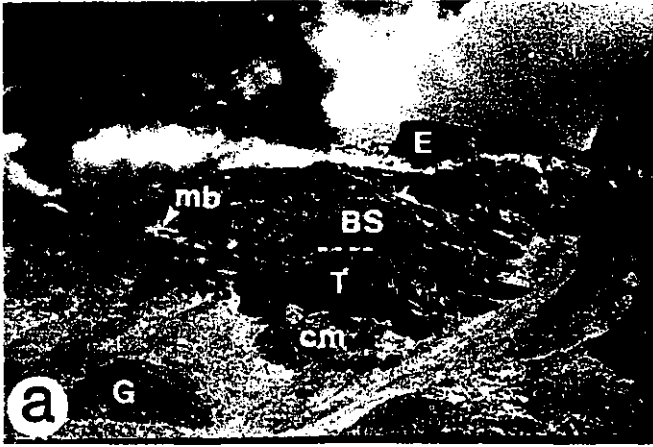
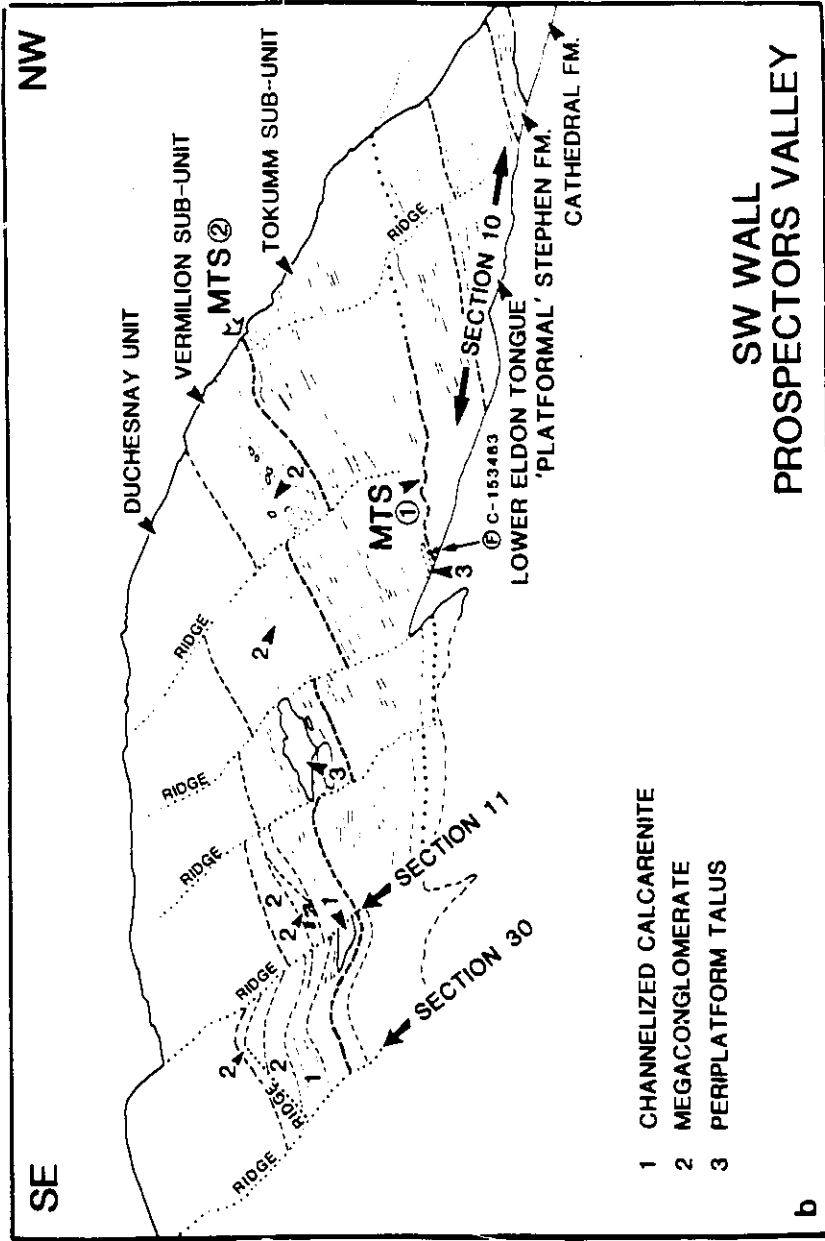


PLATE 44: SOUTHWEST WALL OF PROSPECTORS VALLEY

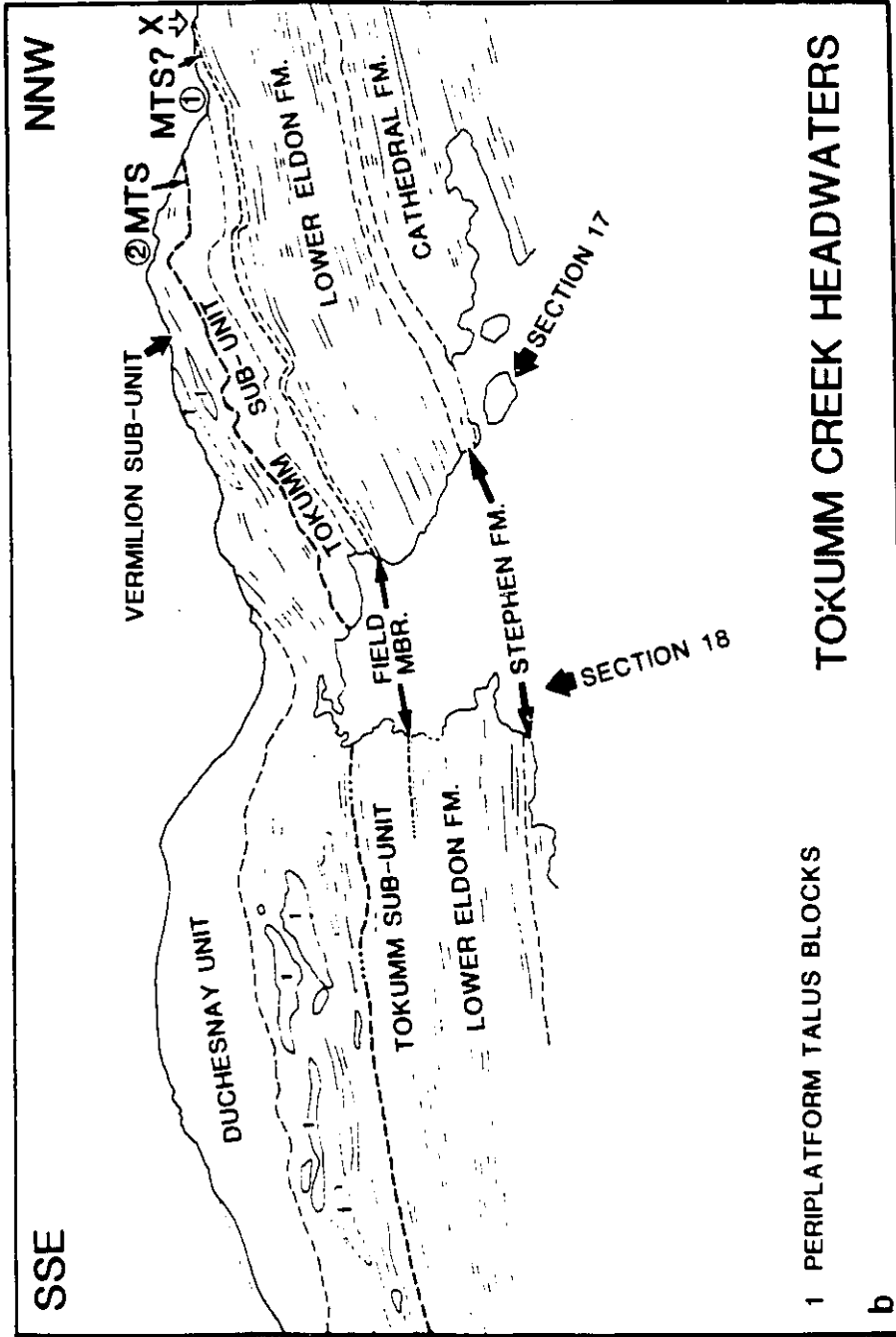


- a: Lower and middle Chancellor strata on the southwest wall of Prospectors Valley. The valley trend is approximately parallel to depositional strike. View from the valley floor towards the west.
- b: Enlarged line drawing based on photograph, below. Platformal rocks of the Cathedral, Stephen, and lower Eldon formations pass conformably upward into predominantly deep-water limestones of the Tokumm sub-unit. This sub-unit contains a megatrucaution surface at the base of a widespread siliciclastic marker (intra-Tokumm megatrucaution surface; MTS 1). A second megatrucaution surface (sub-Vermilion megatrucaution surface; MTS 2) is inferred to occur at the base of the Vermilion sub-unit. The Vermilion sub-unit contains spectacular calcarenite-filled slide scars, periplatform talus blocks, and debris flows. The visible part of the ridge is capped by deformed argillites of the Duchesnay unit. For scale, the lower Eldon Tongue in section 10 has a stratigraphic thickness of about 100 m.



a

PLATE 45: TOKUMM HEADWATERS

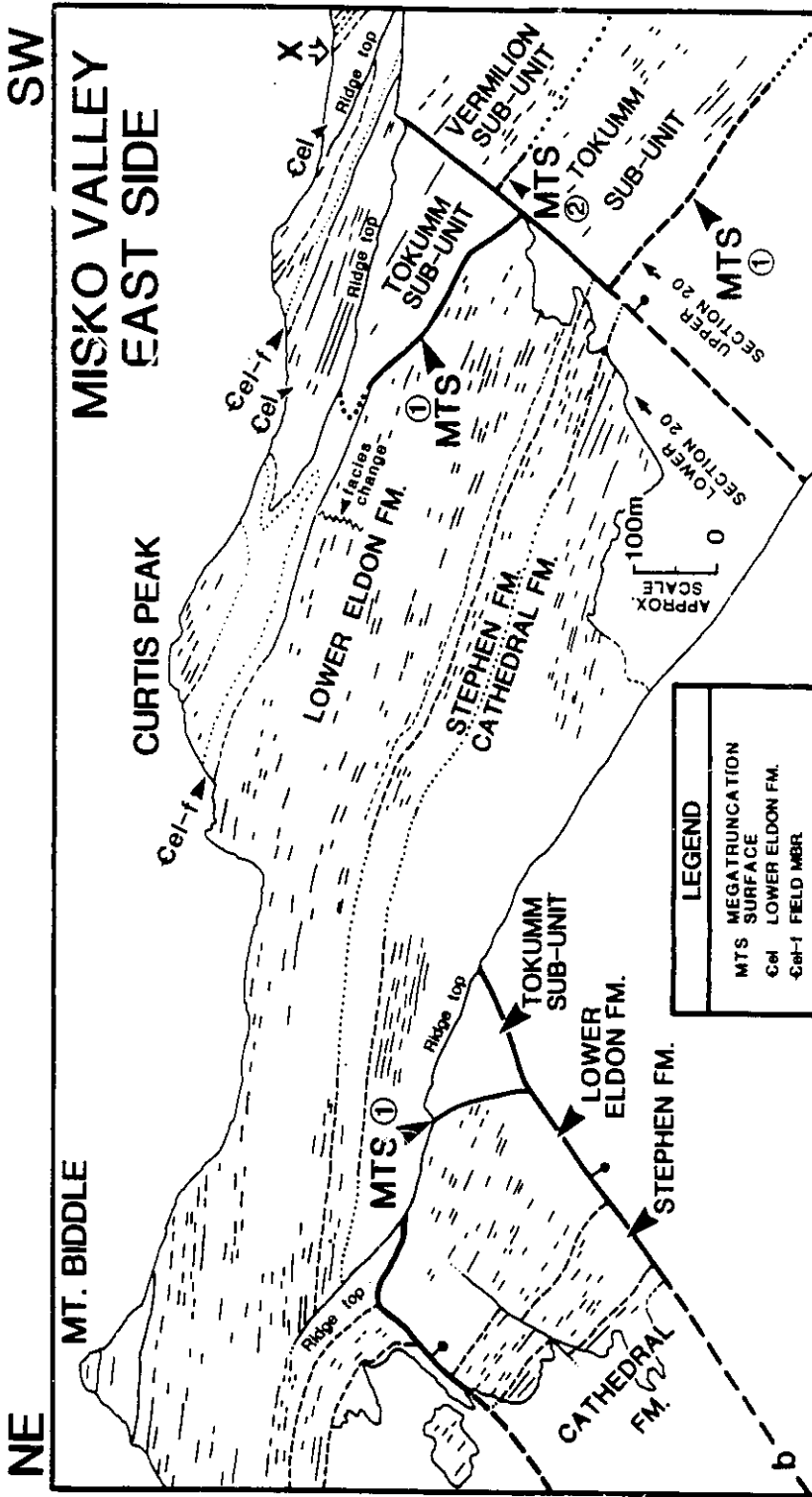


a: Tokumm and Vermilion sub-units overlying platformal strata of the Cathedral, Stephen and lower Eldon formations in the headwaters of Tokumm Creek. View towards the west.

b: Enlarged line drawing based on photograph, below. The Vermilion sub-unit contains conspicuous periplatform talus blocks at this locality. The lower boundary of this sub-unit is inferred to be a megaturuncation surface (sub-Vermilion megaturuncation surface; MTS 2). The tentative position of the intra-Tokumm megaturuncation surface (MTS 1) seen on the opposite side of the ridge is also shown. The "X" (upper right) marks a point on the ridge also visible in Plate 46. For scale, the lower Eldon Formation in section 17 has a stratigraphic thickness of about 215 m.



PLATE 46: MISKO VALLEY: EAST SIDE

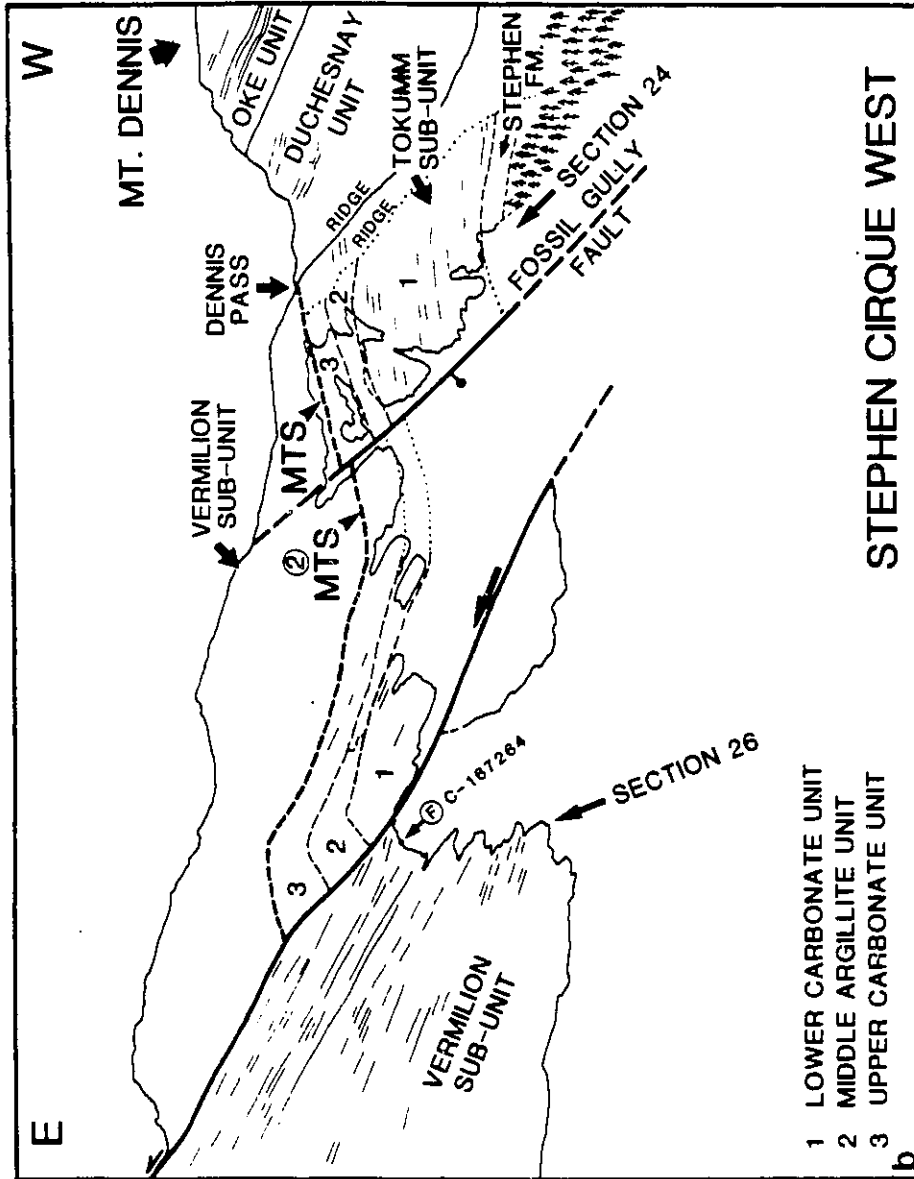


a: The key, cross-strike exposure of the facies change at the level of the Eldon Formation in Biddle cirque. This exposure is on the opposite side of ridge and slightly northwest of the exposure shown in Plate 45. Note the gradual facies change (fc) from massive, medium grey burrow-mottled limestones (left) to dark grey, thin-bedded limestones of deeper water aspect (right) in the lower Eldon Formation. The trace of the intra-Tokumm megatrust surface is indicated by a series of arrows.

b: Enlarged line drawing based on the photograph below. The Cathedral and Stephen formations continue unchanged to the normal fault, and are not exposed farther west. The lower Eldon Formation is truncated by the intra-Tokumm megatrust surface (MTS 1), which continues west of the fault. A closeup of this feature is shown in Plate 48c. The sub-Vermilion megatrust surface (MTS 2) is poorly exposed at this locality. The "X" (upper right) marks a point on the ridge also visible in Plate 45.



PLATE 47: STEPHEN CIRQUE WEST



a: The Tokumm and Vermilion sub-units in the western part of Stephen cirque. View towards the SSW.

b: Line drawing based on photograph below. The Tokumm sub-unit (units 1-3 in diagram) has been thinned substantially beneath the sub-Vermilion megatrustation surface (MTS 2) in the western part of the cirque. It is overlain by monotonous slate of the Vermilion sub-unit, which continue to the west side of Dennis Pass. The deep-water succession is underlain by platformal strata of the Cathedral and Stephen formations in this part of the cirque. [Note: the apparent reverse displacement on the Fossil Gully Fault is an artifact of perspective]. For scale, the Tokumm sub-unit in section 24 has a stratigraphic thickness of about 180 m.



PLATE 48: OUTCROP PHOTOGRAPHS - McARTHUR UNIT

STRATIGRAPHY, WEST WALL OF PROSPECTORS VALLEY

- a: Complete sequence exposed on the southwest wall of Prospectors Valley, a short distance northwest of section 10. The base of the sequence is marked by platformal strata of the Cathedral (C), platformal Stephen (S) and lower Eldon (E) formations. The platform margins for these stratigraphic units presumably lie a short distance farther southwest, beneath the ridge. Gradationally overlying the platformal sequence are deep-water strata of the Tokumm (To) and Vermilion (V) sub-units of the lower Chancellor, and the Duchesnay unit (D) of the lower middle Chancellor. Note the conspicuous grey marker at the top of the Vermilion sub-unit (arrow). View towards the northwest.

TOKUMM SUB-UNIT

- b: **Marble Canyon:** the cliffs overlooking Marble Canyon expose the Tokumm sub-unit (To) and the lower Vermilion sub-unit (V). The upper siliciclastic marker (sm) of the Tokumm sub-unit contains an exotic megablock, and crops out just above the top of the talus. A periplatform talus block (mb) is also visible in the Vermilion sub-unit at the top of the cliff. View north from Highway 93.
- c: **Biddle cirque:** intra-Tokumm megatruncation surface (marked by arrows), separating massive argillites (A) of the basal Tokumm sub-unit and thin-bedded limestones (LS) of the lower Eldon Formation in section 20. The megatruncation surface cuts downward to the right in this exposure. This locality is also shown in Plate 46. Figure is 1.8 m tall.
- d: **Curtis cirque area:** cross-strike exposure of the contact between the Tokumm (To) and Vermilion (V) sub-units (arrows). This contact is inferred to be a near-bedding-parallel segment of a megatruncation surface. The intra-Tokumm megatruncation surface is seen in the foreground (dashed line; dots trace the top of a small ridge). The lower Eldon Formation crops out beneath the surface. View towards the south from the top of section 20.
- e: **Monarch cirque:** ribbon limestones of the Tokumm sub-unit in the upper part of section 27.

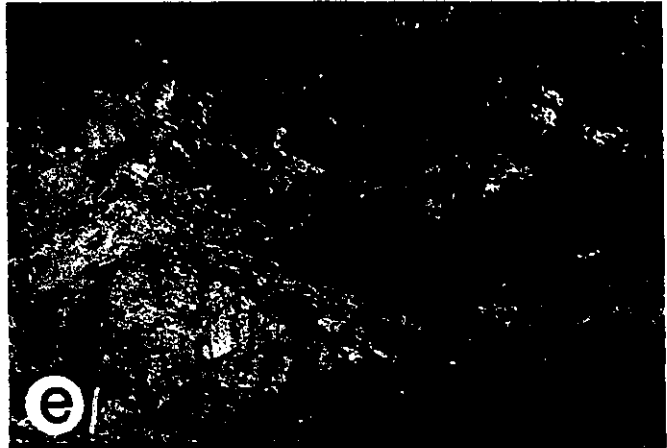
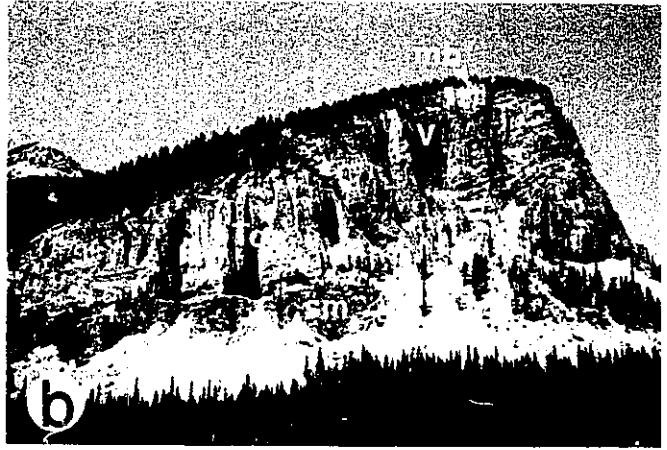
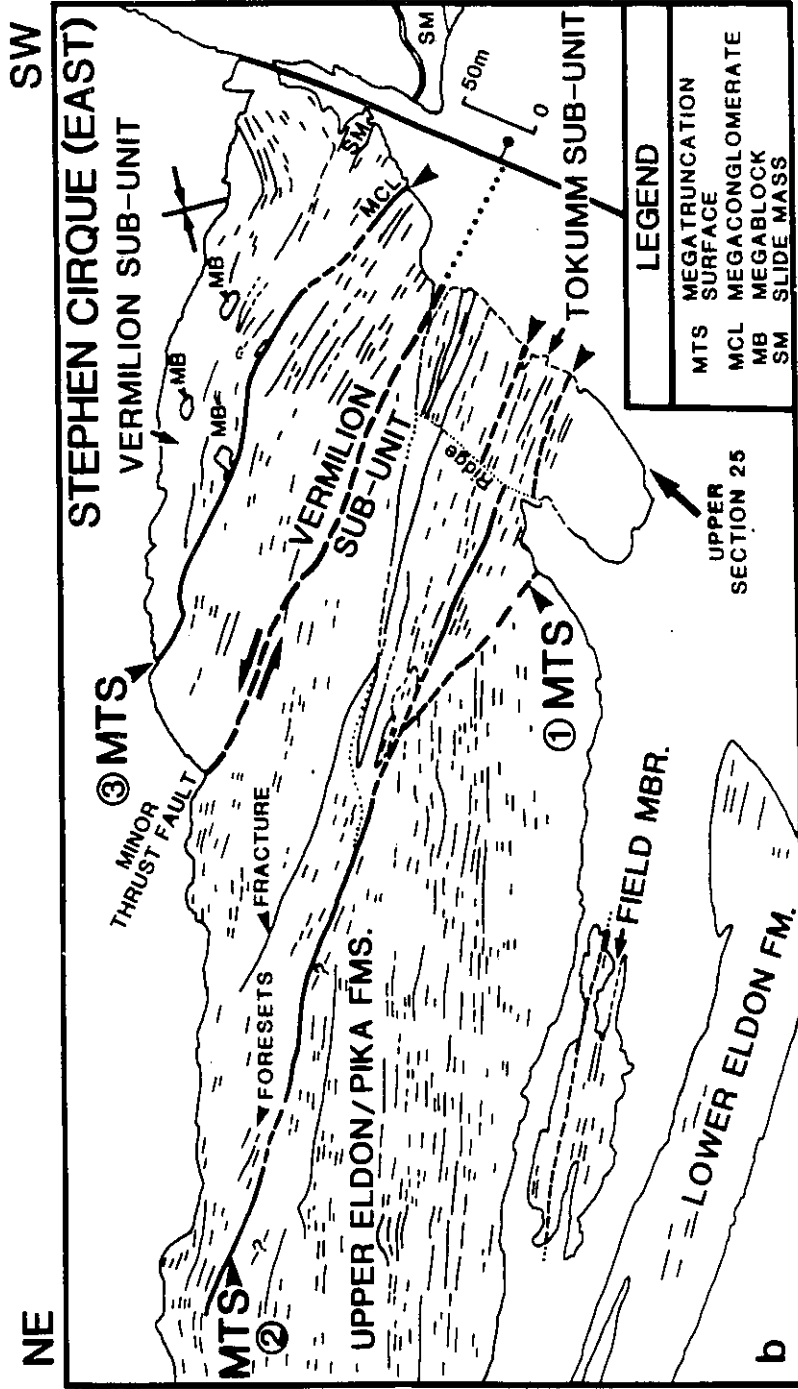


PLATE 49: STEPHEN CIRQUE EAST

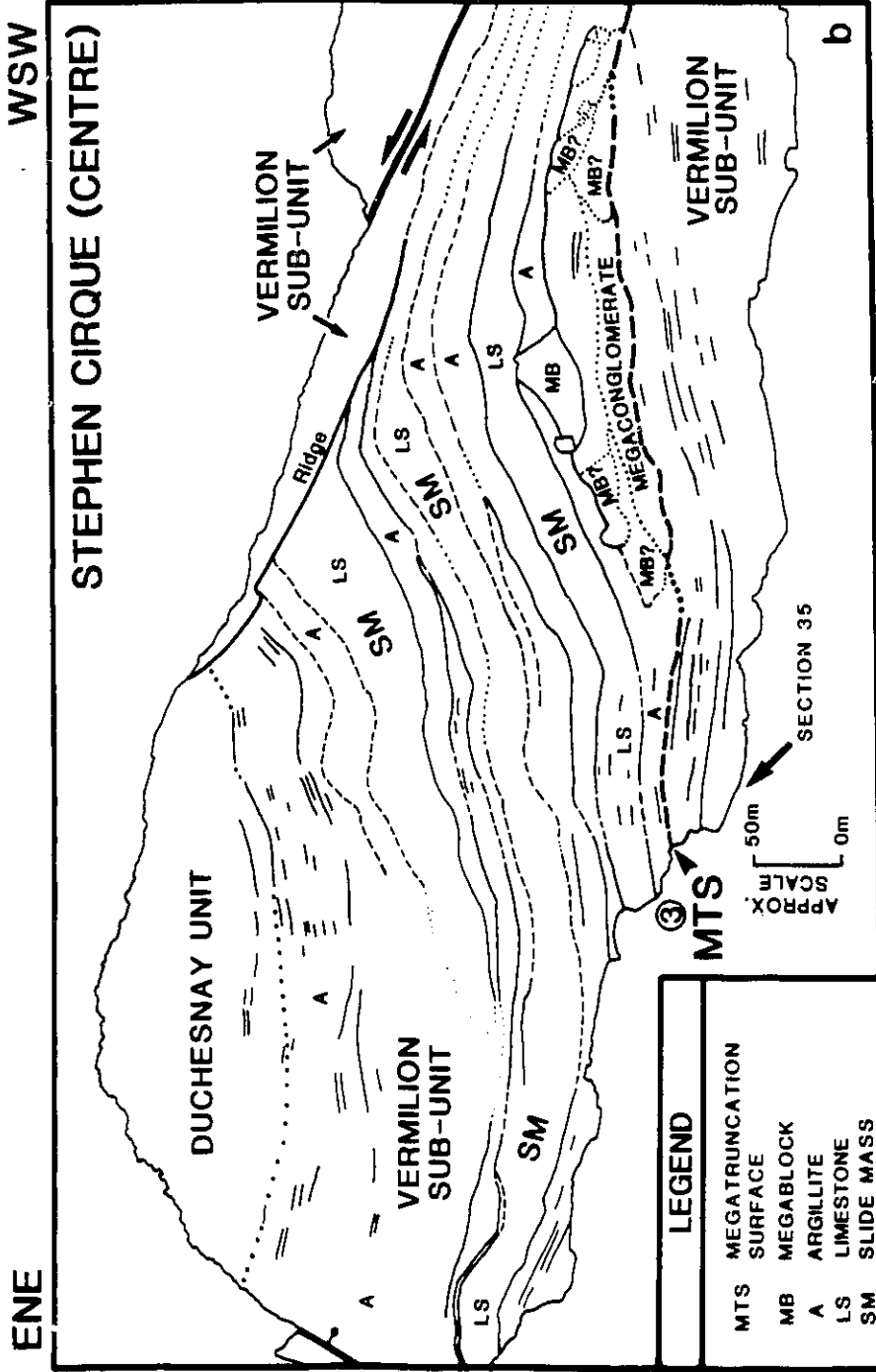


a: Eastern part of the key, cross-strike exposure at the level of the upper Eldon and Pika formations in Stephen cirque. The series of arrows outline megatracuncation surfaces traversing the sequence. View towards the southeast. Numbers indicate where the megatracuncation surfaces intersect section 25.

b: Enlarged line drawing based on photograph, below. Bedded, peritidal platform strata (mostly destructively dolomitized) of the upper Eldon and Pika formations are truncated by three megatracuncation surfaces, all of which intersect section 25. The intra-Tokumm megatracuncation surface (MTS 1) is overlain by an anomalously thin Tokumm sub-unit, and is cut out by the more laterally extensive sub-Vermilion megatracuncation surface (MTS 2). The latter surface is overlain by the predominantly argillaceous Vermilion sub-unit. The intra-Vermilion megatracuncation surface (MTS 3) intersects the skyline, and is also identifiable on the opposite side of the ridge in Duchesnay Basin (Plate 51). It is locally overlain by a dolomitized megaconglomerate (MCL). The stratigraphy traversed by section 25 can be traced across the normal fault at right into Plate 50.



PLATE 50: STEPHEN CIRQUE CENTRE

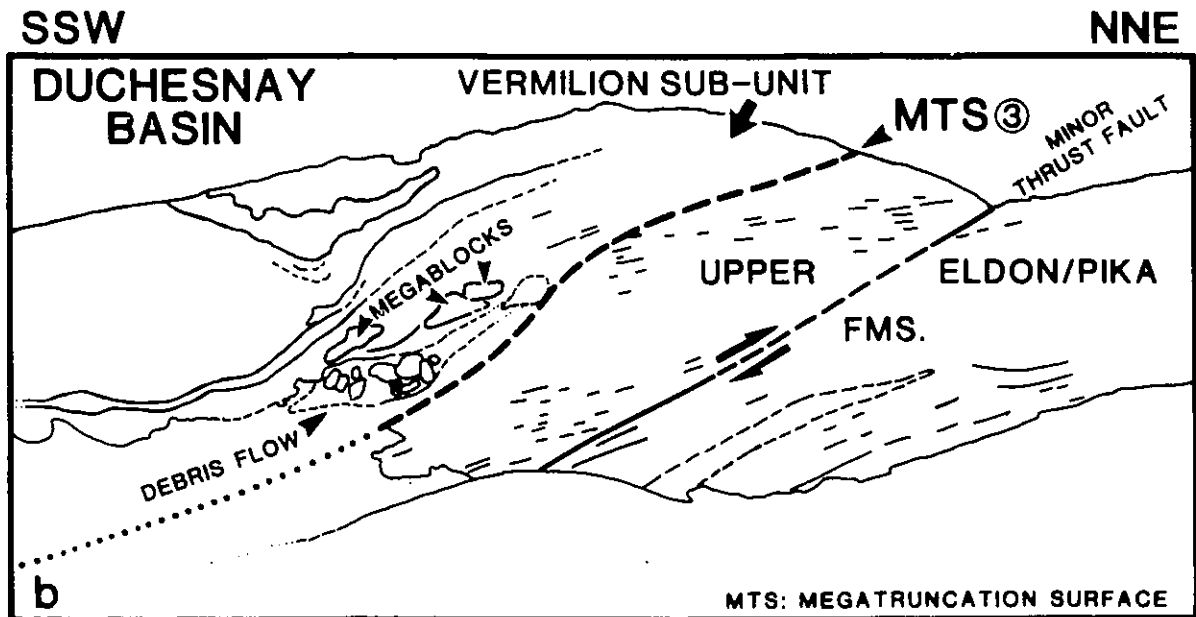


- a: Central part of the key, cross-strike exposure at the level of the upper Eidon and Pika formations in Stephen cirque. The lower series of arrows outlines the intra-Vermilion megatruncation surface (MTS 3). mb: megablock at top of large megaconglomerate. View towards the south.
- b: Line drawing based on photograph, below. The Vermilion sub-unit is composed of intercalated argillite and ribbon limestone, and contains large, elongate slide masses (SM). The intra-Vermilion megatruncation surface (MTS 3) is near bedding-parallel, and is extremely subtle in section 35. It becomes more obvious laterally, where it underlies a major megaconglomerate. Section 26 is just off the edge of the diagram to the right, and is shown in Plate 47.



PLATE 51: DUCHESNAY BASIN

- a: Truncation of the upper Eldon-Pika sequence in Duchesnay basin, on the opposite side of the ridge from Stephen cirque east. Arrows outline the trace of the intra-Vermilion megatruncation surface. View towards the west.
- b: Line drawing of photograph, at right. The intra-Vermilion megatruncation surface (MTS 3) is locally overlain by a megaconglomerate containing Epiphyton boundstone megablocks. Structurally deformed argillaceous strata of the Vermilion sub-unit are exposed above the surface.



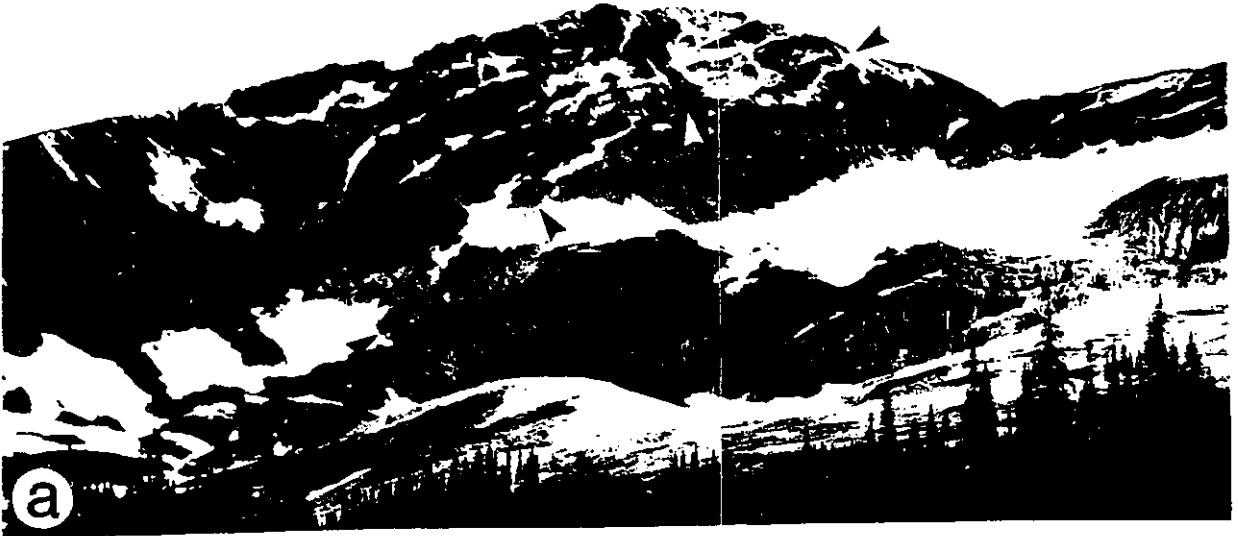


PLATE 52: VERDANT CIRQUE - NORTHWEST WALL

- a: Aerial view showing the key, cross-strike exposure at the level of the Eldon and Pika formations on the northwest wall of Verdant cirque. The black and white arrows outline the sub-Vermilion and intra-Vermilion megatruncation surfaces, respectively. View towards the north.
- b: Line drawing based on photograph, at right. Platformal strata of the upper Eldon/Pika formations are truncated by the near bedding-parallel sub-Vermilion megatruncation surface (MTS 2), which is directly overlain by deep-water strata of the Vermilion sub-unit. The slope sequence contains at least five megaconglomerate bodies (some of which are amalgamated), as well as the subtle, near bedding-parallel, intra-Vermilion megatruncation surface (MTS 3). The latter feature is better defined on the opposite wall of the cirque (Plate 54).

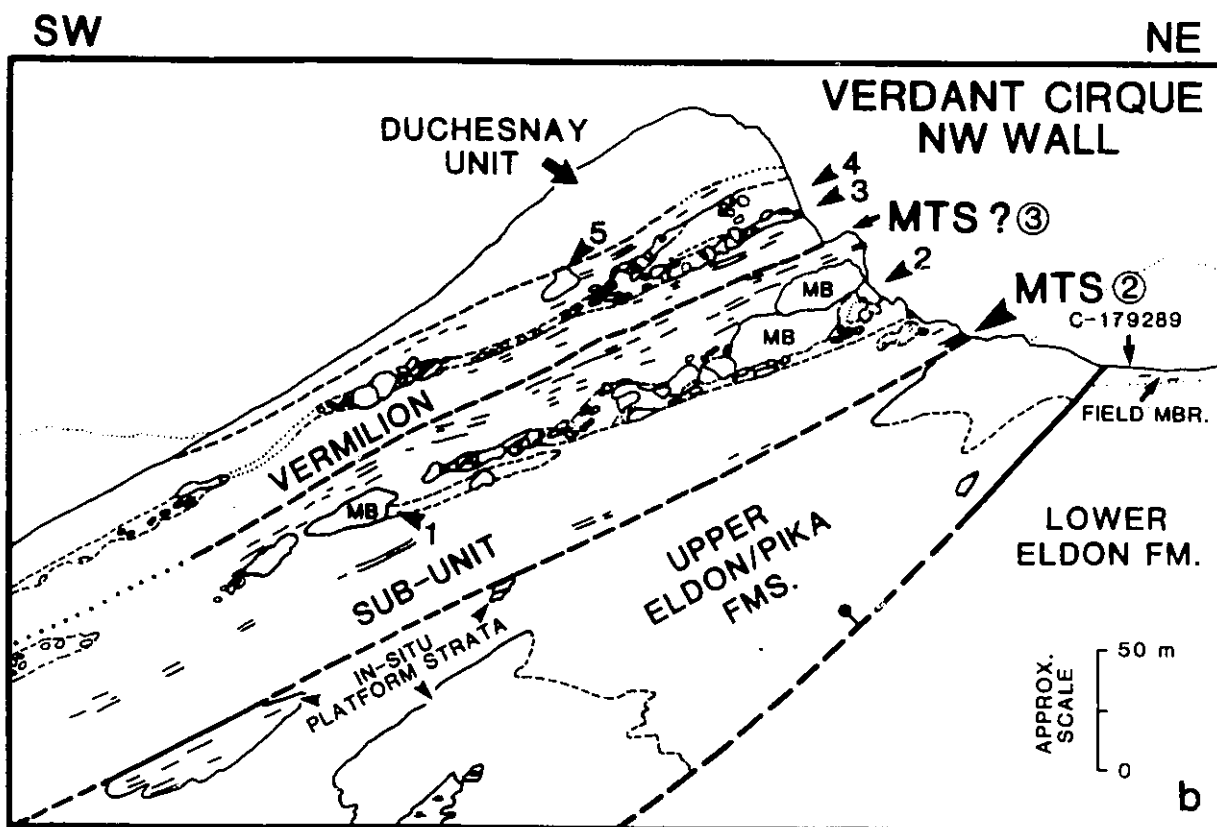
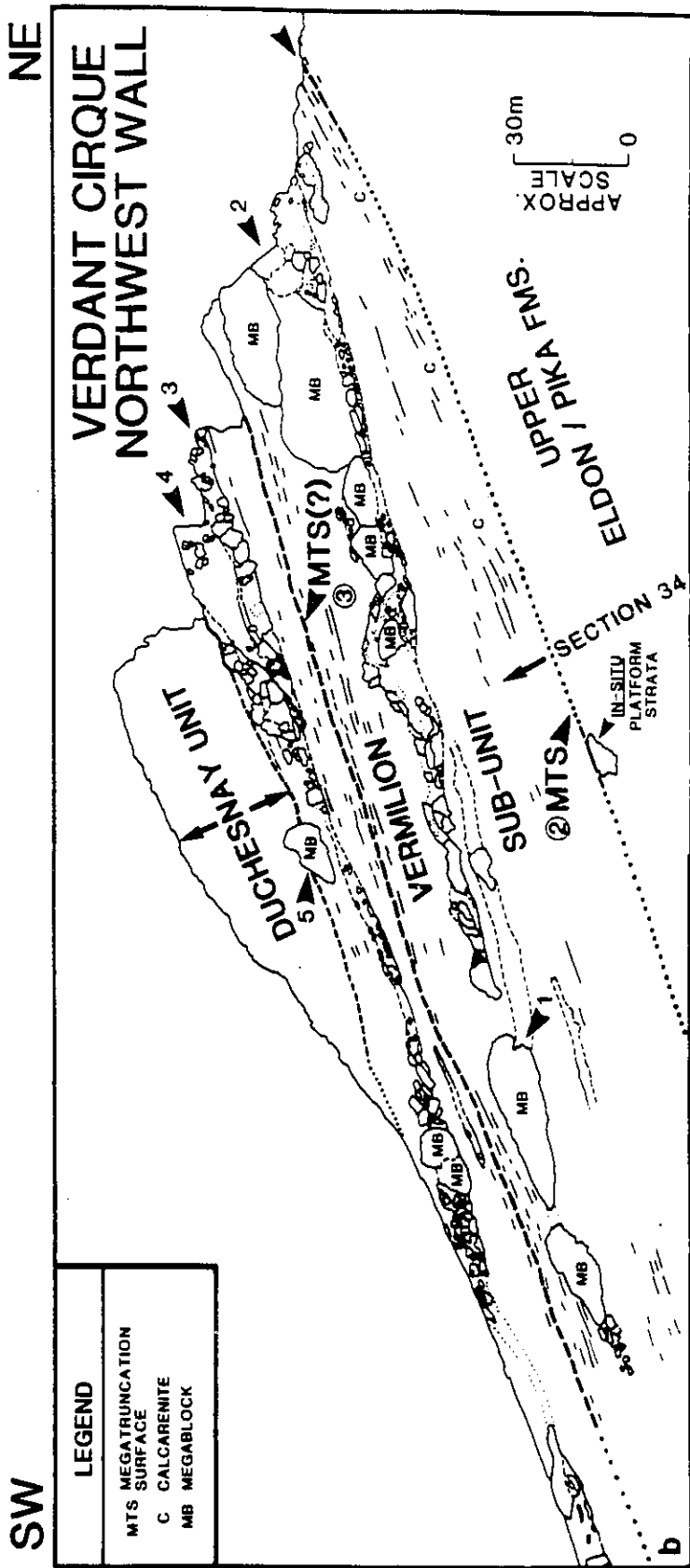




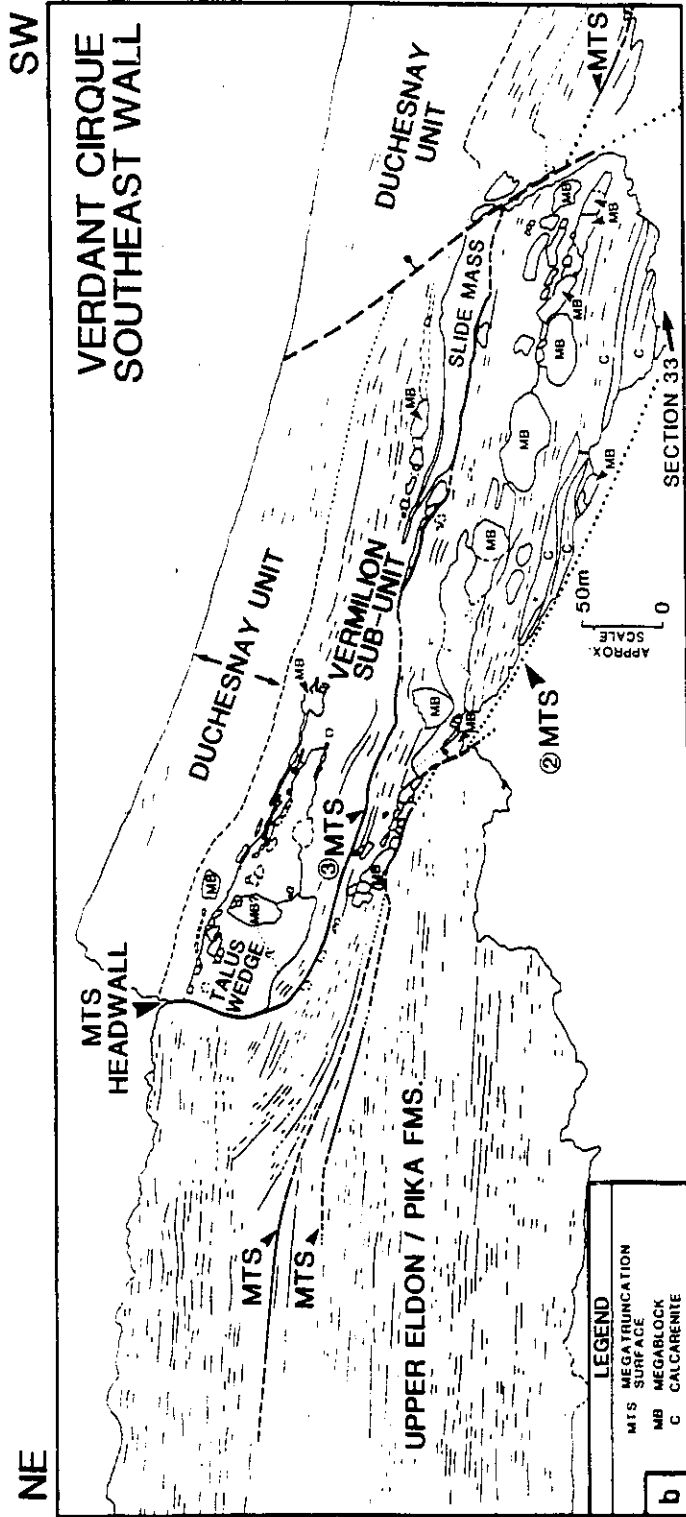
PLATE 53: VERDANT CIRQUE - NORTHWEST WALL



- a: Detailed view of the northwest wall of Verdant cirque shown in Plate 52. View towards the north.
- b: Line drawing based on photograph, below. The lower and upper series of arrows outline the sub-Vermilion and intra-Vermilion megatruncation surfaces, respectively. This exposure is described in Plate 52.



PLATE 54: VERDANT CIRQUE - SOUTHEAST WALL



a: The key, cross-strike exposure at the level of the upper Eldon and Pika formations on the southeast wall of Verdant cirque. The arrow sets outline the megatruncation surfaces traversing the sequence at this locality. View towards the south.

b: Line drawing of photograph below. This is the most spectacular and revealing view of the truncated Eldon/Pika margin in the study area. Bedded, peritidal platform strata were initially truncated by two surfaces, which converge to form a single, sub-Vermilion megatruncation surface laterally (MTS 2). Both surfaces roll over and disappear into sub-horizontal platform bedding at left. The sub-Vermilion megatruncation surface is overlapped by the predominantly argillaceous Vermilion sub-unit, which contains prominent megaconglomerates and calcarenite bodies. Subsequent progradation of the platform is indicated by the prominent foresets above this surface. The outer platform failed a second time along the intra-Vermilion megatruncation surface (MTS 3), which has a near-vertical headwall. This surface becomes bedding-parallel laterally, and is difficult to recognize. Minor failures along the truncated margin subsequently deposited the prominent talus wedge that abuts the escarpment.



PLATE 55: OUTCROP PHOTOGRAPHS - VERMILION SUB-UNIT

- a: **Prospectors Valley:** closeup of the southwest wall of Prospectors Valley, showing prominent, allochthonous carbonate masses in the Vermilion sub-unit (V). The grey limestone cliffs in the lower part of the photo belong to the Tokumm sub-unit (To). The elongate periplatform talus block (t) is also illustrated in Plate 44. The large carbonate mass at the upper left (m) is the prominent carbonate marker at the top of the Vermilion sub-unit (see Plate 48a), and is composed mainly of megaconglomerate and subordinate ribbon limestone (closeup shown in (e) below). View towards the southwest.
- b: **Tokumm Creek headwaters:** contact (arrowed) between ex-ribbon limestone of the Tokumm sub-unit (lower right-hand corner) and dominantly argillaceous rocks of the Vermilion sub-unit (V) in section 17. This abrupt contact is inferred to be the trace of the sub-Vermilion megatruncation surface through the area.
- c: **Mt. Dennis:** contact (arrowed) between the Vermilion sub-unit (V) and reddish-weathering, dolomitic slates and argillites of the Duchesnay unit on the east ridge of Mt. Dennis. The prominent carbonate marker in the uppermost Vermilion sub-unit is composed, in part, of massive limestone conglomerate with megaclasts or massive interbeds of oolitic grainstone. Tight, partly overturned folds (f) occur in this unit and in the overlying slates. Dennis Pass is situated just out of the photo to the right. O: Oke unit. View towards the northwest.
- d: **Verdant Creek:** aerial view towards the north of the truncated Eldon-Pika margin on the northeast side of Verdant Creek. The light grey exposures on the right are sub-horizontal peritidal strata of the Eldon and Pika formations (E-P). These strata are truncated by the sub-Vermilion megatruncation surface (arrows), which is overlain by inclined, dark brown-grey strata assigned to the Vermilion sub-unit (V).
- e: **Prospectors Valley:** closeup view of the contact between the Vermilion sub-unit (V) and monotonous, silty dolomitic argillite of the Duchesnay unit (D) above section 11. The prominent carbonate marker at the top of the Vermilion sub-unit is composed of megaconglomerate and subordinate ribbon limestone. Figure (circled) for scale.

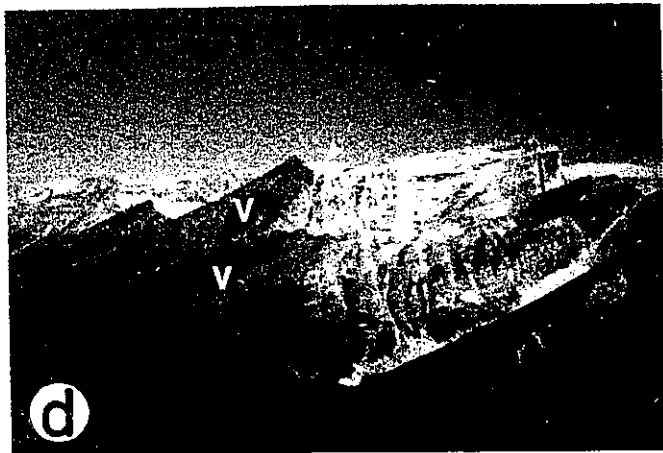
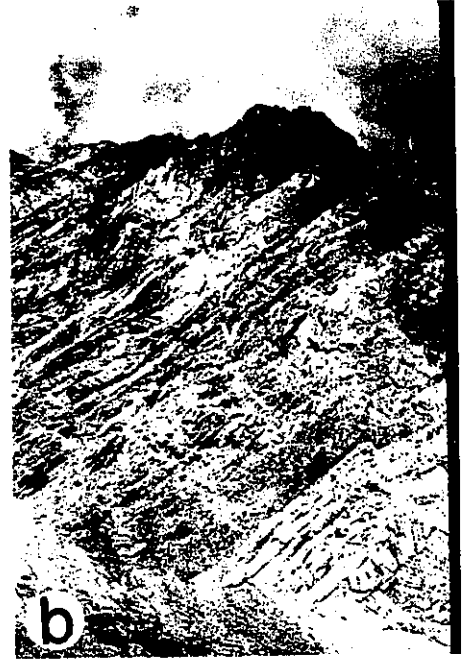
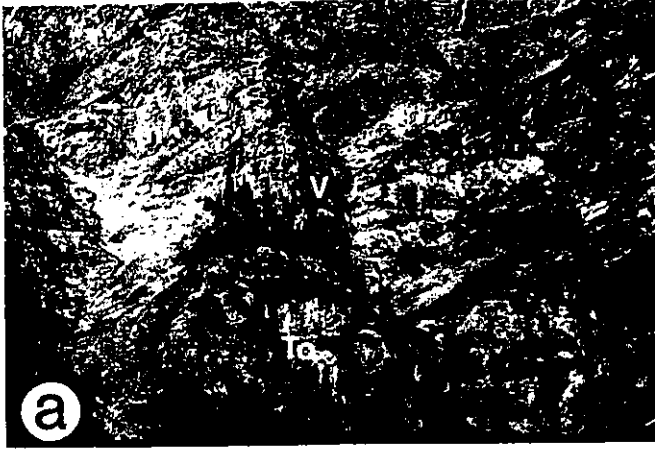


PLATE 56: OUTCROP PHOTOGRAPHS - DUCHESNAY UNIT

- a: **Mt. Dennis North:** type section of the Duchesnay unit (D) on the north side of Mt. Dennis (section 1). The uppermost Vermilion sub-unit (V) contains a thick sequence of monotonous, ribbon limestone, which may be an enormous slide block. The type section has a disadvantage in that a major offset is necessary along a major conglomerate marker in the treed area at centre. View towards the south.
- b: **Miller Pass:** abrupt, planar contact between undifferentiated Eldon/Pika platform strata (EP) and deep-water strata of the Duchesnay unit (D). Arrow indicates the gully used to measure section 12. View looking west.
- c: **Miller Pass:** closeup of the contact between undifferentiated platform strata of the Eldon/Pika formations (EP) and deep-water strata of the Duchesnay unit (D) on the inaccessible cirque wall above section 12. The contact is abrupt and apparently bedding-parallel, and is inferred to be a drowning surface.
- d: **Mt. Dennis South:** reference section of the Duchesnay unit (D) on the opposite side of Mt. Dennis from the type section shown in (a) above. The base of the succession is in the treed area at the lower right. Note the well defined contact with resistant carbonate strata of the overlying Oke unit (O). View looking northwest.
- e: **Hamilton cirque south:** contact between irregular ribbon-type limestones of the Pika Formation (P) and monotonous, dolomitic argillite of the Duchesnay unit (D).

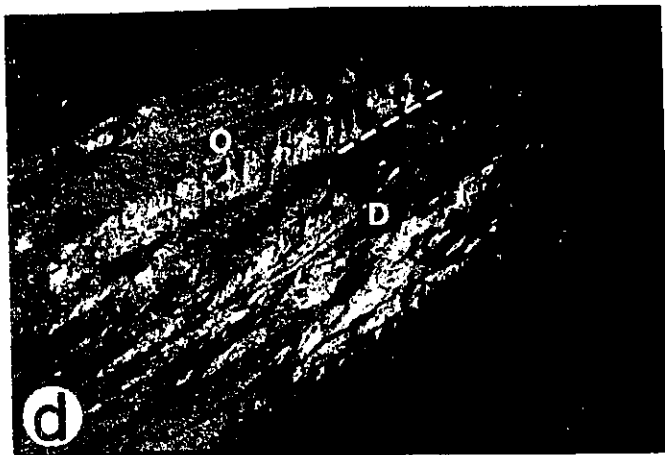
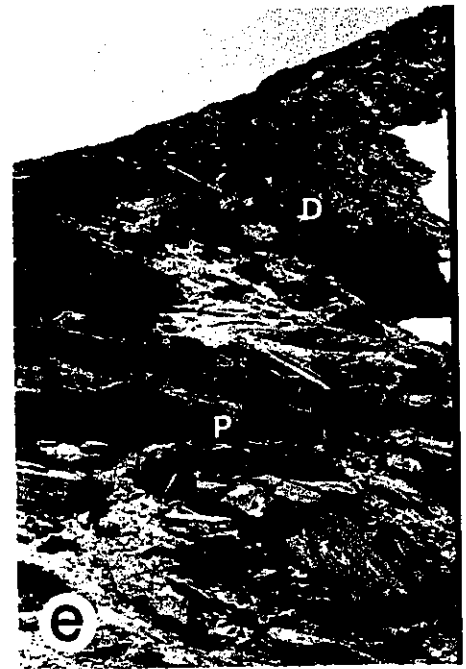
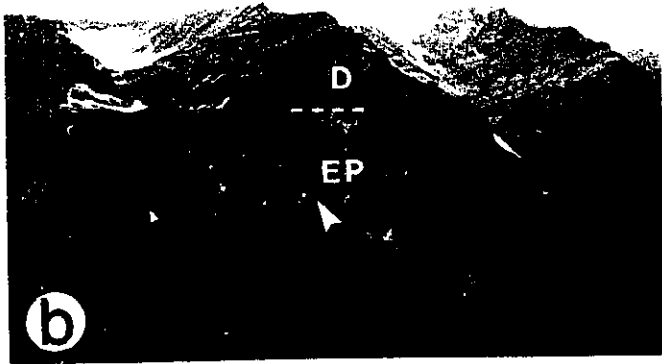
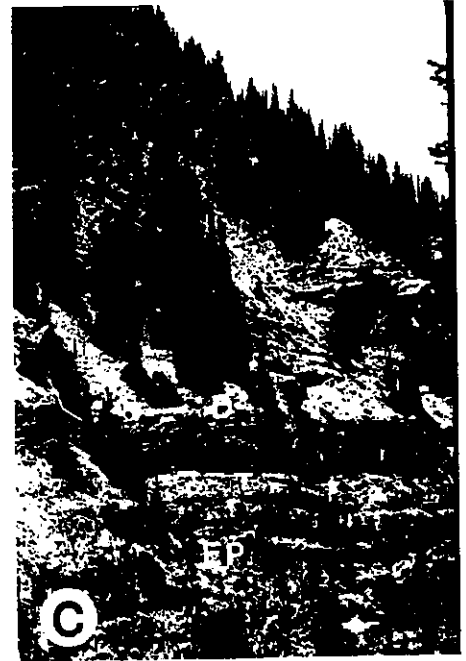
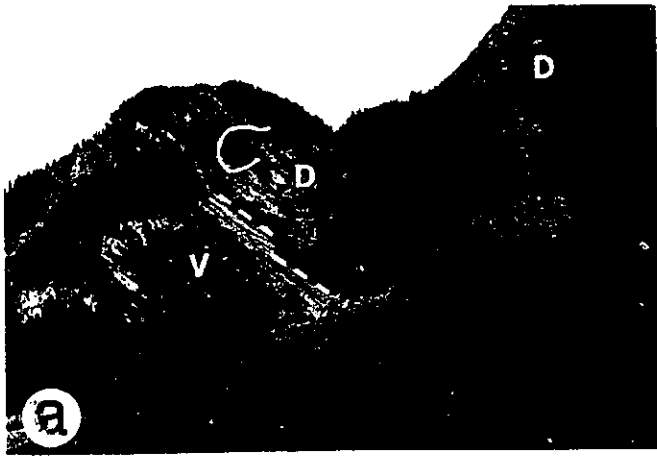
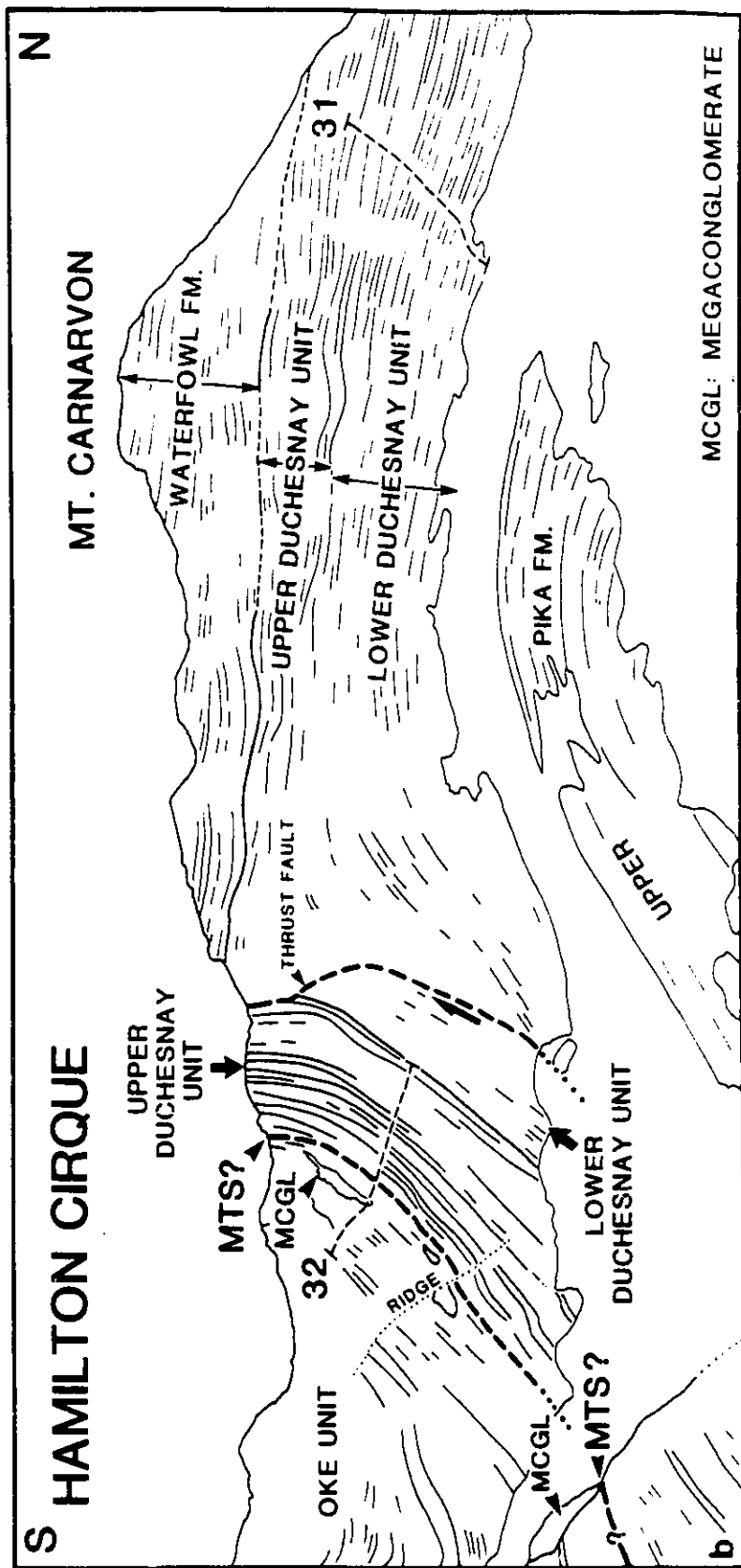


PLATE 57: HAMILTON CIRQUE



- a: Key, cross-strike exposure at the level of the Arctomys-Waterfowl formations and equivalent strata in Hamilton cirque. View towards the west.
- b: Line drawing based on photograph below. To the right of the thrust fault ("Hamilton cirque north"), broadly folded platform carbonate rocks and minor ribbon limestone of the Pika Formation are succeeded by dark brown, deep shelf argillite of the lower Duchesnay unit. These pass upward into argillite-based, metre-scale shoaling-upward cycles of the upper Duchesnay unit, which in turn are overlain by burrow-mottled and burrow-stratified limestones of the Waterfowl Formation. Part of this section was traversed by section 31. On the left (south) side of the thrust fault ("Hamilton cirque south"), section 32 starts at the contact between the lower and upper Duchesnay unit, and traverses a probable megatunaucation surface. The overlying Oke unit contains a prominent megaconglomerate (see Plate 30d), and is composed mainly of argillite in its lower part. The megablock in the foreground (MCGL, extreme left) is part of a megaconglomerate, and measures 22.5x49.5 m. It occurs at the same stratigraphic level as the megaconglomerate in section 32. The remainder of the Oke unit is composed of severely deformed and unmeasurable ribbon carbonates. For scale, the stratigraphic thickness of the upper Duchesnay unit (below the MTS) in section 32 is about 70 m.



PLATE 58: OUTCROP PHOTOGRAPHS - OKE UNIT

- a: **Mt. Oke:** type section of the Oke unit (and reference section for the Duchesnay unit) on the east side of Mt. Oke (section 7). The section starts in argillite-dominated, deep-water strata of the upper Duchesnay unit (D), which pass upward into resistant, grey-weathering carbonate rocks of the Oke unit (O). The sequence is capped by slates of the upper Chancellor (UC; see (d) below). View towards the west.
- b: **Misko Mountain:** reference section for the Oke unit (O) at Misko Mountain (section 16), about 5.5 km northwest of the type section. The section is overlain by a thick, relatively recessive sequence of upper Chancellor slates (UC). View towards the southwest.
- c: **Miller Pass:** contact between the Duchesnay unit (D) and resistant, grey-weathering carbonate rocks belonging to the Oke unit (O) near Miller Pass. The upper Oke unit is severely deformed at this locality. View towards the west.
- d: **Mt. Oke:** Contact between bedded, deep-water carbonate strata of the Oke unit (O) and monotonous, dark grey slates of the upper Chancellor (UC) at the peak of Mt. Oke (top of section 7). Note prominent slate band in the upper part of the Oke unit (beneath "O"). View towards the northwest.

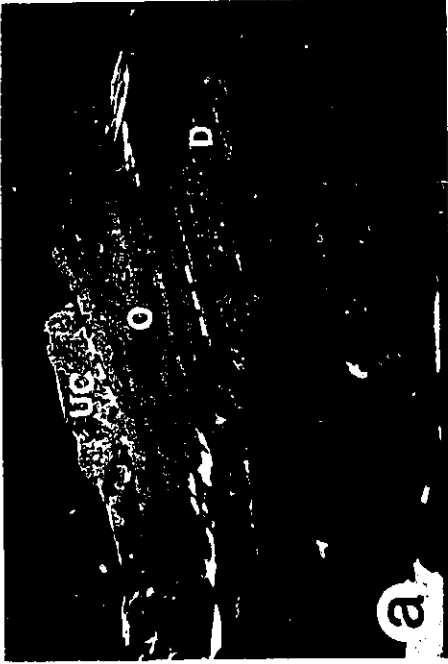
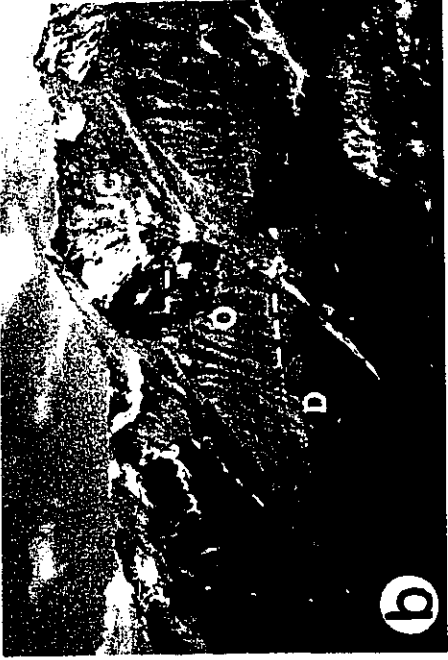
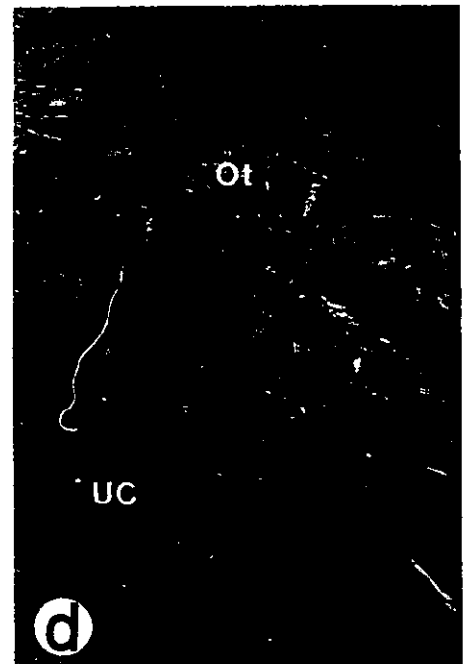
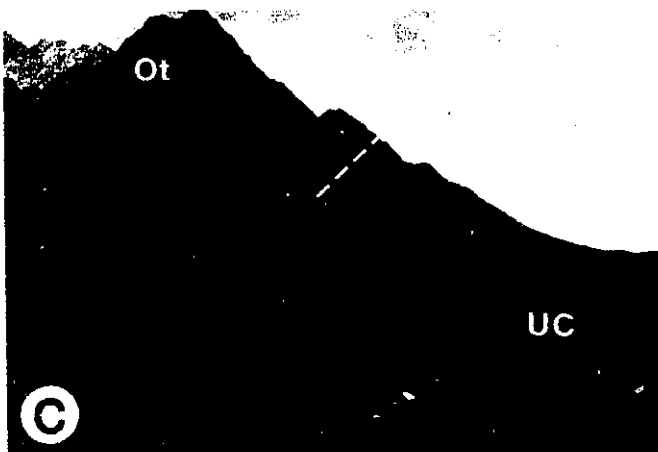
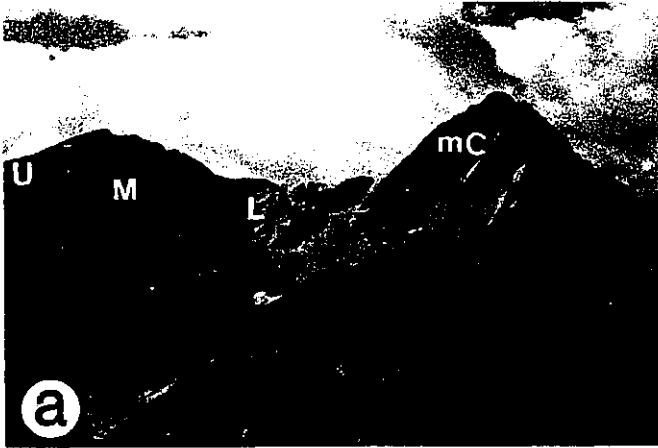


PLATE 59: OUTCROP PHOTOGRAPHS - UPPER CHANCELLOR

- a: **Mt. Laussedat:** section AC-150/154, measured by J.D. Aitken in 1966. This is the only complete, relatively undeformed stratigraphic section through the upper Chancellor. The upper Chancellor consists of three units: a lower, recessive, slate-dominated sequence (L), a middle, resistant carbonate and slate sequence (M), and an upper, recessive, slate-dominated sequence (U). The section commences at the top of the resistant middle Chancellor (mC) division. View towards the north.
- b: **Mt. Hurd:** monotonous, banded slates of the upper Chancellor on the south side of Mt. Hurd. The slightly more resistant, brown-weathering bands in the lower part of the photo are dolomitic slates.
- c: **Mt. Daer:** transition between the upper Chancellor (UC) and Ottertail Formation (Ot). The recessive slates on the right (which become severely deformed a short distance farther down the same ridge) pass upward into more resistant, interbedded slates and ribbon limestones. The base of the Ottertail is placed at the base of the continuous carbonate sequence. View towards the northwest.
- d: **Mt. Daer area:** closeup of transition beds between the upper Chancellor (UC) and the Ottertail Formation (Ot) on a ridge intermediate between Mt. Daer and Mt. Harkin. Resistant, brown-weathering bands of ribbon limestone are intercalated with black slate in the foreground. View towards the west.



APPENDIX 1

APPENDIX 1

BIOSTRATIGRAPHIC DATA

This appendix summarizes all of the fossil data acquired during the present study. All of the collections were identified by Dr. W.H. Fritz, whose reports have been reproduced in an updated and modified format. The collections mainly contain polymeroid and agnostid trilobites, and are currently being stored at the Geological Survey of Canada in Ottawa on behalf of Parks Canada.

Fossils have also been collected from various parts of the Chancellor by a number of other workers. The major sources of fossil data are summarized below:

1. **Naiset Formation:** Deiss (1940); McIlreath (1977a; his Appendix I); Aitken (in press, a).
2. **Takakkaw Tongue:** Fritz (1971); McIlreath (1977a; his Appendix I); Aitken (in press, a).
3. **"Basinal" Stephen Formation:** Rasetti (1951); Fritz (1971); McIlreath (1977a; his Appendix I); Aitken (in press, a); plus innumerable reports on the fauna of the Burgess Shale and Stephen Fossil Beds.
4. **McArthur unit:** Rasetti (1951; Park Mountain section); McIlreath (1977a; his Appendix I); Collins *et al.* (1983; their locality 15); Aitken (in press, a).
5. **Middle Chancellor:** Cook (1975; his Appendix)
6. **Upper Chancellor:** Cook (1975; his Appendix)

GSC REPORT C6-WHF-1987:

1. **GSC locality:** C-153354 (AC/DS-4-8)
Location: Section DS-5 (Numa Mountain N)
Coordinates: N 51°06'54" W 116°07'03"
Stratigraphic position: talus from lowermost part of section; probably derived from Vermilion sub-unit.

Hemirhodon sp.

Remarks: Bolaspidella Zone.
2. **GSC locality:** C-153361 (AC/DS-11-14)
Location: Vicinity of section 12 (Miller Pass 1)
Coordinates: N 50°41'45" W 115°37'40"
Stratigraphic position: talus derived from basal Duchesnay unit.

Hemirhodon sp.

Remarks: Bolaspidella Zone.
3. **GSC locality:** C-153362 (AC/DS-12-14)
Location: Section 12 (Miller Pass 1)
Coordinates: N 50°41'45" W 115°37'40"
Stratigraphic position: basal Duchesnay unit (in-situ)

Zacanthoides? sp.
Modocia sp.

Remarks: Bolaspidella Zone.
4. **GSC locality:** C-153363 (AC/DS-13-14)
Location: Section 12 (Miller Pass 1)
Coordinates: N 50°41'45" W 115°37'40"
Stratigraphic position: basal Duchesnay unit (in-situ)
Remarks: Non-diagnostic
5. **GSC locality:** C-153364 (AC/DS-14-14)
Location: Section 12 (Miller Pass 1)
Coordinates: N 50°41'45" W 115°37'40"
Stratigraphic position: basal Duchesnay unit (in-situ)

Hemirhodon sp.

Remarks: Bolaspidella Zone.
6. **GSC locality:** C-153365 (AC/DS-15-14)
Location: Vicinity of section 12 (Miller Pass 1)
Coordinates: N 50°41'45" W 115°37'40"
Stratigraphic position: basal Duchesnay unit (talus)

Hyalithes sp.
Modocia sp.
Peronopsis sp.

Remarks: Bolaspidella Zone.
7. **GSC locality:** C-153366 (AC/DS-16-14)
Location: Vicinity of section 12 (Miller Pass 1)
Coordinates: N 50°41'45" W 115°37'40"
Stratigraphic position: basal Duchesnay unit (talus)

Byronia sp.
Hemirhodon sp.
sponge spicule
Bolaspidella? sp.

Remarks: Bolaspidella Zone.
8. **GSC locality:** C-153367 (AC/DS-17-14)
Location: Vicinity of section 12 (Miller Pass 1)
Coordinates: N 50°41'45" W 115°37'40"
Stratigraphic position: basal Duchesnay unit (talus)

Hyalithes sp.
inarticulate brachiopod

Remarks: Bolaspidella Zone
9. **GSC locality:** C-153368 (AC/DS-18-14)
Location: Vicinity of section 12 (Miller Pass 1)
Coordinates: N 50°41'45" W 115°37'40"
Stratigraphic position: basal Duchesnay unit (talus)

Modocia sp.
Peronopsis fallax (Linnarsson) 1869

Remarks: Bolaspidella Zone

10. **GSC locality:** C-153405 (AC/DS-53-61)
Location: Misko Pass
Coordinates: N 51°16'33" W 116°17'12"
Stratigraphic position: upper Duchesnay unit (talus; spot locality)
- agnostids
- Remarks:** too deeply weathered for identification
11. **GSC locality:** C-153411 (AC/DS-59-65A)
Location: Section DS-2 (North Gully)
Coordinates: N 51°24'36" W 116°26'36"
Stratigraphic position: Naiset Formation, 44.6-49.5 m above base
- Syspacephalus perola? (Walcott) 1917
- Remarks:** Plagiura - "Poliella" Zone
12. **GSC locality:** C-153415 (AC/DS-63-68)
Location: Section DS-3 (Wedge Gully)
Coordinates: N 51°25'21" W 116°27'00"
Stratigraphic position: Naiset Formation, 13.2-20.0 m above base
- Amecephalus sp.
Piaziella? sp.
Stephenaspis sp.
Syspacephalus perola? (Walcott) 1917
Wenkchemnia sp.
- Remarks:** Plagiura - "Poliella" Zone
13. **GSC locality:** C-153416 (AC/DS-64-68a)
Location: Section DS-3 (Wedge Gully)
Coordinates: 51°25'21" W 116°27'00"
Stratigraphic position: Naiset Formation, 20.0-24.9 m above base
- Wenkchemnia? sp. (cranidium only)
Syspacephalus perola? (Walcott) 1917
- Remarks:** "Plagiura - Poliella" Zone
14. **GSC locality:** C-153423 (AC/DS-71-72)
Location: Wapta Mountain, north face (spot locality)
Coordinates: N 51°27'45" W 116°28'57"
Stratigraphic position: Eldon-equivalent strata
- inarticulate brachiopods
agnostoid trilobites
- Remarks:** not diagnostic
15. **GSC locality:** C-153438 (AC/DS-86-86)
Location: Marble Canyon, west side (spot locality)
Coordinates: N 51°11'15" W 116°07'57"
Stratigraphic position: Tokumm sub-unit, immediately above upper siliciclastic marker
- Ptychagnostus elegans? (Tullberg) 1880
Ptychagnostus cf. P. gibbus (Linnarsson) 1869
smooth agnostoids?
- Remarks:** Ptychagnostus gibbus zone.
16. **GSC locality:** C-153456 (AC/DS-104-76A)
Location: Section DS-4 (Haffner Creek North)
Coordinates: N 51°10'04" W 116°06'19"
Stratigraphic position: Tokumm sub-unit, upper siliciclastic marker
- agnostids, too badly altered for identification
linear organic imprint
- Remarks:** not diagnostic
17. **GSC locality:** C-153466 (AC/DS-114-115a)
Location: Section DS-4 (Haffner Creek North)
Coordinates: N 51°10'04" W 116°06'19"
Stratigraphic position: Duchesnay unit, talus tied to unit 12.8-17.6 m above base of unit
- trilobite, too weathered for identification
- Remarks:** not diagnostic
18. **GSC locality:** C-153482 (AC/DS-130-144)
Location: Vicinity of section DS-10 (Prospectors Valley 2)
Coordinates: N 51°13'41" W 116°10'47"
Stratigraphic position: Talus, probably derived from lower Eldon Formation or Tokumm sub-unit
- Olenoides? sp.
Zacanthoides? sp.
- Remarks:** the above collection cannot be dated more closely than Middle Cambrian.

19. **GSC locality:** C-153483 (AC/DS-131-144)
Location: Section DS-10 (Prospectors Valley 2)
Coordinates: N 51°13'41" W 116°10'47"
Stratigraphic position: Tokumm sub-unit, 70 m above base of sub-unit
- Ptychagnostus intermedius (Tullberg, 1880)
trilobite thorax
- Remarks:** Ptychagnostus gibbus Zone.
20. **GSC locality:** C-154511 (AC/DS-159-180a)
Location: Misko Pass
Coordinates: N 51°16'33" W 116°17'12"
Stratigraphic position: Talus tied to Duchesnay unit
- agnostids (deeply weathered)
cf. Bosworthia simulans Walcott, 1919
- Remarks:** This collection cannot be dated.
21. **GSC locality:** C-154517 (AC/DS-164-184)
Location: Section DS-9 (Prospectors Valley 1)
Coordinates: N 51°13'13" W 116°10'10"
Stratigraphic position: lower Eldon Formation, 2.5-27.8 m above base
- Kootenia cf. K. burgessensis Walcott, 1918
- Remarks:** In and near the Burgess Quarry, 6-spined Kootenia pygidia of this type are known from the Pagetia bootes faunule and from a small faunule within the Boundary Limestone, or, in other words, from the lower part of the Bathyriscus-Elrathina Zone. Elsewhere, pygidia of this type have a much wider range.
22. **GSC locality:** C-154526 (AC/DS-173-193)
Location: Vicinity of section DS-10 (Prospectors Valley 2)
Coordinates: N 51°13'41" W 116°10'47"
Stratigraphic position: talus, probably derived from lower Eldon Formation or Tokumm sub-unit
- Bathyriscus? (minus pygidium)
Elrathina? sp.
Elrathina sp.
Peronopsis columbiensis? Rasetti, 1951
- Remarks:** Bathyriscus-Elrathina Zone. Peronopsis columbiensis is known to locally range from the Pagetia bootes faunule into the Bathyriscus adaeus
- faunule within the Bathyriscus-Elrathina Zone.
23. **GSC locality:** C-154533 (AC/DS-180-199)
Location: Section DS-10 (Prospectors Valley 2)
Coordinates: N 51°13'41" W 116°10'47"
Stratigraphic position: Tokumm sub-unit, 39.7 - 47.5 m above base of sub-unit.
- Elrathina? sp.
- Remarks:** Bathyriscus-Elrathina Zone?
24. **GSC locality:** No number. Samples loaned by Phil Esslinger (formerly a student at the University of Calgary) from his personal collection for study (all samples collected outside of National and Provincial Parks).
Location: Vicinity of section 12 (Miller Pass 1)
Coordinates: N 50°41'45" W 115°37'40"
Stratigraphic position: basal Duchesnay unit (talus)
- Oria? sp.
Athabaskiella sp.
Hemirhodon sp.
Modocia sp.
Brachyaspidium? sp.
Trymataspis sp.
- Remarks:** Bolaspidella Zone.

GSC REPORT C5-WHF-1987:

25. **GSC locality:** No number. Samples loaned by Chris Schultze (formerly a student at the University of Calgary) from his personal collection for study (all samples collected outside of National and Provincial Parks).
Location: Vicinity of section 12 (Miller Pass 1)
Coordinates: N 50°41'45" W 115°37'40"
Stratigraphic position: basal Duchesnay unit (talus)

Hemirhodon sp.

Athabaskiella sp.

Peronopsis fallax Linnarsson, 1869

Molaria sp.

cf. Ottoia sp.

Hyalithes sp.

unidentified organic (?) film

Vauxia magna? Rigby 1980

unidentified cylindrical tube

Byronia annulata Matthew 1899

Hyalithus sp.

Eifellia sp.

inarticulate brachiopods

Leptomitus sp.

Orria sp.

Hemirhodon amplipyge Robison 1964

Modocia sp.

Modocia? sp.

Remarks: The presence of the trilobites Athabaskiella sp., Hemirhodon sp., Orria sp. and Modocia sp. indicate the fossils are from blocks derived from the Bolaspidella Zone. The softbodied fossils Molaria sp., cf. Ottoia sp., and Vauxia sp., and the presence of parts usually not preserved on Hyalithes sp. and Eifellia sp. indicate an unusual degree of preservation. Mapping in this area indicates that the strata are on the basinward side of the nearby dividing line between the middle carbonate and the outer detrital belts. The trilobites Athabaskiella sp., Hemirhodon sp., and Orria sp. suggest a slope environment, as that is their environment elsewhere. The general lack of agnostids, such as the expected genus Hypagnostus, is puzzling, and might be attributed to a high slope position that is above the critical depth for the genus. All of the fossils display a remarkable lack of depositional or tectonic distortion.

GSC REPORT E-2-1988-WHF:

26. **GSC locality:** C-166508 (AC/DS-194-217)
Location: Below section DS-30 (Prospectors Valley 4)
Coordinates: N 51°13'22", W 116°10'00"
Stratigraphic position: Tokumm sub-unit, not measured in

Peronopsis fallax (Linnarsson), 1869

Remarks: Probably within the interval that is equivalent to the Bathyriscus-Elrathina Zone (range of P. fallax quoted by Robison (1982) is from within the Ptychagnostus praecurrens Zone into the Ptychagnostus atavus Zone of the outer detrital belt.

27. **GSC locality:** C-166512 (AC/DS-198-221a)

Location: Section DS-11 (Prospectors Valley 3)

Coordinates: N 51°13'30" W 116°10'30"

Stratigraphic position: Tokumm sub-unit, 2.5-16.4 m below base of upper siliciclastic marker unit.

cf. Solenopleurella sp.

2 deeply weathered ptychoparioid trilobites

Remarks: Weathering has removed the diagnostic features from these fossils, and therefore an age assignment cannot be given.

28. **GSC locality:** C-166530

Location: Section DS-4 (Haffner Creek North)

Coordinates: N 51°10'04" W 116°06'19"

Stratigraphic position: Tokumm sub-unit, 39.0-45.7 m above base of second siliciclastic marker.

Peronopsis interstricta (White), 1874

Remarks: This assemblage belongs to the outer detrital Ptychagnostus gibbus Zone that is also present in the Field Member of the Eldon Formation (Robison, 1982, p. 133).

29. **GSC locality:** C-167322 (AC/DS-237-248a)
Location: in vicinity of Section DS-10 (Prospectors Valley 2)
Coordinates: N 51°13'41" W 116°10'47"
Stratigraphic position: talus, probably derived from lower Eldon Formation or Tokumm sub-unit

agnostid pygidium (poorly preserved)
Lingulella sp.

ptychoparioid trilobite (poorly preserved)
Zacanthoides? sp. (cranidium and partial thorax)

Remarks: Middle Cambrian. Assemblage not diagnostic enough for narrower assignment.

30. **GSC locality:** C-166618 (AC/DS-303-296)
Location: Section DS-17 (Tokumm Headwaters 1)
Coordinates: N 51°17'41", W 116°17'14"
Stratigraphic position: lower Eldon Formation, 43.6-54.8 m above base of formation

Bathyriscus adaeus? Walcott, 1916
Peronopsis sp., cf. P. columbiensis Rasetti, 1951.

Remarks: Although this collection is very small, incomplete, and tectonically distorted, it suggests a correlation with the Bathyriscus adaeus fauna described by Rasetti (1951, p. 106) from what is now considered the lower part of the Eldon Formation.

31. **GSC locality:** C-166634 (AC/DS-319-308)
Location: Section DS-18 (Tokumm Headwaters 2)
Coordinates: N 51°17'29", W 116°17'14"
Stratigraphic position: uppermost Tokumm sub-unit, 0-19.7 m below top of sub-unit

Kootenia sp.
sponge spicules, cf. Eifellia sp.

Remarks: Middle Cambrian

32. **GSC locality:** C-166635 (AC/DS-320-308a)
Location: Section DS-18 (Tokumm Headwaters 2)
Coordinates: N 51°17'29", W 116°17'14"
Stratigraphic position: uppermost Tokumm sub-unit, 0-19.7 m below top of sub-unit

Bathyriscus? sp.
Kootenia, aff. K. burgessensis Reeser, 1942
Pachyaspsis sp.
cf. Rowia sp. and Elrathia sp.

Remarks: The trilobites in this collection are tectonically distorted and forms other than aff. K. burgessensis are rare. The Rowia-like cranidia resemble those in the Pika Formation, which is lower Bolaspidella Zone in age, whereas the remainder of the collection is most suggestive of the Bathyriscus-Elrathina Zone.

33. **GSC locality:** C-166700 (AC/DS-386-376)
Location: Section DS-20 (Mt. Biddle)
Coordinates: N 51°18'27", W 116°18'48"
Stratigraphic position: lower Eldon Formation (basal Eldon "black band")

Bathyriscus adaeus Walcott, 1916
cf. Ehmannia sp.

Elrathina spinifera Rasetti, 1951

Oryctocephalus sp.

Pachyaspsis? sp.

Pagetia sp.

Peronopsis columbiensis Rasetti, 1951

Solenopleurella sp.

sponge spicules, cf. Protospongia sp.

Tonkinella stephenensis Kobayashi, 1935

Remarks: The faunule listed above is part of the Bathyriscus adaeus faunule, Bathyriscus-Elrathina Zone, known from the basal strata of the Eldon Formation (Rasetti, 1951).

34. **GSC locality:** C-166707 (AC/DS-393-393)
Location: Section DS-21 (Curtis cirque)
Coordinates: N 51°17'58", W 116°17'59"
Stratigraphic position: Tokumm sub-unit, 57.7 m above base of sub-unit

Ehmaniella sp.

Lingulella sp.

Peronopsis fallax (Linnarsson), 1869

aff. Zacanthoides sexdentatus Rasetti, 1951

Remarks: Probably from the Bathyriscus-Elrathina Zone

35. **GSC locality:** C-166720 (AC/DS-406-406a)
Location: vicinity of Section DS-22 (The Monarch, North Face)
Coordinates: N 51°02'56", W 115°52'17"
Stratigraphic position: Talus, probably from "basinal" Stephen Formation

Kootenia sp. (1 pygidia with 6 pairs of spines)

Remarks: Middle Cambrian

36. **GSC locality:** C-167262 (AC/DS-448-450a)
Location: Section DS-26 (Stephen cirque centre 1)
Coordinates: N 51°22'45", W 116°26'34"
Stratigraphic position: talus, most probably from Vermilion sub-unit

Olenoides sp.

Remarks: The pygidium of the Olenoides in this collection resembles those in collection C-167264 (below).

37. **GSC locality:** C-167264 (AC/DS-450-453)
Location: Section DS-26 (Stephen cirque centre 1)
Coordinates: N 51°22'45", W 116°26'34"
Stratigraphic position: talus securely tied to Vermilion sub-unit

Modocia? sp.

Olenoides mariumensis? Reeser, 1942
Orria elegans Walcott, 1916
Peronopsis segmenta? Robison, 1964
Utaspis mariumensis? Resser, 1935
sponge spicules, cf. Protospongia sp.

Remarks: The above collection belongs to the Bolaspidella Zone, and probably comes from a level above that occupied by the Field Member of the Eldon Formation. The collection contains two pygidia questionably assigned to Olenoides mariumensis. They are also strikingly similar to those of Olenoides wahsatchensis (Hall and Whitfield) 1877, known from much older strata (Glossopleura Zone) in Idaho (Reeser, 1939).

38. **GSC locality:** C-167278 (AC/DS-464-462)
Location: Section DS-27 (Monarch cirque 1)
Coordinates: N 51°02'56", W 115°52'17"
Stratigraphic position: talus securely tied to upper Takakkaw Tongue (above Cathedral megabreccia)

Glossopleura sp.
Kootenia sp.
Nisusia sp.

Remarks: Glossopleura Zone.

39. **GSC locality:** C-167289 (AC/DS-475-471)
Location: vicinity of Section DS-27 (Monarch cirque 1)
Coordinates: N 51°02'56", W 115°52'17"
Stratigraphic position: talus, downslope from "basinal" Stephen Formation exposures

Chancia sp.
Ehmaniella? sp.
Elrathina? sp.
hyolith
Kootenia sp.
Olenoides sp.

Remarks: The material in this collection is limited and poorly preserved, but suggests a position within the Glossopleura or Bathyuriscus-Elrathina Zones. The latter is tentatively favoured.

40. **GSC locality:** C-167291 (AC/DS-477-471a)
Location: vicinity of Section DS-28
Coordinates: N 51°02'16", W 115°50'58"
Stratigraphic position: talus downslope from "basinal" Stephen Formation

delicate film outlining bodies of a priapulid-like worm (no proboscis showing)

Remarks: Burgess-like preservation; no age assigned.

GSC REPORT C4-WHF-1989:

41. **GSC locality:** C-179217 (AC/DS-524-523)
Location: Section DS-4 (Haffner Creek North)
Coordinates: N 51°10'00", W 116°06'30"
Stratigraphic position: talus tied to lowermost Duchesnay unit

probable trilobite remains

Remarks: Fossils too poorly preserved for identification.

42. **GSC locality:** C-179248 (AC/DS-556-556)
Location: about 600 m east of base of Section DS-31 (Hamilton Lake North); corresponds to GSC locality 75299 in Cook (1975)
Coordinates: N 51°27'50", W 116°34'24"
Stratigraphic position: ribbon limestone of deep-water origin equivalent to uppermost Pika Formation

Micromitra sp.
Modocia sp.
Nisusia sp.
Orria sp.
Pegmatreta sp.

Peronopsis segmenta? Robison, 1964
Trymataspis pristina? Robison, 1964

Remarks: Bolaspidella Zone. The above collection reflects a slope environment, and not the restricted environment of the typical Pika Formation.

43. **GSC locality:** C-179249 (AC/DS-557-557)
Location: beneath base of Section DS-31 (Hamilton Lake North)
Coordinates: N 51°27'36", W 116°35'06"
Stratigraphic position: ribbon limestone of deep-water origin equivalent to uppermost Pika Formation

Bolaspidella? sp.
Modocia sp.
Peronopsis segmenta? Robison, 1964
Ptychagnostus hybridus? (Brogger, 1878)

Remarks: Bolaspidella Zone. The fossils in this collection are tectonically deformed. It contains an abundance of agnostids, a type of trilobite not found in the typical restricted fauna of the Pika Formation.

44. **GSC locality:** C-179289 (AC/DS-596-601)
Location: at top of ridge immediately east of Section DS-34 (Verdant Creek South)
Coordinates: N 51°06'12", W 115°58'06"
Stratigraphic position: Field Member of Eldon Formation

Alokistocare sp.
Bathyriscus sp.
Elrathina sp.
Leptomitus? sp.
Peronopsis cf. P. scutalis (Salter, 1872)

Remarks: Bathyriscus-Elrathina Zone. The Alokistocare in this collection is the same as that in the Field Member of the Eldon Formation on Mt. Field (cf. GSC locs. 89025, 89026, 89027), which suggests a high horizon within the zone.

45. **GSC locality:** C-179290 (AC/DS-597-606a)
Location: Section DS-34, Verdant Headwaters North
Coordinates: N 51°06'00" W 115°58'30"
Stratigraphic position: talus, probably derived from Vermilion sub-unit

Leptomitus? sp.
Protospongia sp.

Remarks: The ranges of the above sponges are too broad for the purposes of present correlations.

46. **GSC locality:** C-179296 (AC/DS-603-606a)
Location: Section DS-34, Verdant Headwaters North
Coordinates: N 51°06'00" W 115°58'30"
Stratigraphic position: talus, probably derived from Vermilion sub-unit

trilobite thorax

Remarks: Not diagnostic.

47. **GSC locality:** C-179299 (AC/DS-607-617a)
Location: Vicinity of section DS-33, Verdant Headwaters South
Coordinates: N 51°05'56" W 115°57'56"
Stratigraphic position: talus at base of cirque wall composed of Vermilion sub-unit and Duchesnay unit.

Hemirhodon sp.

Remarks: Bolaspidella Zone.

48. **GSC locality:** C-179300 (AC/DS-608-617a)
Location: Vicinity of section DS-33, Verdant Headwaters South
Coordinates: N 51°05'56" W 115°57'56"
Stratigraphic position: talus at base of cirque wall composed of Vermilion sub-unit and Duchesnay unit. Probably from Vermilion sub-unit.

Athabaskiella sp.
Bathyriscus fimbriatus? sp. Robison, 1964
Bolaspidella sp.
Hemirhodon? sp.
Hypagnostus sp.
Ptychagnostus sp.

Remarks: Bolaspidella Zone.

49. **GSC locality:** C-179301 (AC/DS-609-617a)
Location: North side, Verdant cirque
Coordinates: N 51°06'12" W 115°58'06"
Stratigraphic position: talus, below Field Member exposure at top of ridge

one agnostid pygidium
one ptychoparioid internal cranial mould

Remarks: material not adequate for determination.

50. **GSC locality:** C-179303 (AC/DS-610-628)
Location: Stephen cirque, north side
Coordinates: N 51°23'24" W 116°26'12"
Stratigraphic position: Field Member of Eldon Formation (spot locality)

Bathyriscus sp.
Peronopsis aff. P. scutalus (Salter, 1872)
ptychoparioid trilobite

Remarks: fossils too deeply weathered for useful determination.

51. **GSC locality:** C-179304 (AC/DS-611-628)
Location: Section 25, Stephen cirque east
Coordinates: N 51°23'06" W 116°25'42"
Stratigraphic position: Field Member of Eldon Formation, 0-22.5 m above base of section

Elrathina? sp.
Solenopleurella sp.

Remarks: Bathyriscus-Elrathina Zone. Available fossils not adequate to prove or disprove presence of Field Member.

APPENDIX 2

APPENDIX 2

STRATIGRAPHIC SECTIONS

A1.1 INTRODUCTION

During the 1987, 1988 and 1989 field seasons, 36 stratigraphic sections were measured through Chancellor and equivalent strata (Fig. 2). Graphic plots of all these sections are provided in this appendix to illustrate the stratigraphic data on which the conclusions in this thesis are based. Locality information is given in Table A1, and the stratigraphic units traversed by each section are summarized in Table A2.

The stratigraphic columns were plotted at 1:1000 scale in as much detail as space allowed. Slightly more detailed, hand-drawn sections plotted at 1:500 scale remain in the possession of the writer.

The brief descriptive comments to the right of each plot contain a number of abbreviations. These are summarized below:

ALLOCH	ALLOCHTHONOUS	//LAM	HORIZONTAL
ARG	ARGILLITE		PARALLEL LAMINAE
BDG	BEDDING	LS	LIMESTONE
CALC	CALCARENITE	MAX	MAXIMUM
CONGL	CONGLOMERATE	MDST	MUDSTONE
DEFM	DEFORMATION	MED	MEDIUM
DOL	DOLOMITIC; DOLOMITE	MTS	MEGATRUNCATION SURFACE
FRAGS	FRAGMENTS	SDY	SANDY
GRNST	GRAINSTONE	SED STRUC	SEDIMENTARY STRUCTURES
HCS	HUMMOCKY CROSS- STRATIFICATION	SS	SANDSTONE
IRREG	IRREGULAR	SYNSED DEFM	SYNSEDIMENTARY DEFORMATION
ITS	INTRAFORMATIONA L TRUNCATION SURFACE	XLAM	CROSSLAMINAE
LAM	LAMINAE	XBEDS	CROSSBEDS

TABLE A1: SECTION LOCATIONS

<u>SECTION NO.</u>	<u>NAME</u>	<u>COORDINATES</u>
87-DS-1	Mt. Dennis North	N 51°23'00", W 116°28'42"
87-DS-2	North Gully	N 51°24'36", W 116°26'36"
87-DS-3	Wedge Gully	N 51°25'18", W 116°27'06"
87-DS-4	Haffner Creek North	N 51°10'04", W 116°06'19"
87-DS-5	Numa Mountain North	N 51°06'54", W 116°07'03"
87-DS-6	Mt. Oke 1	N 51°16'00", W 116°16'06"
87-DS-7	Mt. Oke 2	N 51°15'48", W 116°16'30"
87-DS-8	Mt. Dennis South	N 51°22'12", W 116°28'06"
87-DS-9	Prospectors Valley 1	N 51°13'13", W 116°10'10"
87-DS-10	Prospectors Valley 2	N 51°13'42", W 116°10'42"
88-DS-11	Prospectors Valley 3	N 51°13'30", W 116°10'30"
88-DS-12	Miller Pass 1	N 50°41'45", W 115°37'40"
88-DS-13	Miller Pass 2	N 50°41'18", W 115°38'06"
88-DS-14	Naiset Point	N 50°53'42" W 115°36'42"
88-DS-15	Wedgewood Peak	N 50°53'36", W 115°38'48"
88-DS-16	Misko Mountain	N 51°17'54", W 116°20'36"
88-DS-16A	Misko Mountain North	N 51°18'18", W 116°21'00"
88-DS-17	Tokumm Headwaters 1	N 51°17'41", W 116°17'14"
88-DS-18	Tokumm Headwaters 2	N 51°17'29", W 116°17'14"
88-DS-19	Mt. Oke South	N 51°15'12", W 116°16'00"
88-DS-20	Mt. Biddle	N 51°18'27", W 116°18'48"
88-DS-21	Curtis cirque	N 51°17'58", W 116°17'59"

TABLE A1 (CONTINUED)

<u>SECTION NO.</u>	<u>NAME</u>	<u>COORDINATES</u>
88-DS-22	The Monarch (North Face)	N 51°02'56", W 115°52'17"
88-DS-23	Natalko Lake	N 51°04'24", W 115°53'18"
88-DS-24	Stephen cirque West	N 51°22'54", W 116°27'00"
88-DS-25	Stephen cirque East	N 51°23'06", W 116°25'42"
88-DS-26	Stephen cirque Centre 1	N 51°22'45", W 116°26'34"
88-DS-27	Monarch cirque 1	N 51°02'56", W 115°52'17"
88-DS-28	Monarch cirque 2	N 51°02'16", W 115°50'58"
89-DS-29	Haffner Creek South	N 51°09'48", W 116°05'54"
89-DS-30	Prospectors Valley 4	N 51°13'18", W 116°10'24"
89-DS-31	Hamilton Lake North	N 51°27'36", W 116°35'06"
89-DS-32	Hamilton Lake South	N 51°27'30", W 116°35'12"
89-DS-33	Verdant Headwaters South	N 51°05'56", W 115°57'56"
89-DS-34	Verdant Headwaters North	N 51°06'12", W 115°58'06"
89-DS-35	Stephen cirque Centre 2	N 51°23'00", W 116°26'12"
89-DS-36	Numa Mountain South	N 51°05'30", W 116°05'42"

TABLE A2: STRATIGRAPHIC SECTIONS

<u>SECTION NO.</u>	<u>LOCATION</u>	<u>UNIT MEASURED</u>	<u>THICKNESS (m)</u>
87-DS-1	Mt. Dennis North	Oke unit Duchesnay unit Vermilion sub-unit	12.5 (I) 402.9 (C) 121.0 (I)
87-DS-2	North Gully	Naiset Fm.	102.2 (I)
87-DS-3	Wedge Gully	Naiset Fm.	105.5 (C)
87-DS-4	Haffner Creek North	Duchesnay unit Vermilion sub-unit Tokumm sub-unit	94.5 (I) 190.1 (C) 147.4 (I)
87-DS-5	Numa Mountain North	Vermilion sub-unit Tokumm sub-unit	190.2 (I)* 4.0 (I)*
87-DS-6	Mt. Oke 1	Duchesnay unit	54.7 (I)
87-DS-7	Mt. Oke 2	Upper Chancellor Oke unit Duchesnay unit	70.0 (I) 319.1 (C) 272.2 (I)
87-DS-8	Mt. Dennis South	Oke unit Duchesnay unit ?Vermilion sub-unit	169.3 (I) 347.8 (C)* 58.2 (i)*
87-DS-9	Prospectors Valley 1	Duchesnay unit Vermilion sub-unit Tokumm sub-unit Eldon Fm. Stephen Fm.(Waputik Mbr.)	+ 194.3 (C)* 201.6 (C)* 99.2 (C) 12.2 (I)
87-DS-10	Prospectors Valley 2	Tokumm sub-unit Eldon Fm. Stephen Fm. (Waputik Mbr.) Cathedral Fm.	107.6 (I) 99.2 (C) 35.4 (C) 5.4 (I)
88-DS-11	Prospectors Valley 3	Vermilion sub-unit Tokumm sub-unit	106.9 (I) 164.9 (I)
88-DS-12	Miller Pass 1	Duchesnay unit Eldon/Pika Fms. Stephen Fm.: Waputik Mbr. Narao Mbr. Cathedral Fm.	+ 517.7 (C) 21.4 (C) 15.0 (C) 15.0 (I)
88-DS-13	Miller Pass 2	Oke unit Duchesnay unit	+ 112.9 (I)

TABLE A2 (CONTINUED)

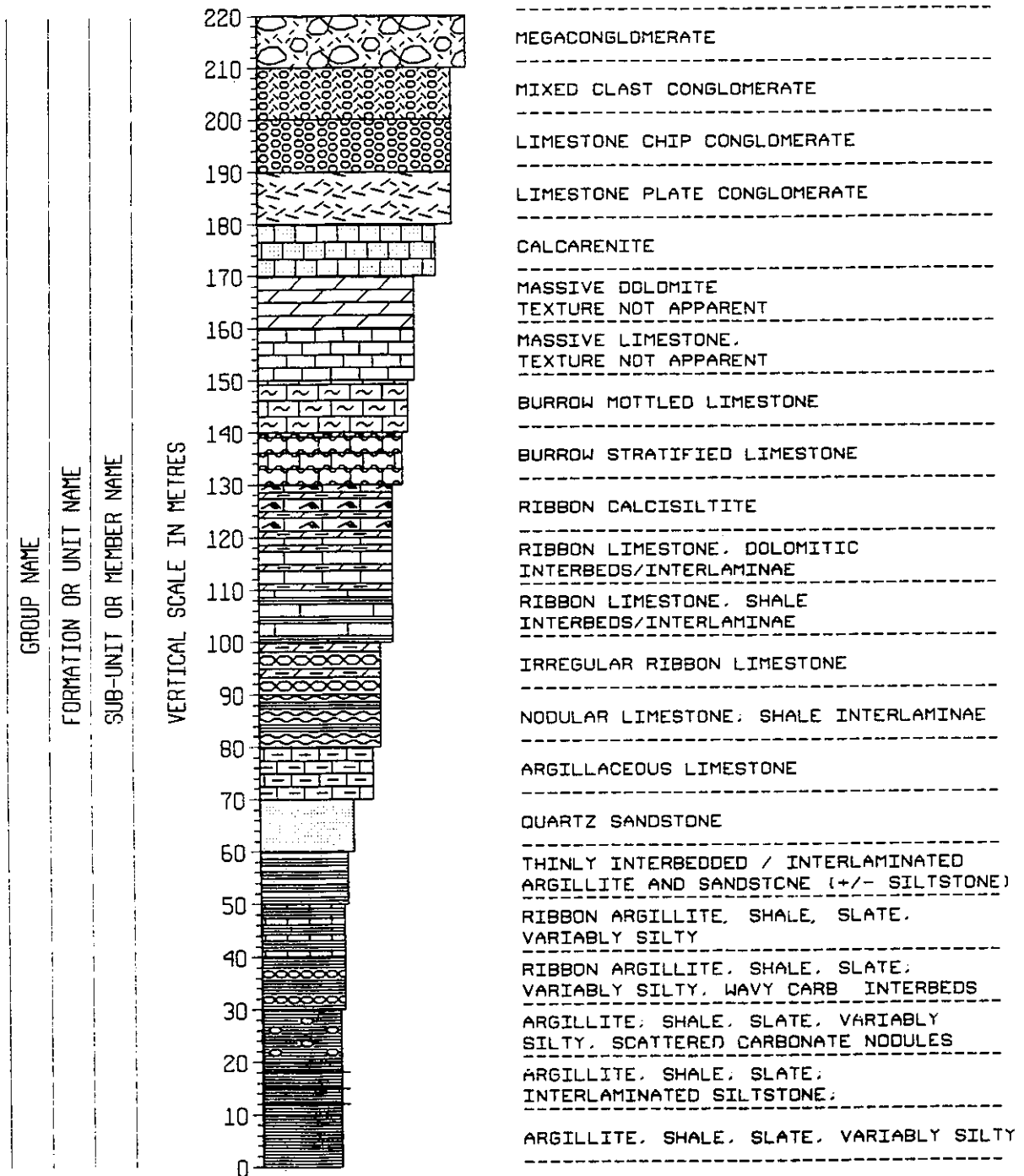
<u>SECTION NO.</u>	<u>LOCATION</u>	<u>UNIT MEASURED</u>	<u>THICKNESS (m)</u>
88-DS-14	Naiset Point	Cathedral Fm. Naiset Fm. Gog Gp.	+ 153.2 (C) +
88-DS-15	Wedgewood Peak	Cathedral Fm. Naiset Fm. Gog Gp.	+ 210.2 (C) +
88-DS-16	Misko Mountain	Upper Chancellor Oke unit Duchesnay unit	10.5 (I) 332.3 (C) 162.4 (I)
88-DS-16A	Misko Mountain North	Duchesnay unit	167.5 (I)*
88-DS-17	Tokumm Headwaters 1	Vermilion sub-unit Tokumm sub-unit Eldon Fm. Stephen Fm. (Waputik Mbr.) Cathedral Fm.	67.7 (I) 144.8 (C) 216.7 (C) 29.0 (C) +
88-DS-18	Tokumm Headwaters 2	Vermilion sub-unit Tokumm sub-unit	123.7 (I) 19.7 (I)
88-DS-19	Mt. Oke South	Duchesnay unit	304.5 (I)
88-DS-20	Mt. Biddle	Vermilion sub-unit Tokumm sub-unit Eldon Fm. (basal black band) Stephen Fm. (Waputik Mbr.) Cathedral Fm.	110.4 (I) 130.1 (C) 82.1 (#) 32.9 (C) +
88-DS-21	Curtis cirque	Vermilion sub-unit Tokumm sub-unit Eldon Fm. (basal black band)	78.6 (I) 95.9 (C) 56.1 (#)
88-DS-22	The Monarch (North Face)	Vermilion sub-unit Tokumm sub-unit "Basinal" Stephen Fm. Upper Takakkaw Tongue Lower Takakkaw Tongue (Cathedral megabreccia)	99.6 (I) 239.4 (C) 177.8 (C) 37.5 (C) +
88-DS-23	Natalko Lake	Tokumm sub-unit "Basinal" Stephen Fm. Upper Takakkaw Tongue	13.5 (I) 149.3 (C) 81.8 (I)
88-DS-24	Stephen cirque West	Vermilion sub-unit Tokumm sub-unit Stephen Fm. (Waputik Mbr.)	90.6 (I) 179.9 (C) +

TABLE A2 (CONTINUED)

<u>SECTION NO.</u>	<u>LOCATION</u>	<u>UNIT MEASURED</u>	<u>THICKNESS (m)</u>
88-DS-25	Stephen cirque East	Vermilion sub-unit Tokumm sub-unit Upper Eldon Fm. Eldon Fm. (Field Mbr.)	193.2 (I) 26.5 (#) 92.9 (#) 22.5 (I)
88-DS-26	Stephen cirque Centre 1	Vermilion sub-unit	190.1 (I)
88-DS-27	Monarch cirque 1	Tokumm sub-unit "Basinal" Stephen Fm. Upper Takakkaw Tongue Lower Takakkaw Tongue (Cathedral megabreccia)	94.4 (I) 84.1 (C) 46.9 (C) +
88-DS-28	Monarch cirque 2	Upper Takakkaw Tongue Lower Takakkaw Tongue (Cathedral megabreccia) Cathedral Fm. Gog Gp.	+ 51.5 (C) 111.3 (C) 11.7 (I)
89-DS-29	Haffner Creek South	Vermilion sub-unit Tokumm sub-unit	123.6 (I) 150.8 (I)
89-DS-30	Prospectors Valley 4	Duchesnay unit Vermilion sub-unit Tokumm sub-unit	+ 134.4 (C) 11.6 (I)
89-DS-31	Hamilton Lake North	Duchesnay unit (undivided) Upper Pika Fm.	157.0 (I) +
89-DS-32	Hamilton Lake South	Oke unit Upper Duchesnay unit	66.6 (I) 72.1 (I)*
89-DS-33	Verdant Headwaters South	Vermilion sub-unit	108.7 (I)
89-DS-34	Verdant Headwaters North	Duchesnay unit Vermilion sub-unit Eldon/Pika Fms. (undiff.)	+ 158.3 (C) 8.9 (#)
89-DS-35	Stephen cirque Centre 2	Vermilion sub-unit	116.9 (I)
89-DS-36	Numa Mountain South	Vermilion unit Tokumm unit	200.6 (I)* 144.4 (I)*

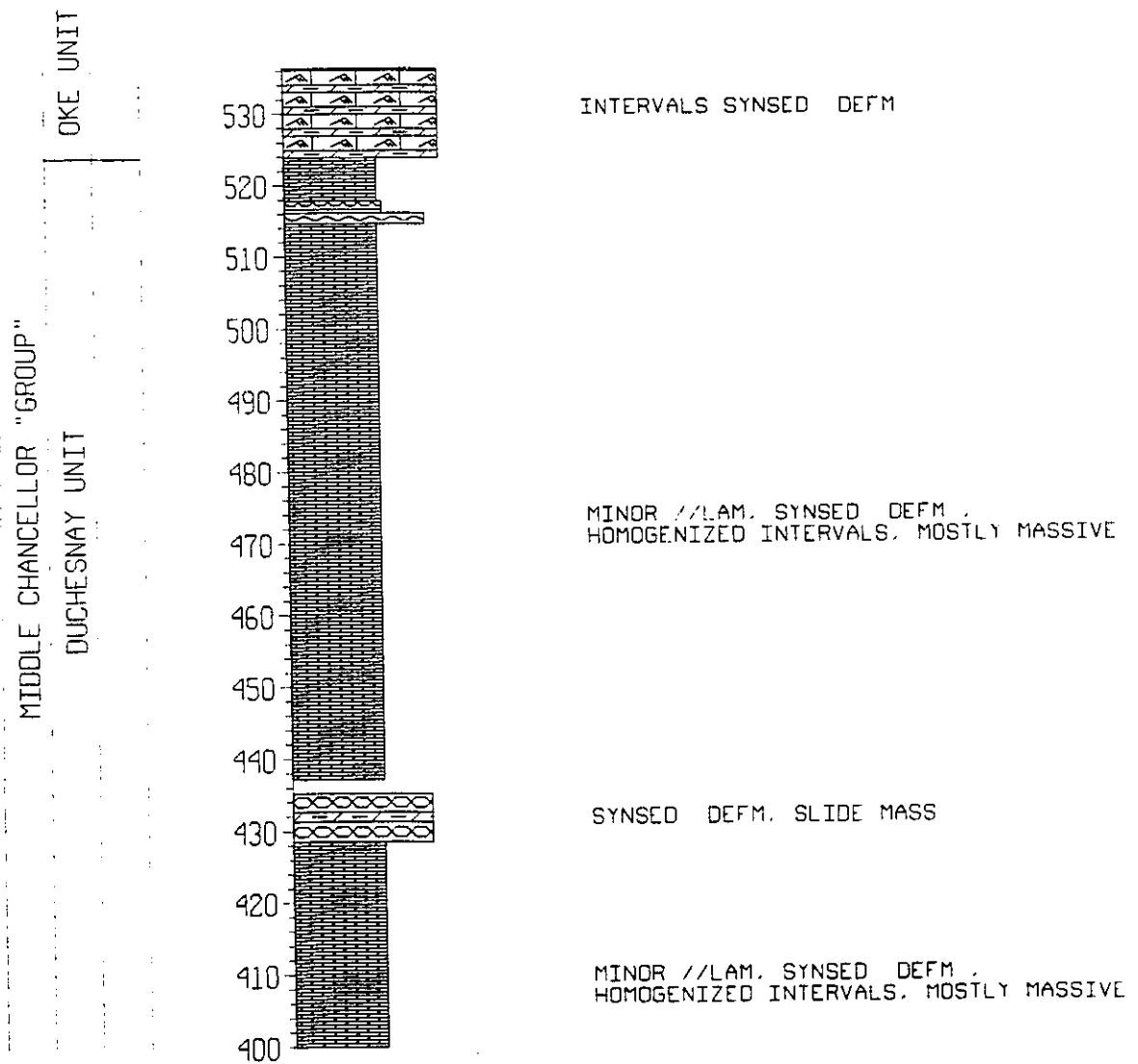
-
- (C) complete stratigraphic section of unit measured
(I) incomplete stratigraphic section of unit measured
* position of unit boundary tentative
+ unit present but not measured
(#) unit thickness variable locally due to downcut by megatruncation surface.

KEY TO STRATIGRAPHIC SECTIONS



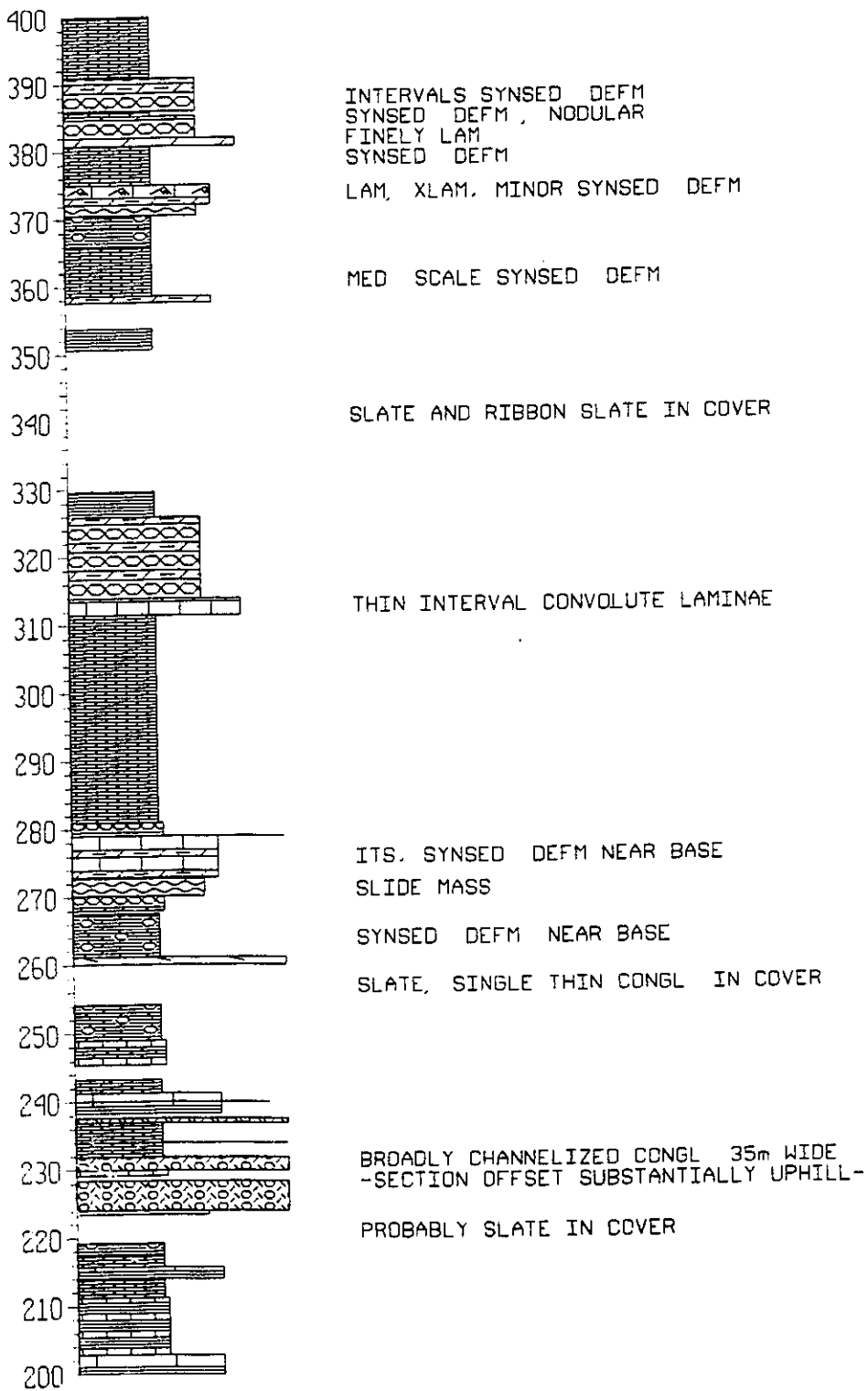
NOTE: DOLOMITIZED VERSIONS OF THESE ROCKS ARE INDICATED BY CONVENTIONAL DIAGONAL LINES IN THE ABOVE LITHOLOGICAL SYMBOLS

SECTION DS-1: MT. DENNIS NORTH

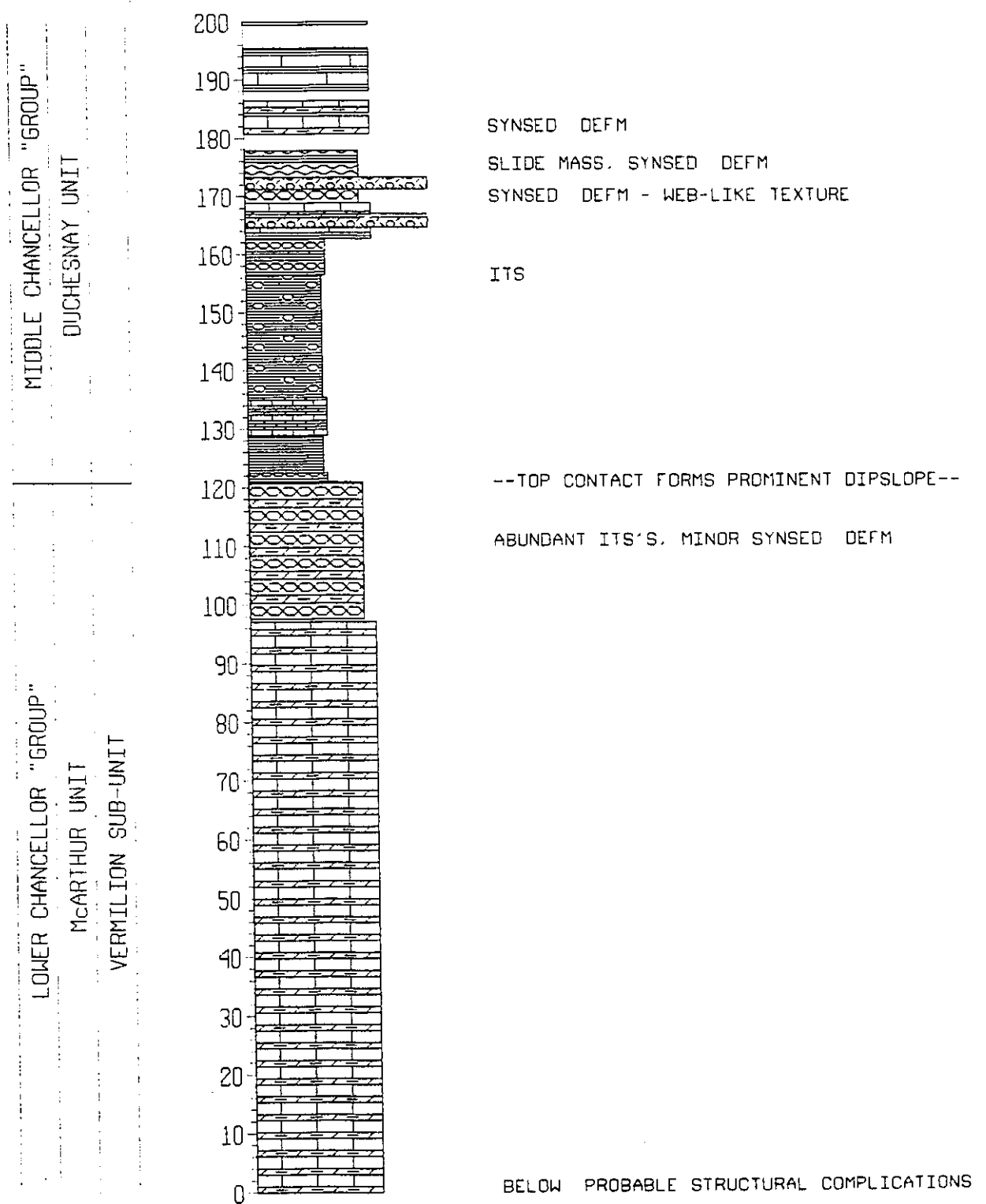


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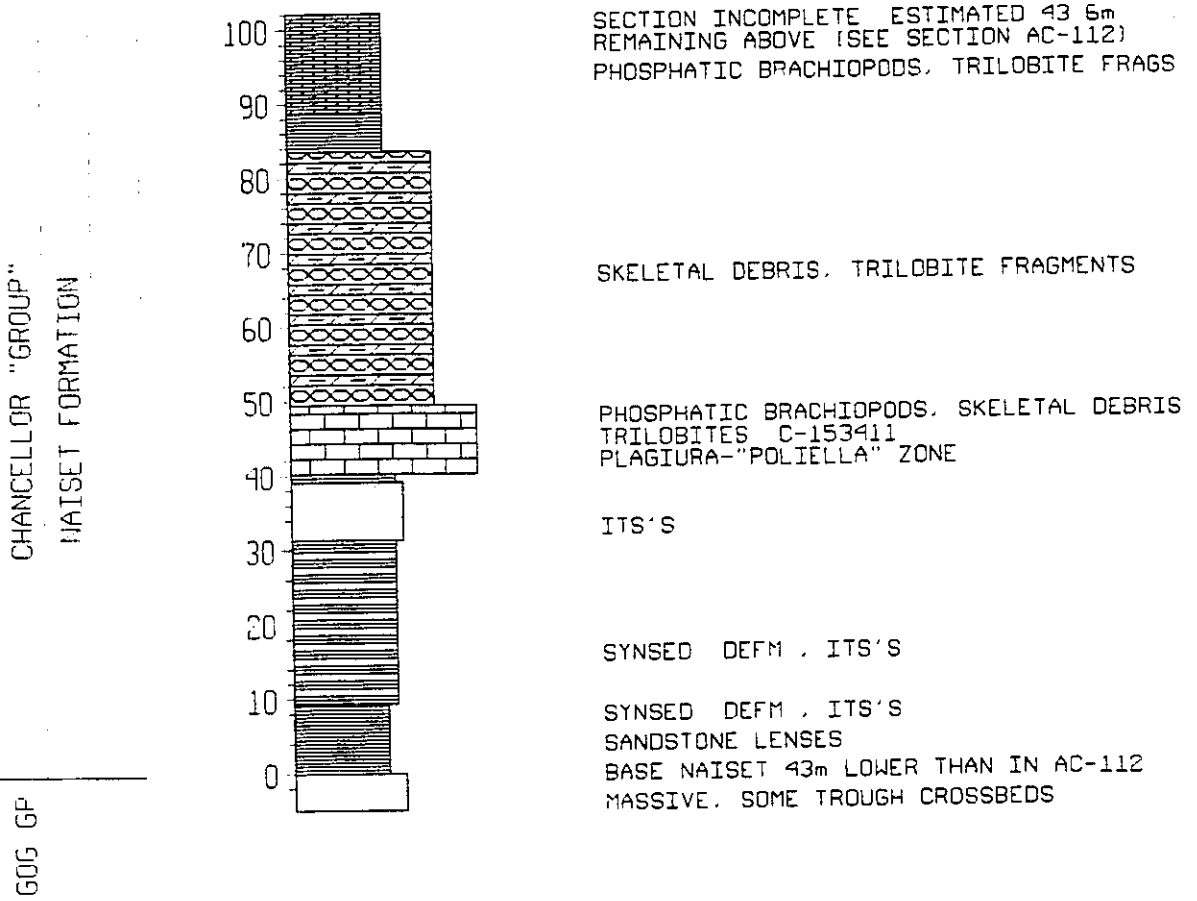
MIDDLE CHANCELLOR "GROUP"
DUCHESNAY UNIT



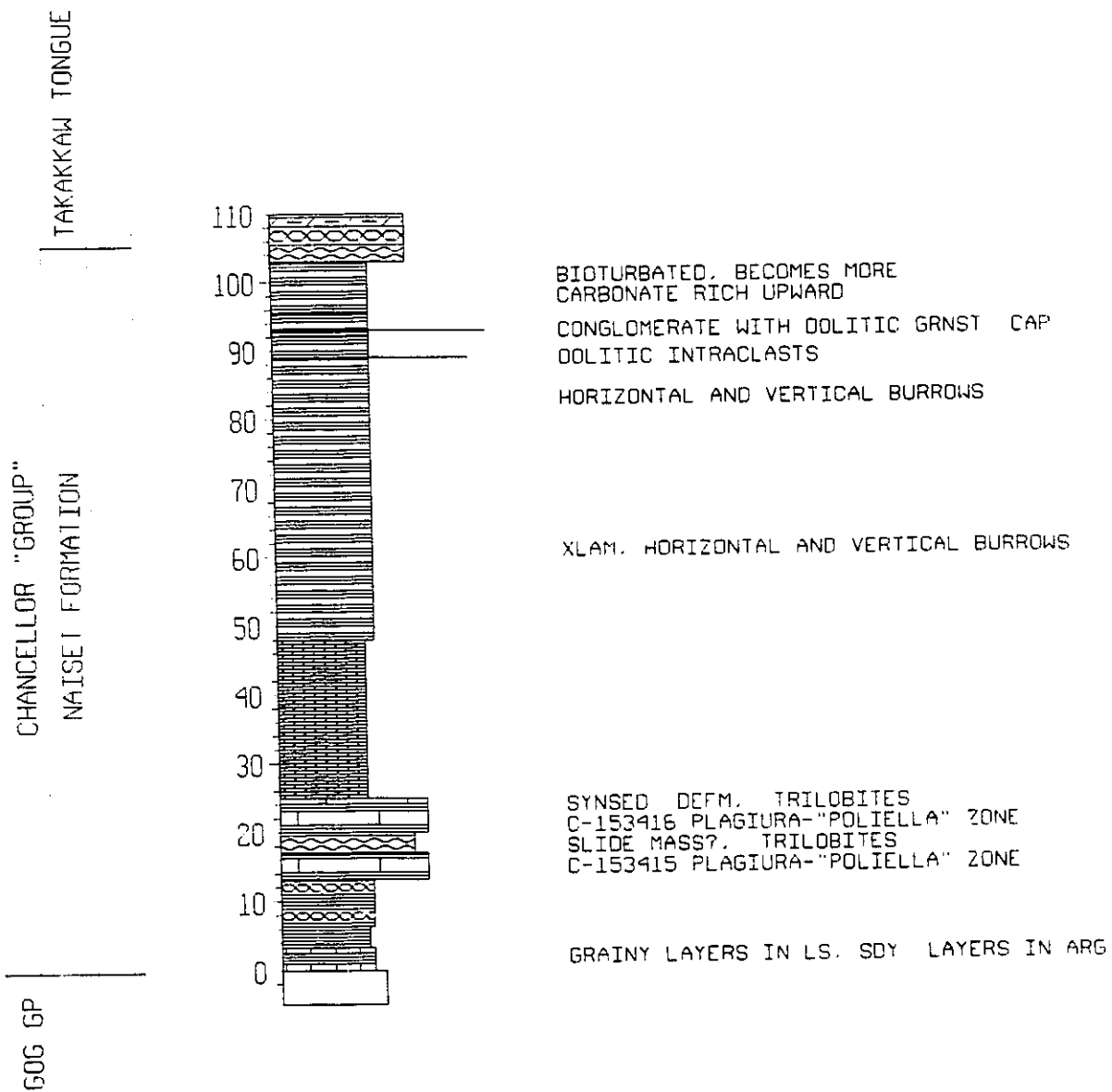
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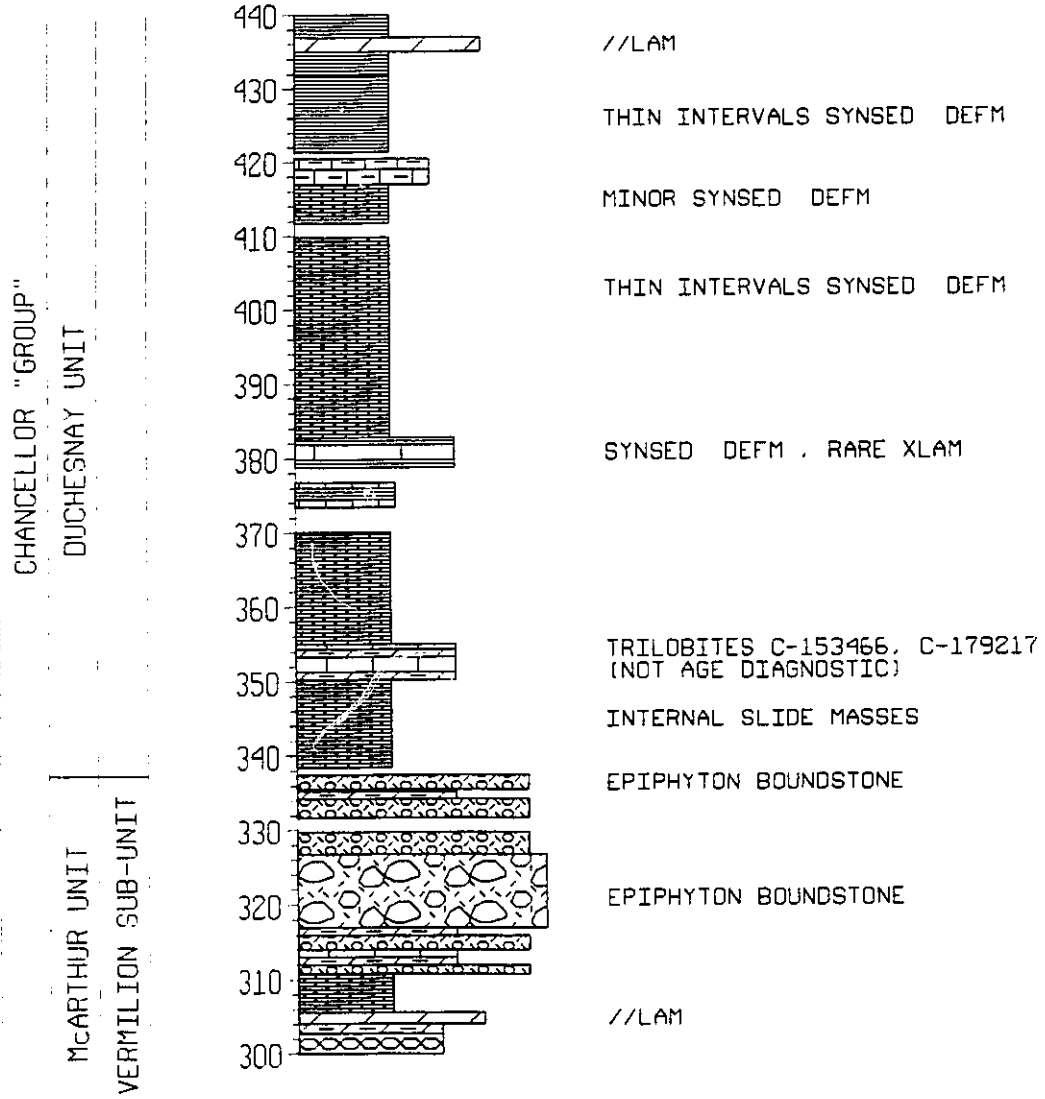
SECTION DS-2: NORTH GULLY



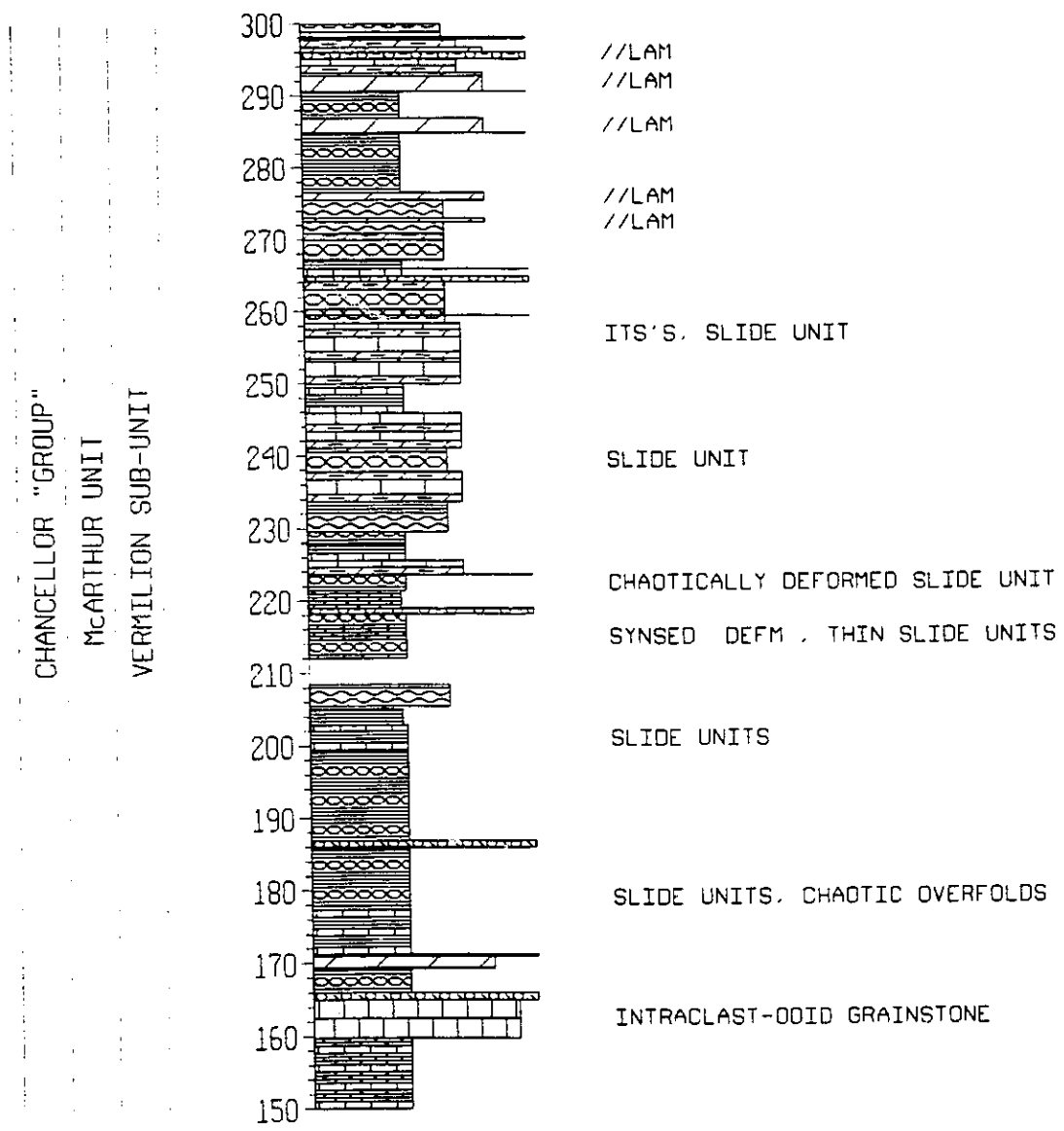
SECTION DS-3: WEDGE GULLY



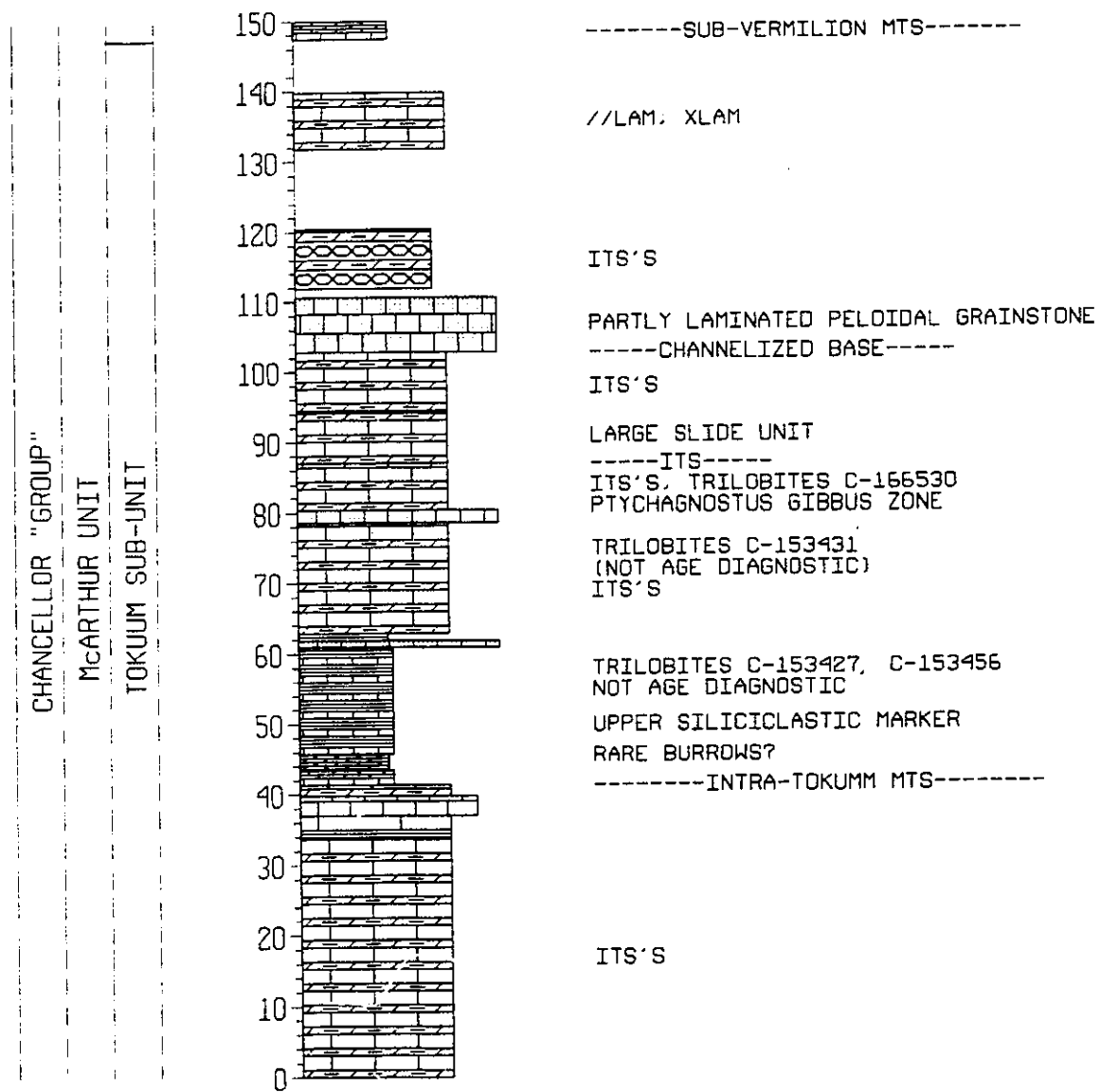
SECTION DS-4: HAFFNER CREEK NORTH



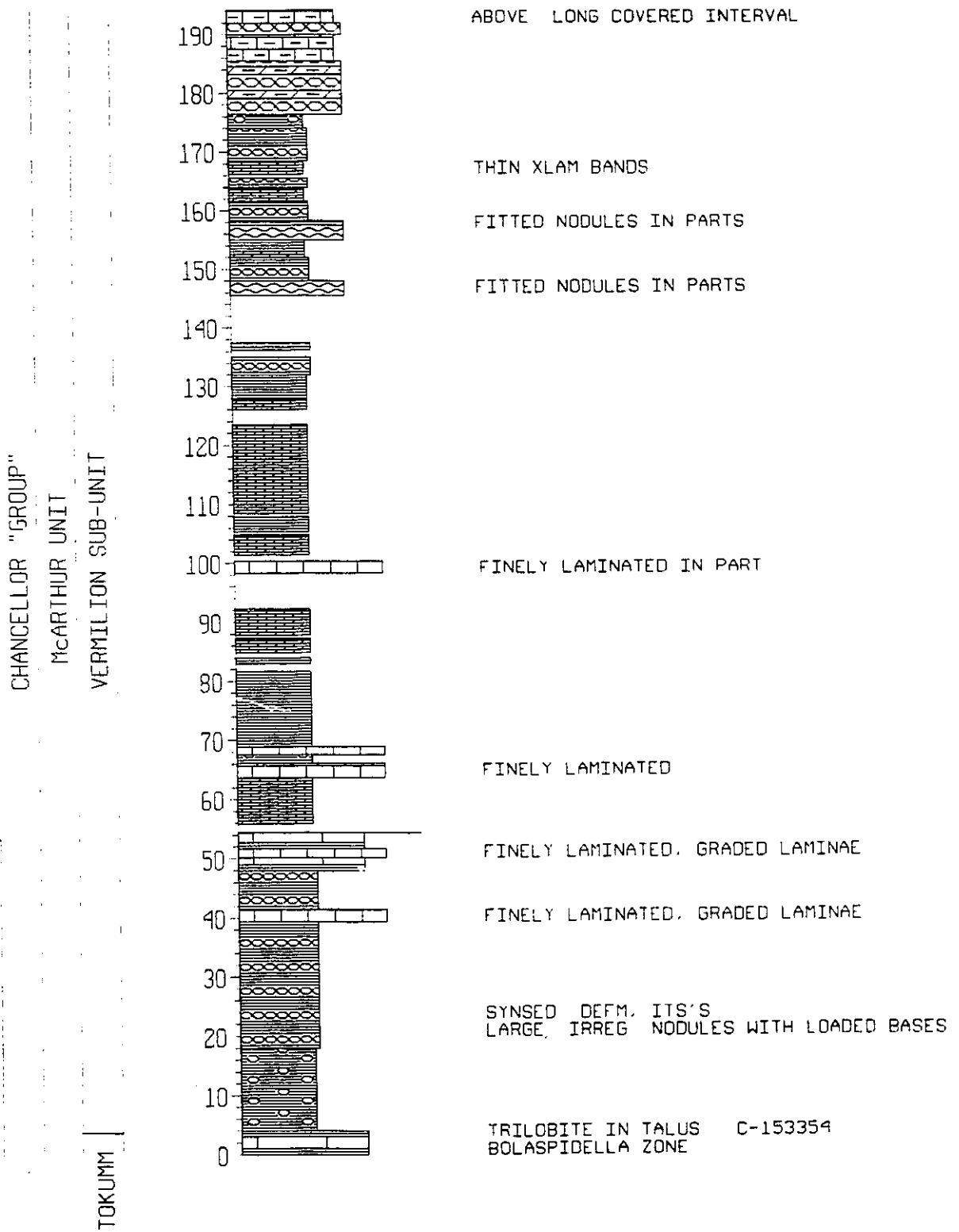
SECTION DS-4 (CONTINUED)



SECTION DS-4 (CONTINUED)

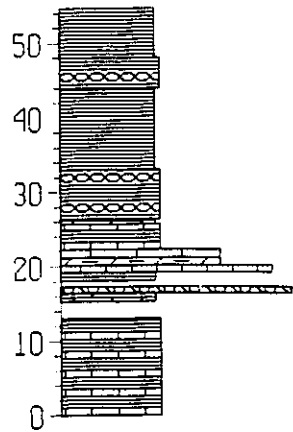


SECTION DS-5: NUMA MOUNTAIN NORTH



SECTION DS-6: MT. OKE 1

CHANCELLOR "GROUP"
DUCHESNAY UNIT

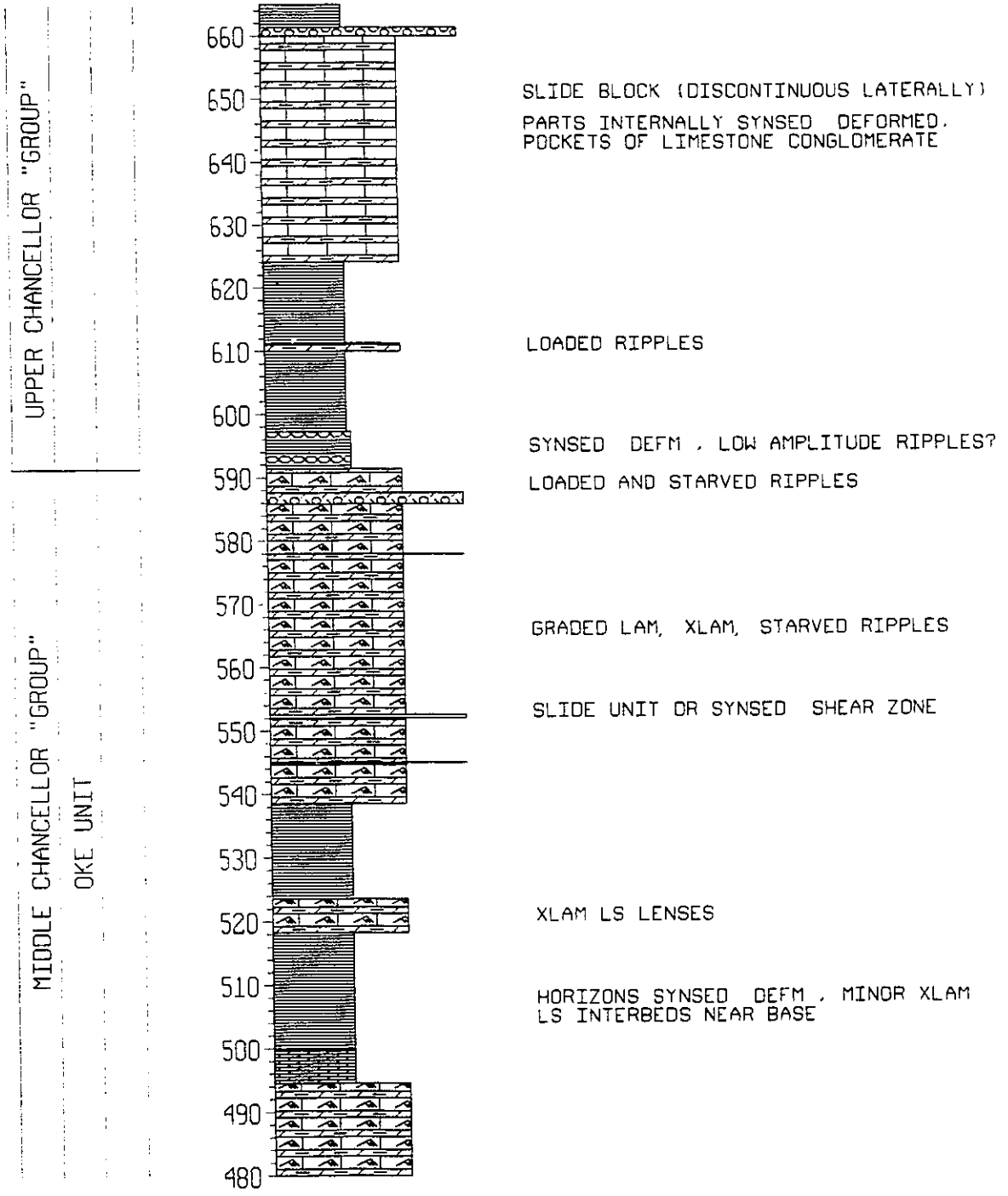


ABOVE COVER, CANNOT BE TIED
ACCURATELY TO SECTION DS-7
RARE SMALL SCALE SYNSED OVERFOLDS

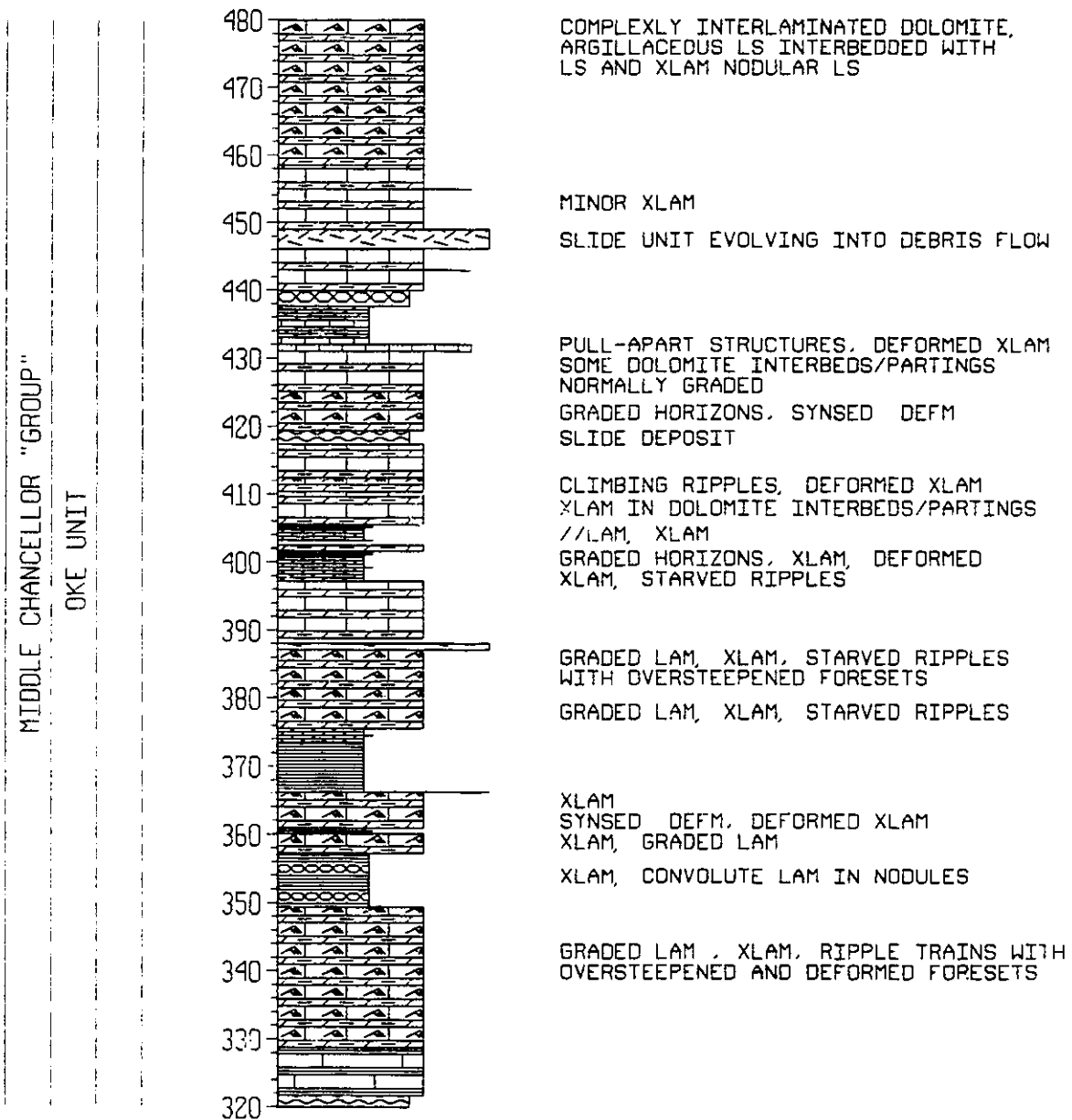
CONVOLUTE LAMINAE IN PARTS
INTRACLAST GRAINSTONE/PACKSTONE

TOP VERMILION UNIT ESTIMATED TO BE A FEW
TENS OF METRES BELOW IN COVER

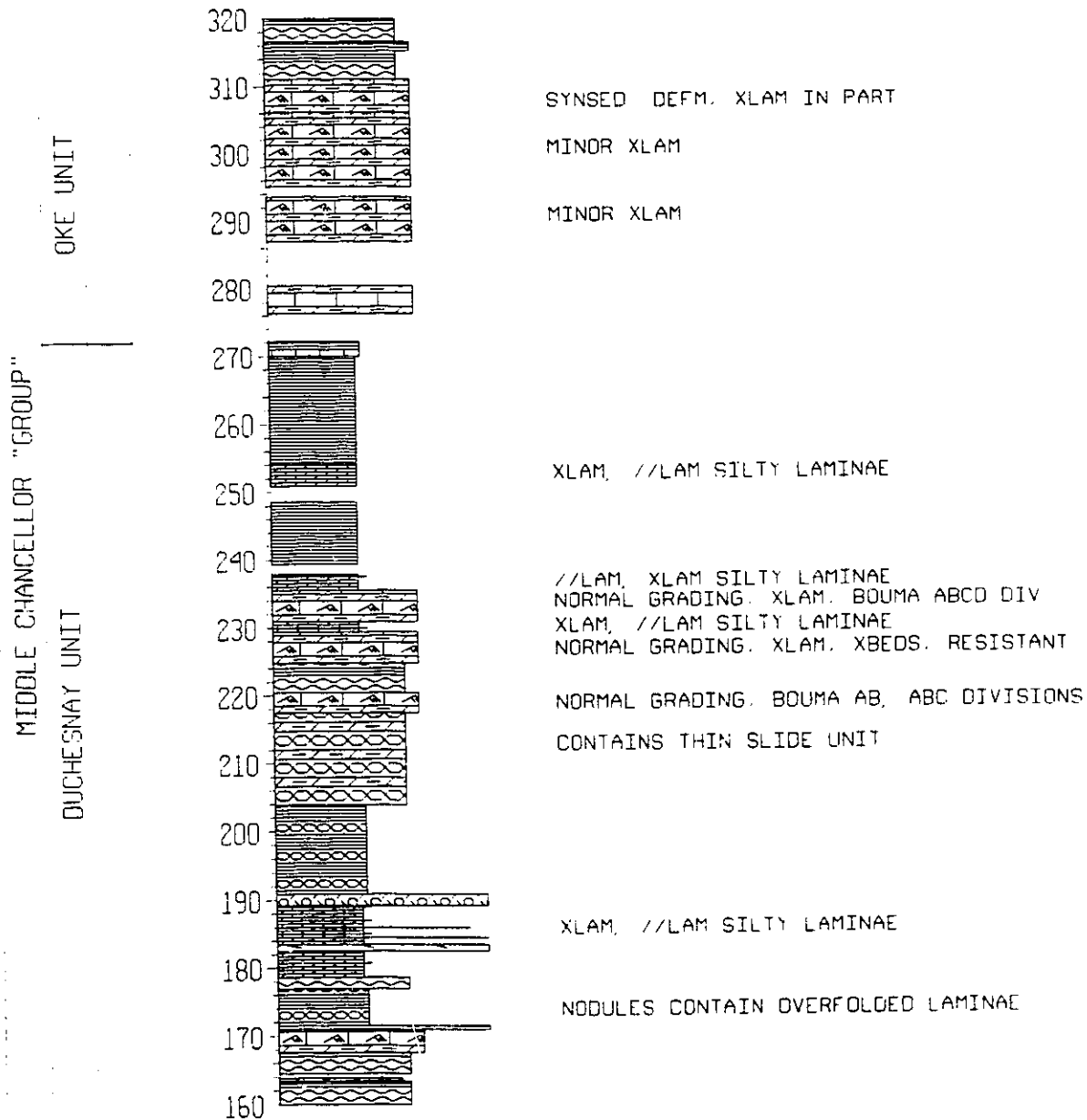
SECTION DS-7: MT. OKE 2



SECTION DS-7 (CONTINUED)

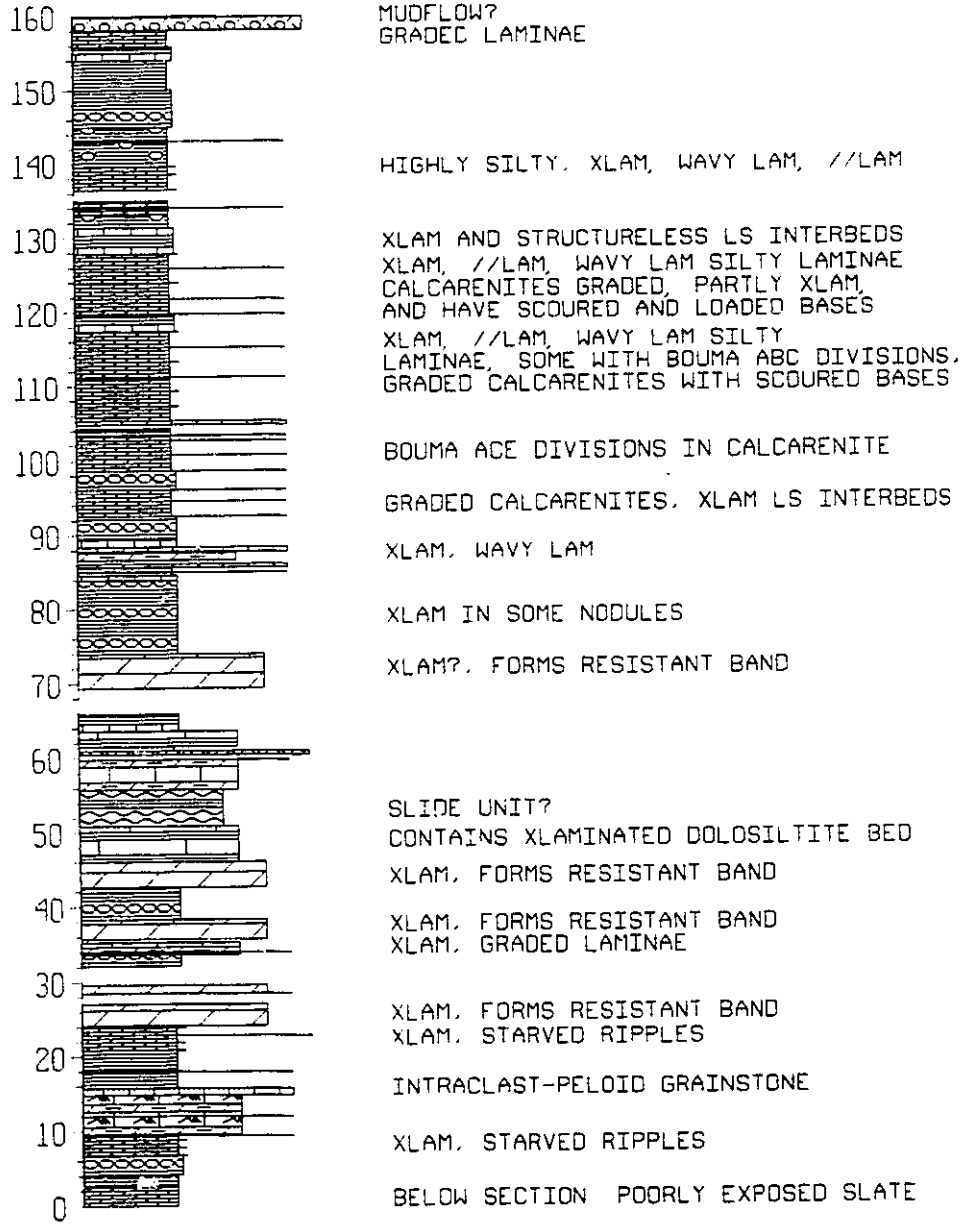


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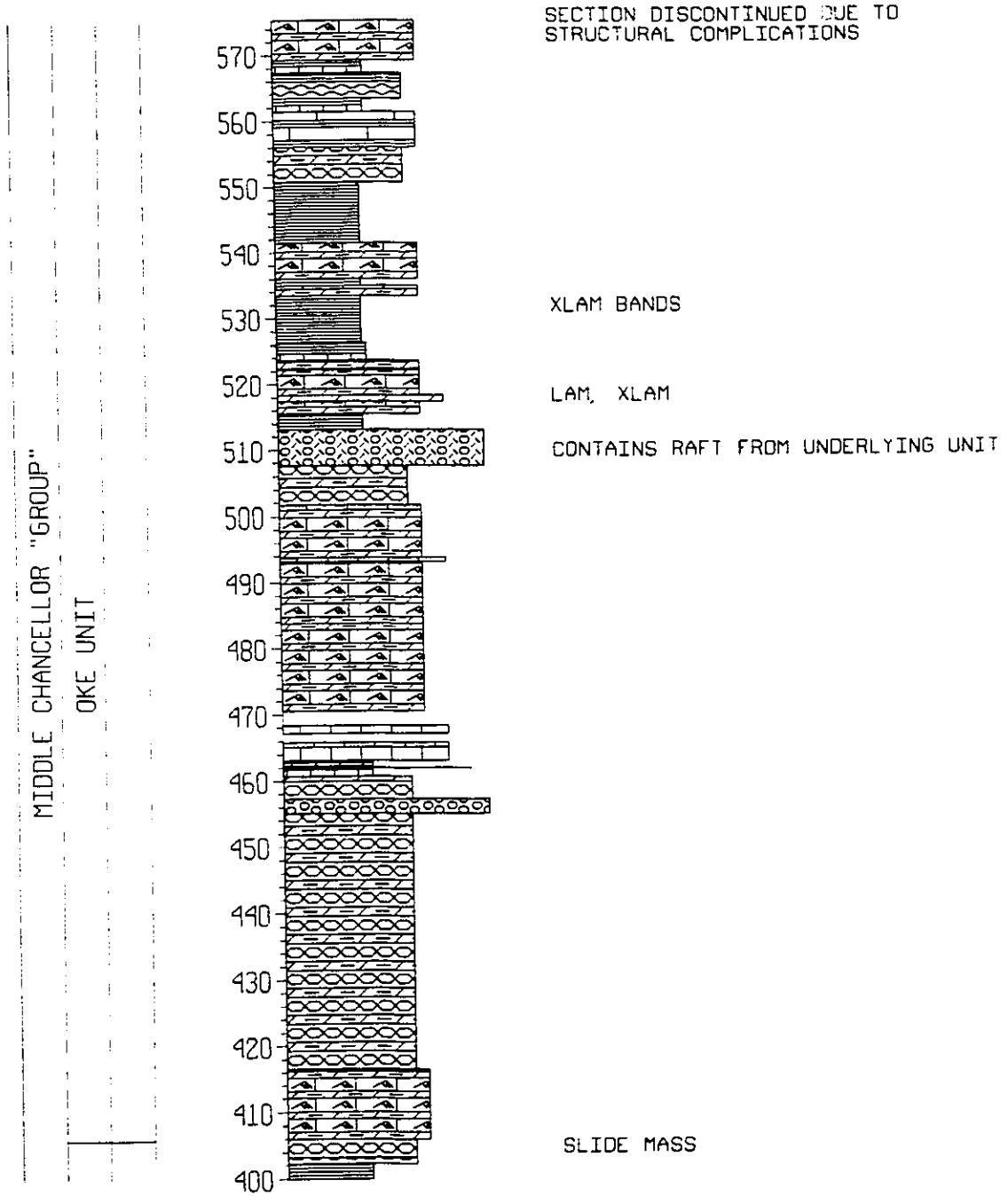


SECTION DS-7 (CONTINUED)

MIDDLE CHANCELLOR "GROUP"
DUCHESNAY UNIT

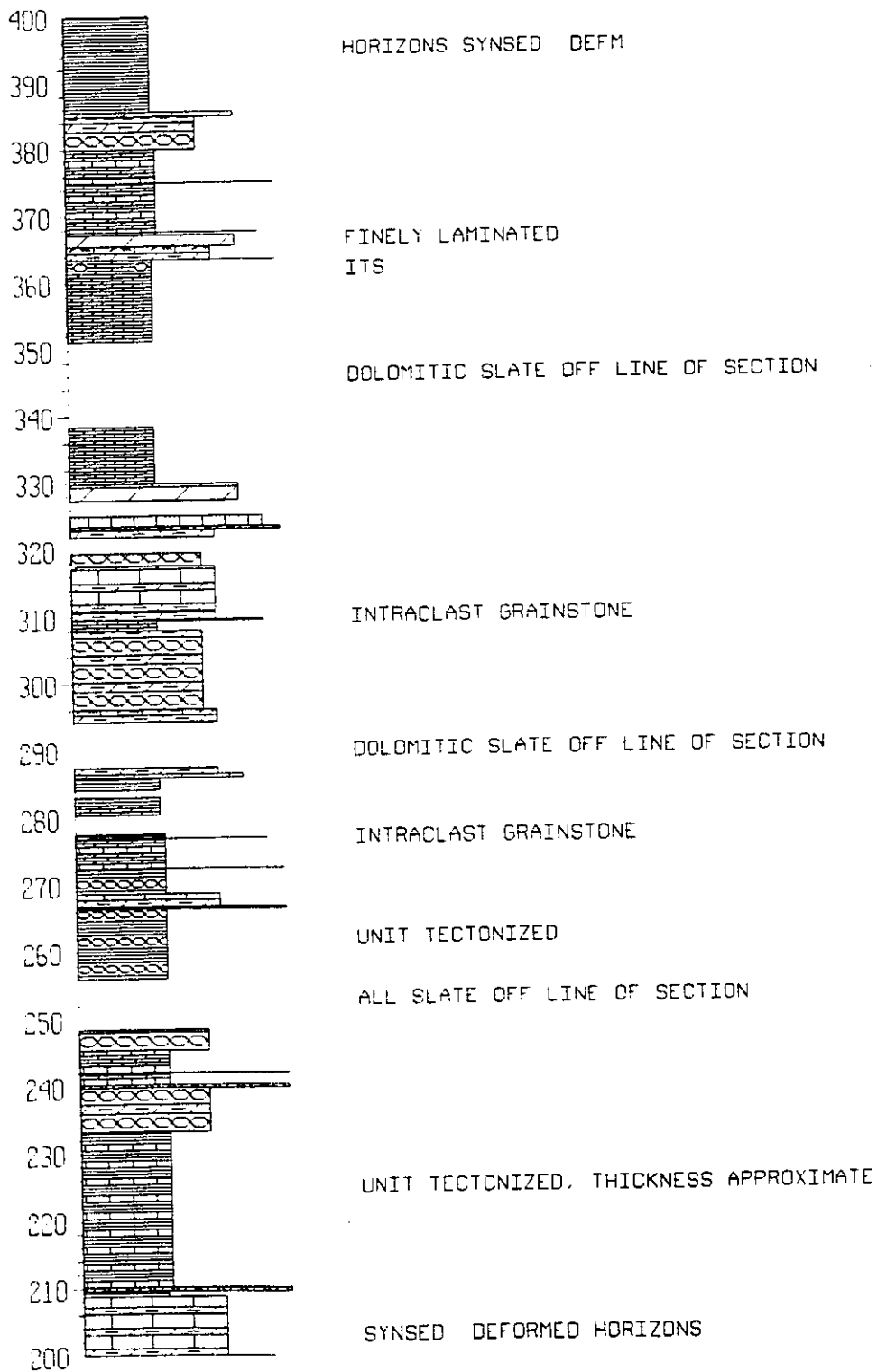


SECTION DS-8: MT. DENNIS SOUTH

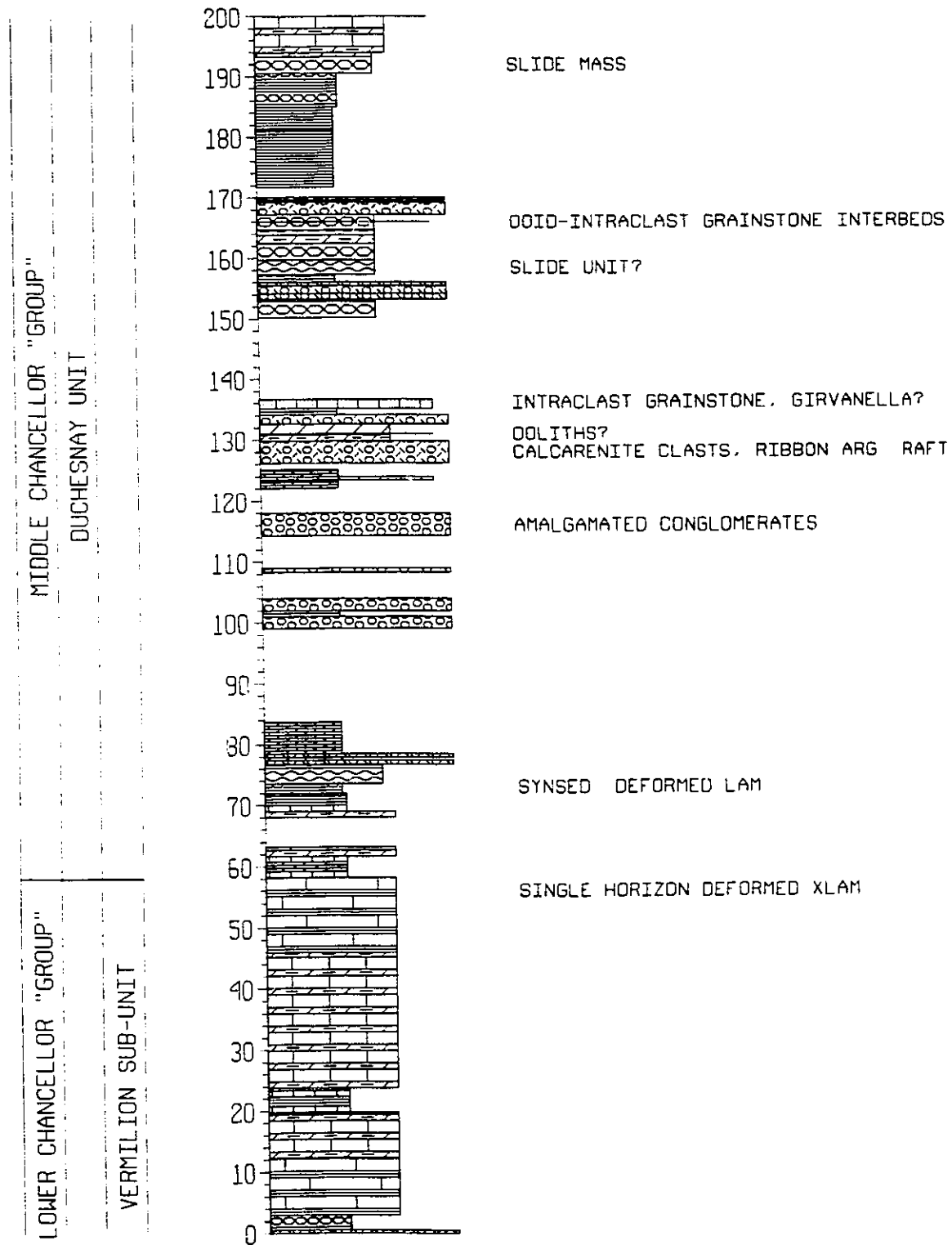


SECTION DS-8 (CONTINUED)

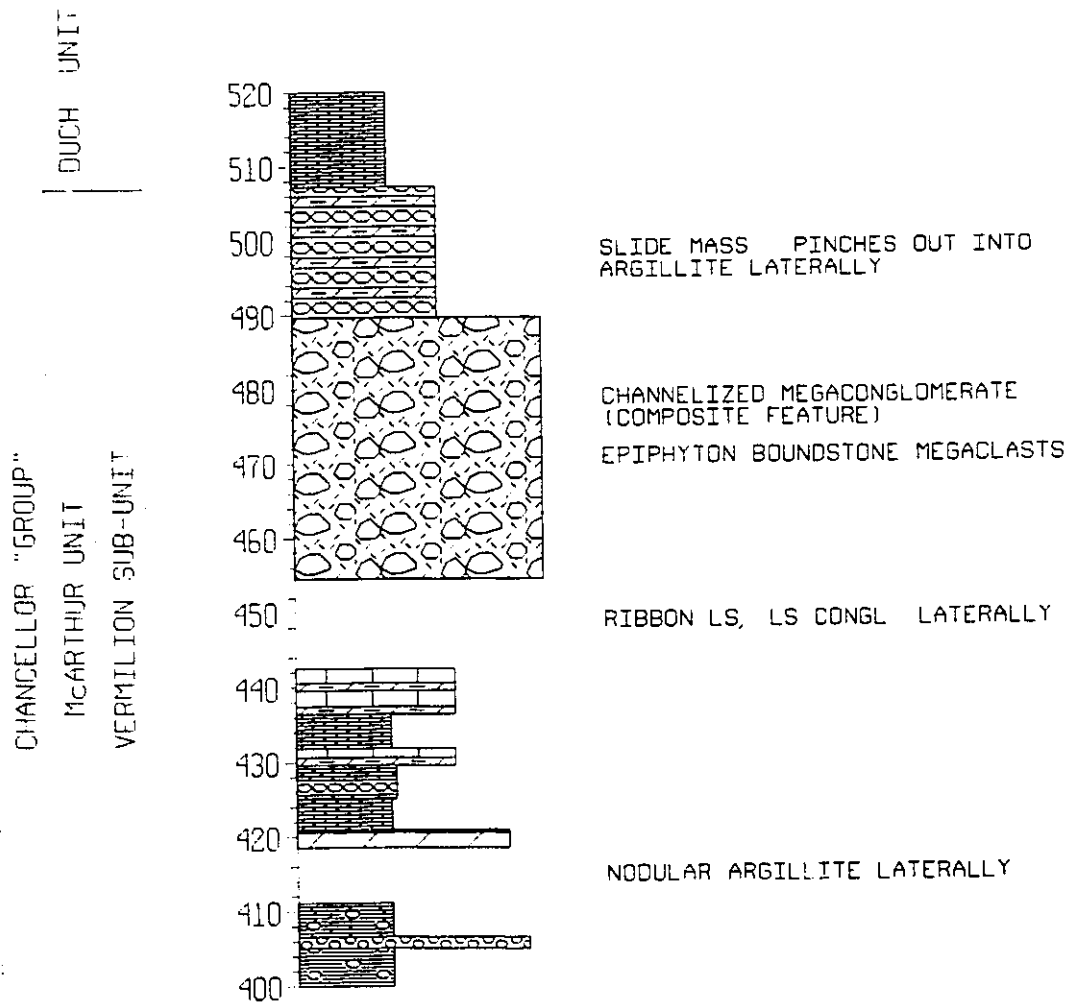
MIDDLE CHANCELLOR "GROUP"
DUCHESNEAU UNIT



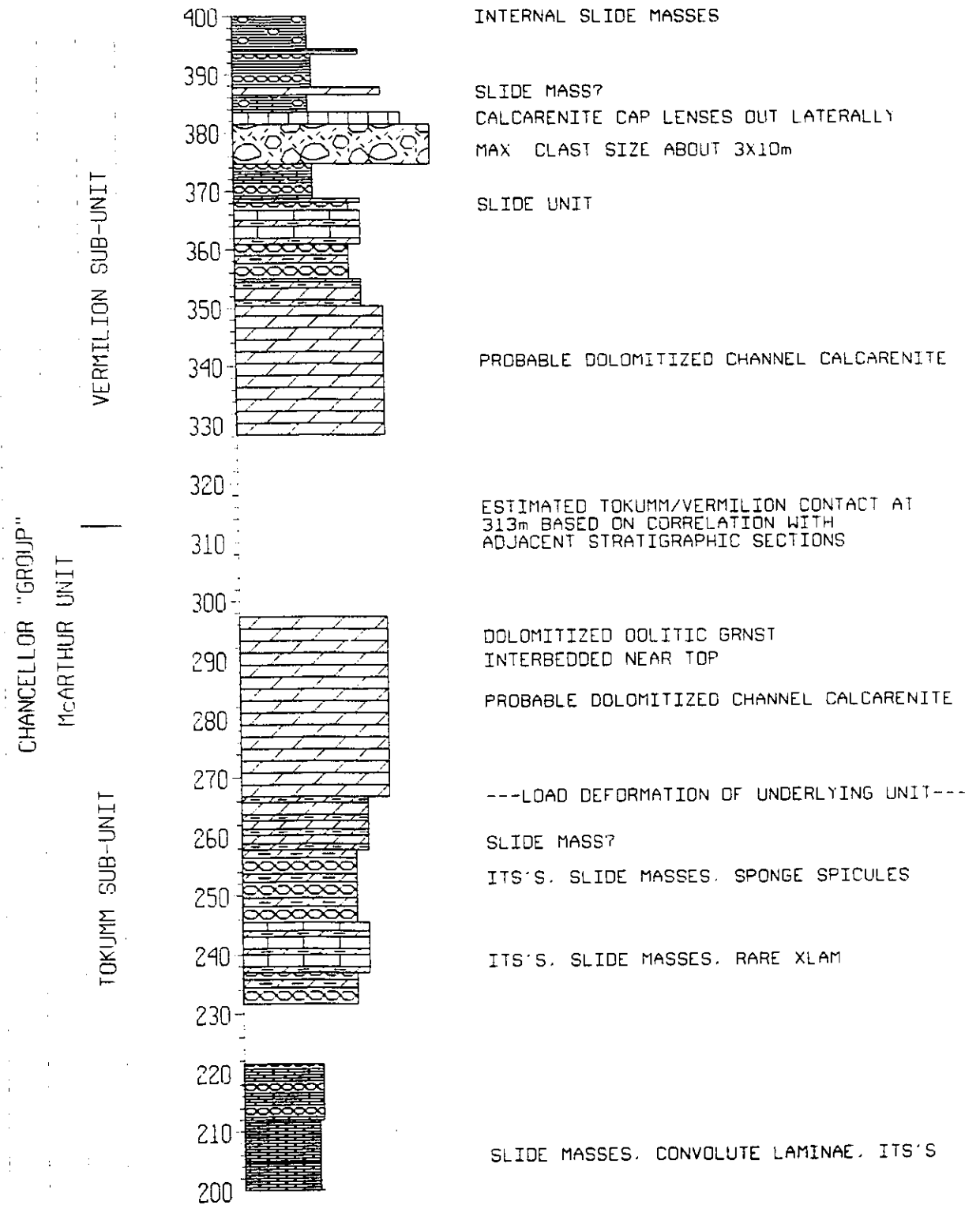
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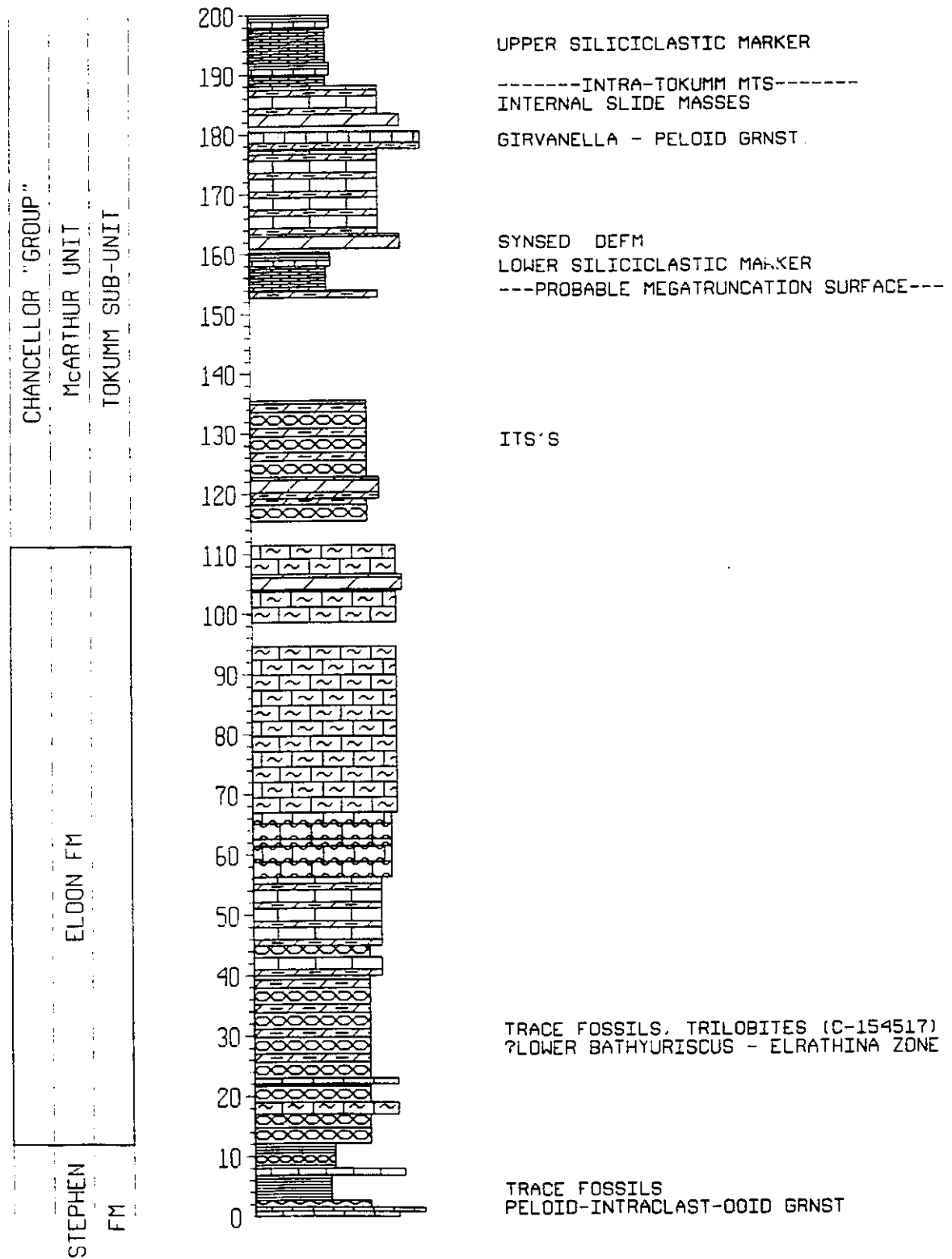
SECTION DS-9: PROSPECTORS VALLEY 1



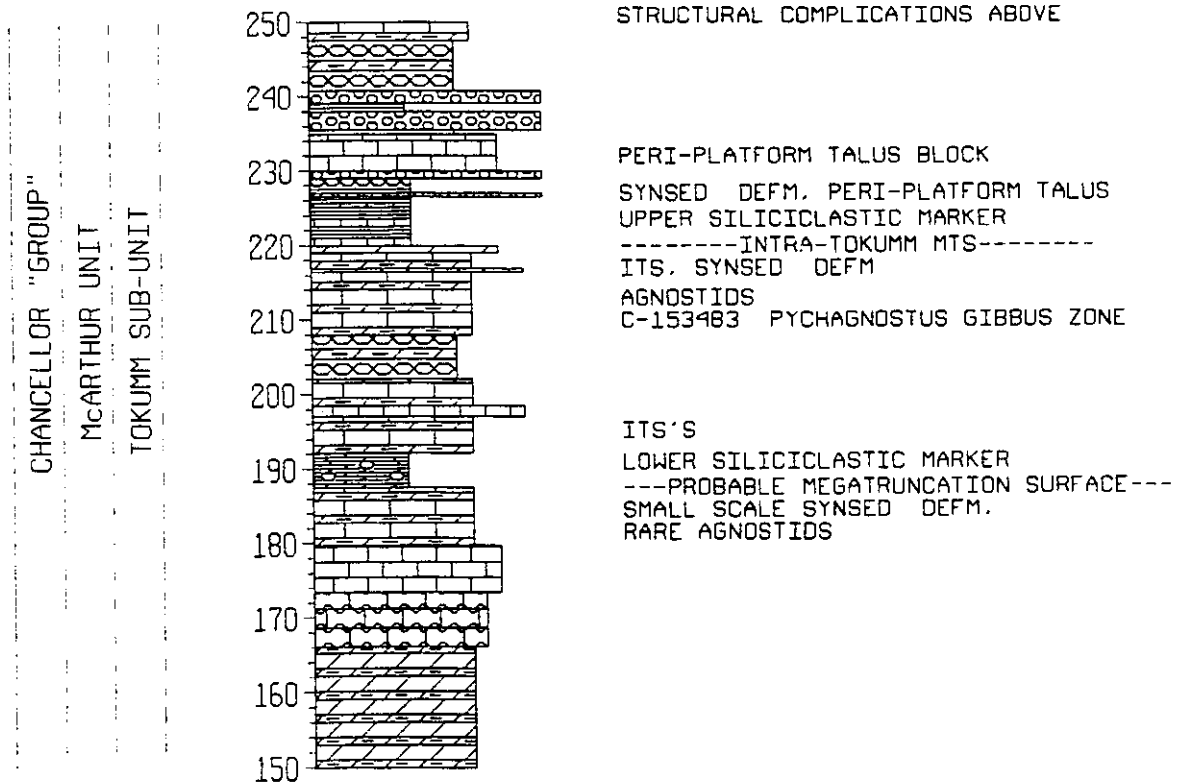
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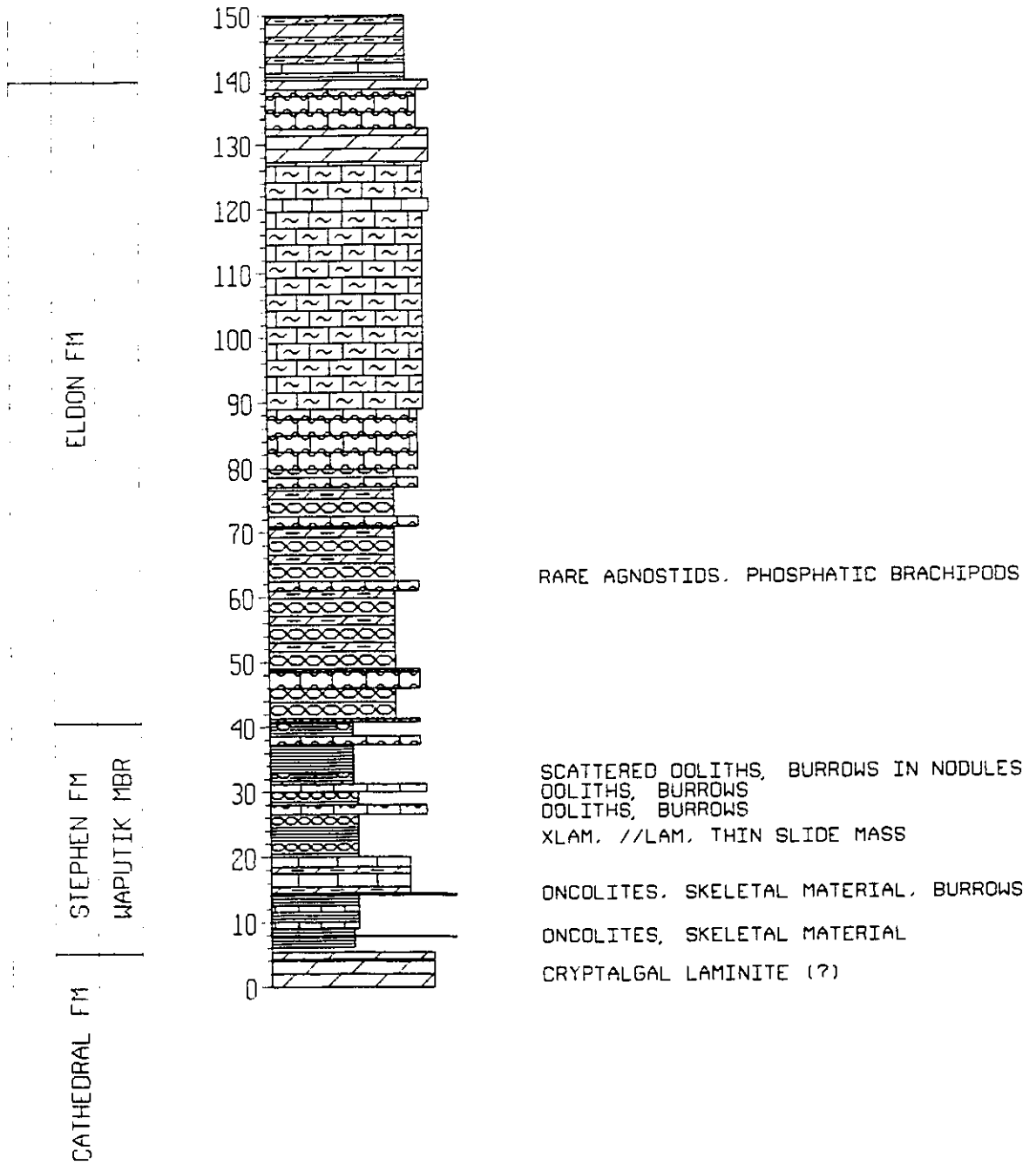
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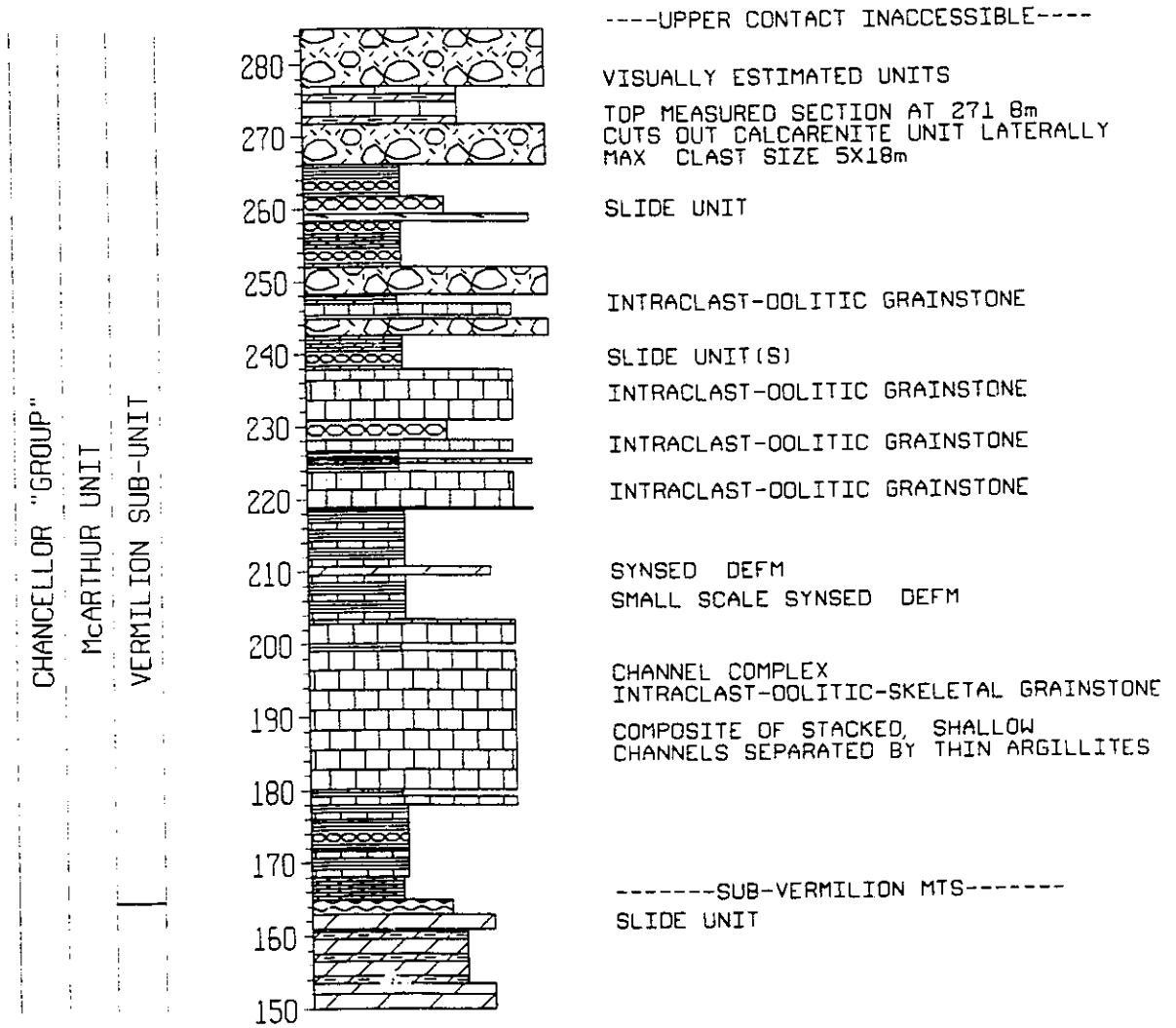
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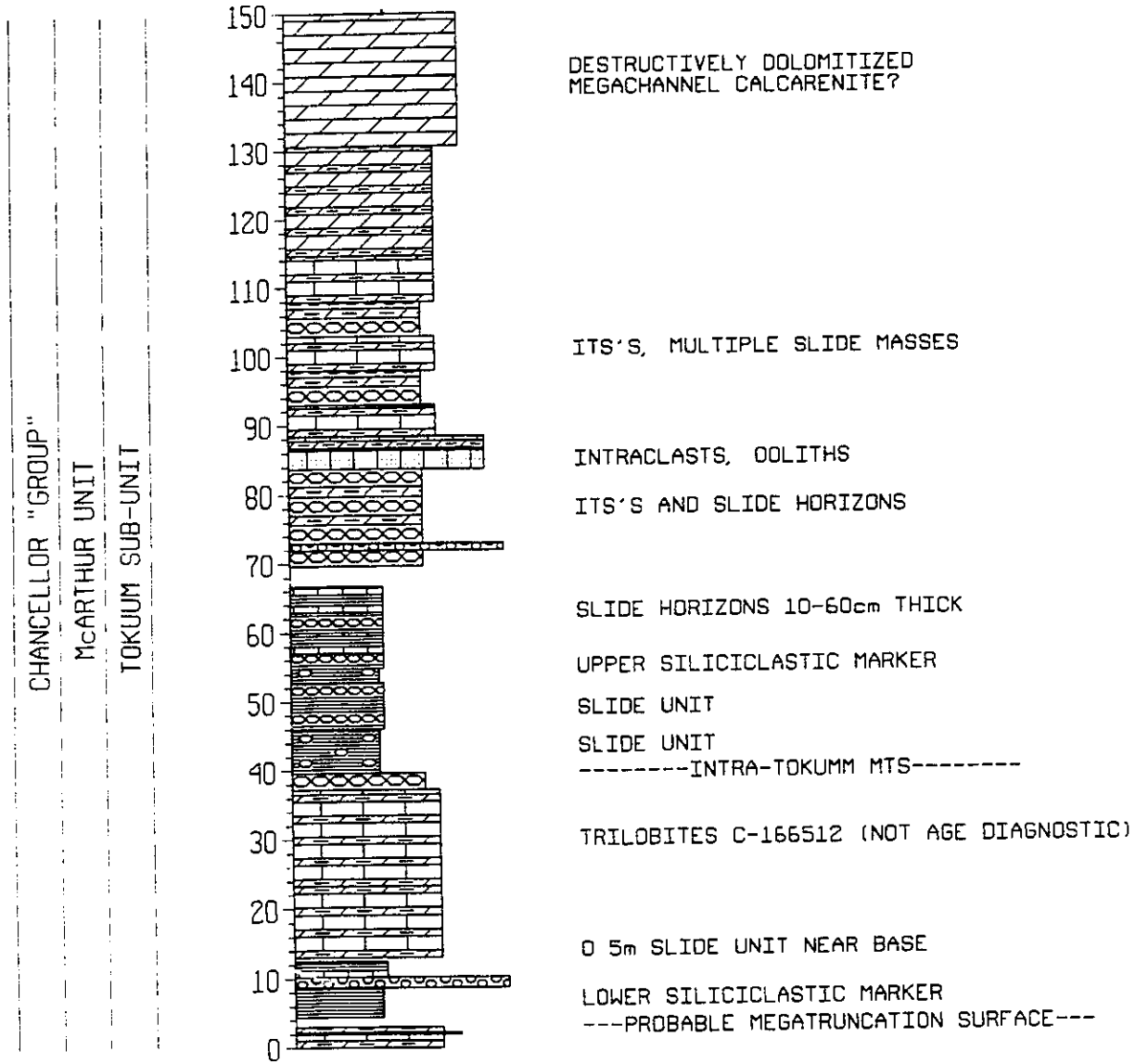
SECTION DS-10 (CONTINUED)



SECTION DS-11: PROSPECTORS VALLEY 3

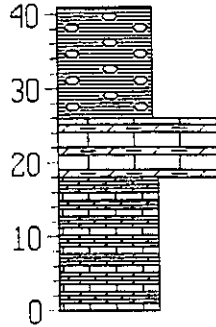


SECTION DS-11 (CONTINUED)



SECTION DS-12: MILLER PASS 1

CHANCELLOR "GROUP"
DUCHESNAY UNIT

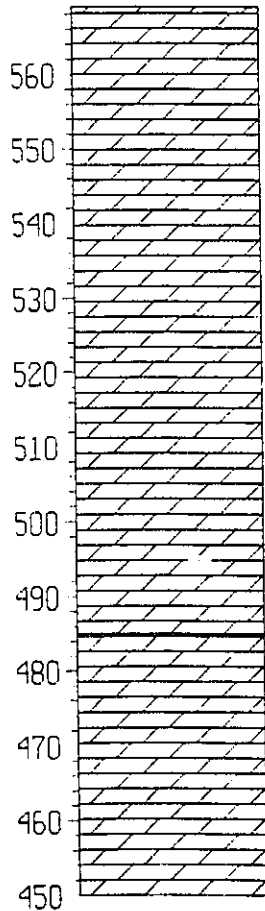


ABOVE STRUCTURAL COMPLICATIONS ABOVE
SLATE CONTINUES UP

COMPOSED OF SLIDE MASSES
COMMON TRILOBITES

COMMON ITS'S, SMALL PERIPLATFORM
CLAST EPIPHYTON BOUNDSTONE
TRILOBITES C-153361 THROUGH C-153368
BOLASPIDELLA ZONE

UNDIVIDED ELDON / PIKA FMS



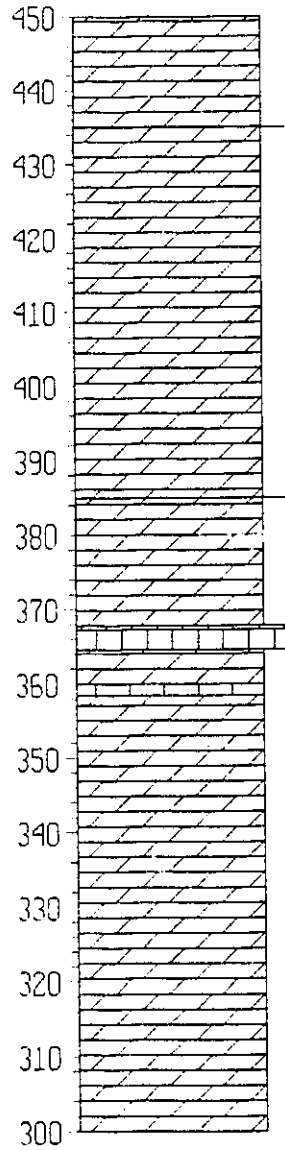
UPPER CONTACT INACCESSIBLE

UPPER 70m NOT DIRECTLY ACCESSIBLE

EX-OOLITIC GRAINSTONE

SECTION DS-12 (CONTINUED)

UNDIVIDED ELDON / PIKA FMS



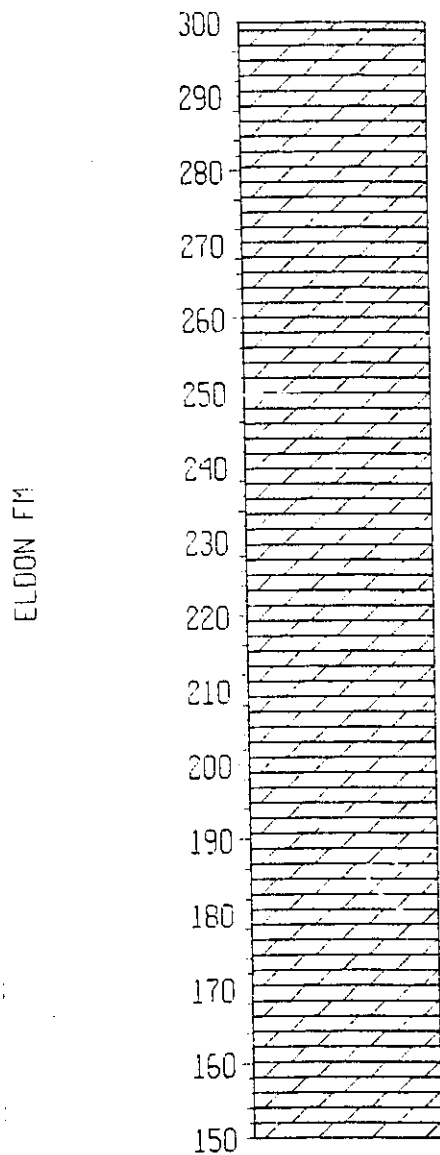
OCCASIONAL RELICT BURROWS, FENESTRAE
EX-OOLITIC GRAINSTONE

GENERALLY MASSIVE. PARTS MEDIUM
TO THICK BEDDED

EX-OOLITIC GRAINSTONE

OOLITIC GRAINSTONE. GRADED LAMINAE
HORIZONTAL BURROWS

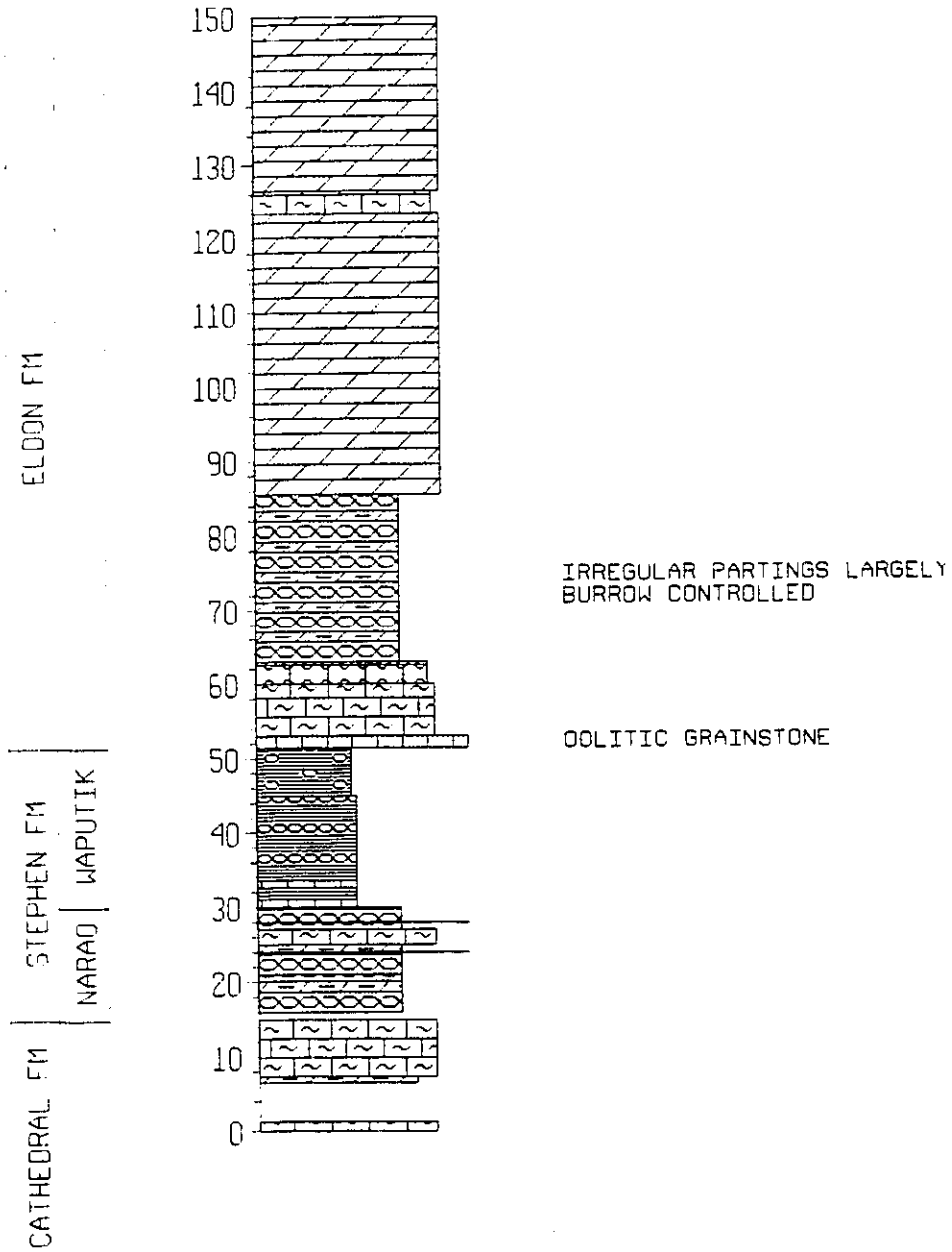
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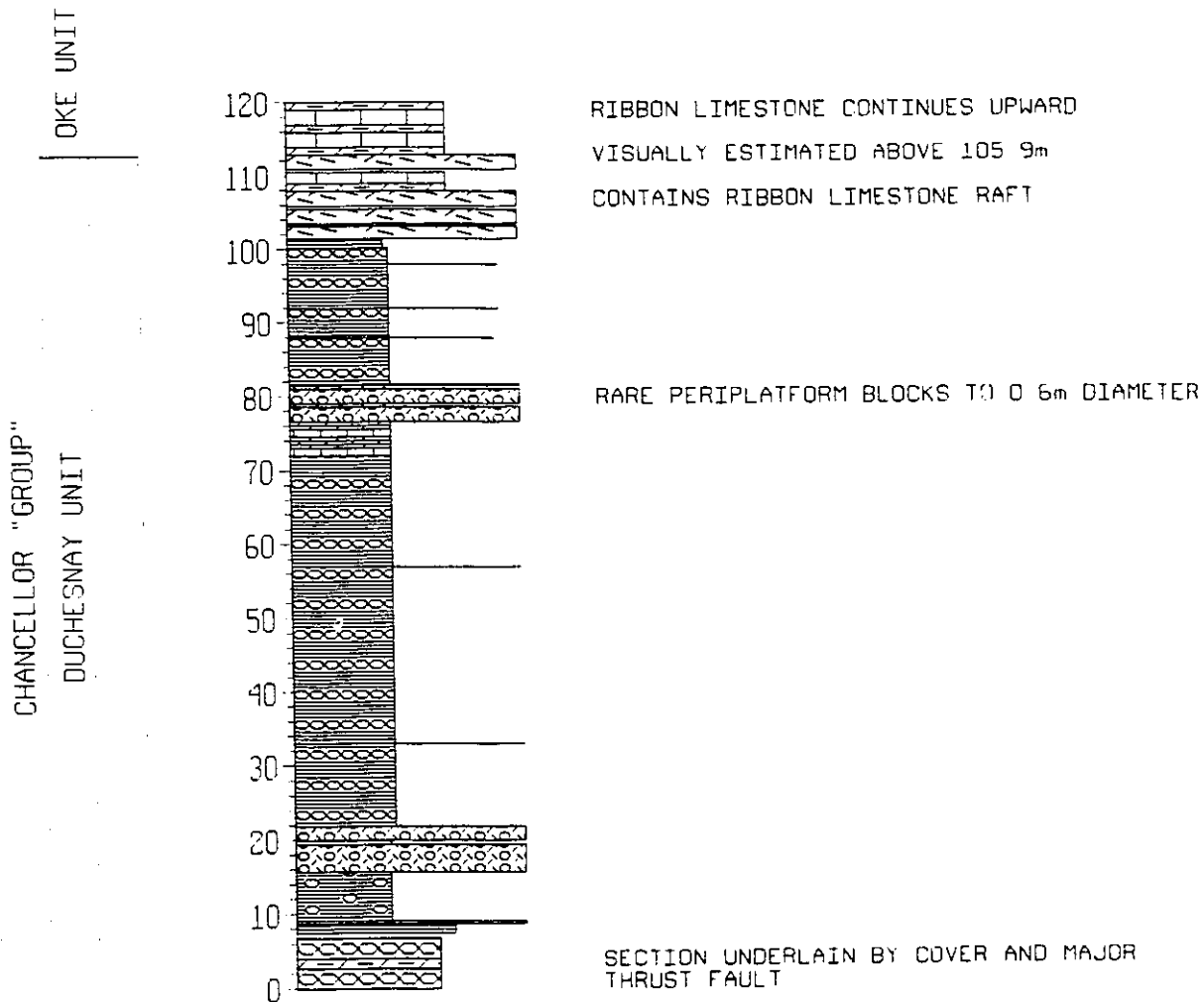
GENERALLY MASSIVE, PARTS
MEDIUM TO THICK BEDDED

ELDON FM

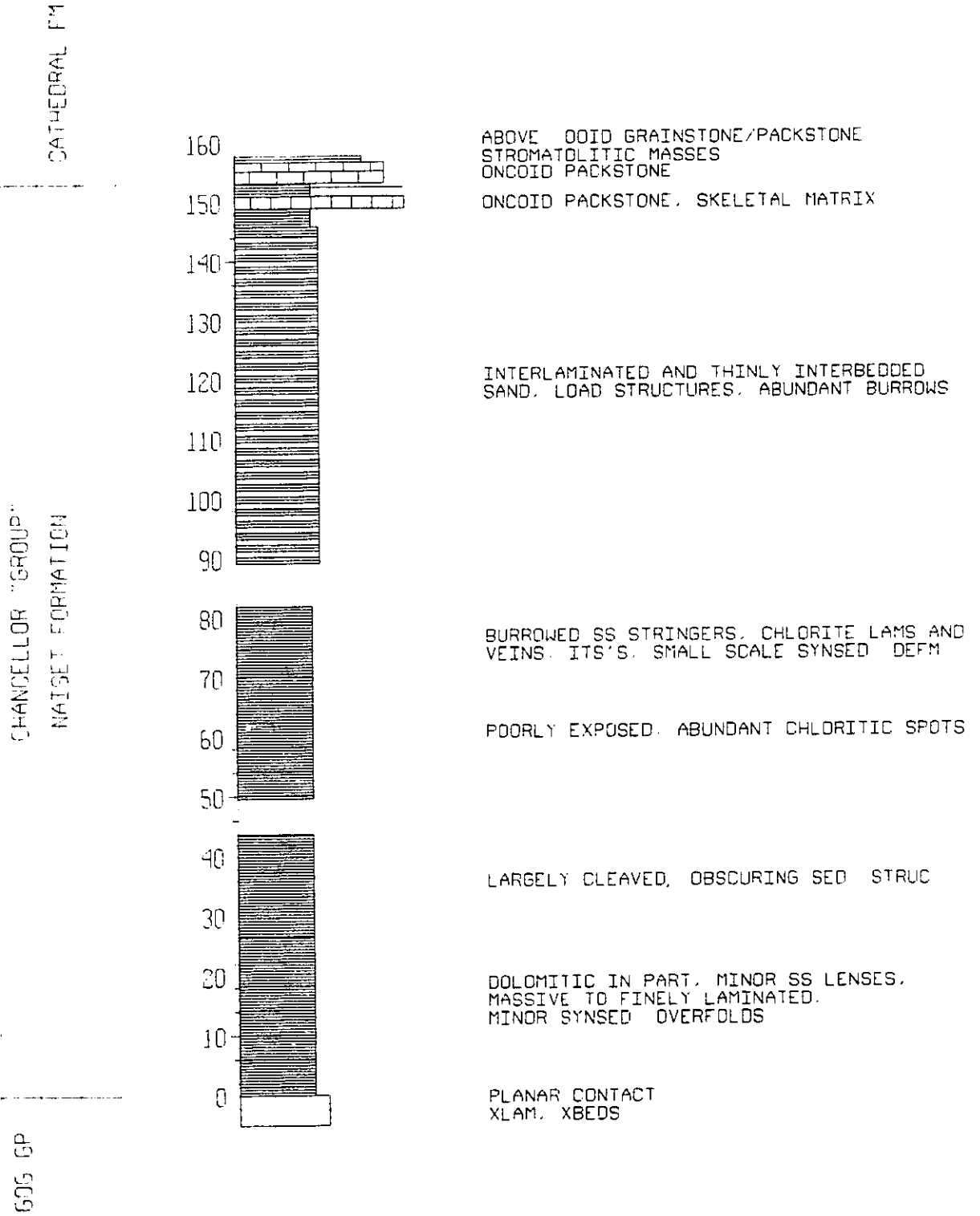
SECTION DS-12 (CONTINUED)



SECTION DS-13: MILLER PASS 2



SECTION DS-14: NAISSET POINT

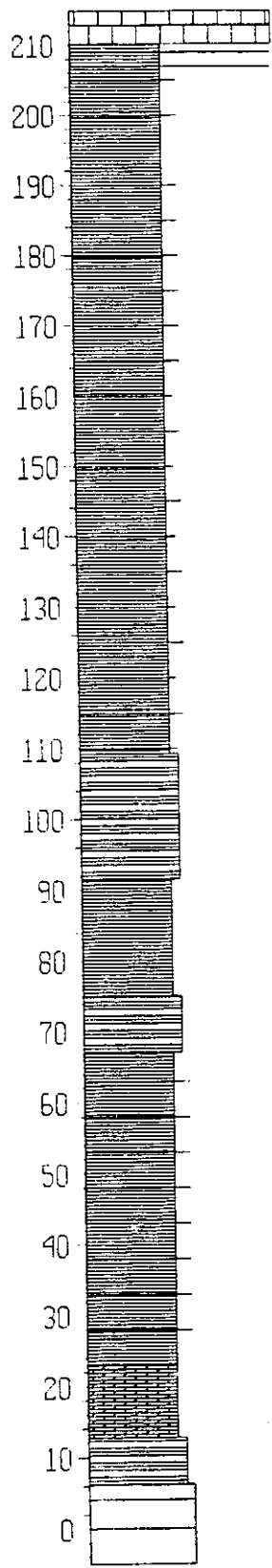


SECTION DS-15: WEDGEWOOD PEAK

CATH FM

CHANCELLOR "GROUP"
NAISET FORMATION

GOS 6P



CROSSBEDDED OOLITIC GRNST
SKELETAL-INTRACLAST GRNST
SKELETAL-INTRACLAST GRNST

MINOR LENTICLES, LENSES SAND,
BURROWS, MONOTONOUS

SILTY AND SANDY LAMINAE, LENSES AND
STRINGERS, BURROWS, SMALL SCALE
SYNSED DEFM

--SECTION OFFSET TO N SIDE CIRQUE--
ABUNDANT BURROWS SYNSED DEFM
CHLORITIC SPOTS

ABUNDANT BURROWS

ITS'S, CHLORITIC SPOTS

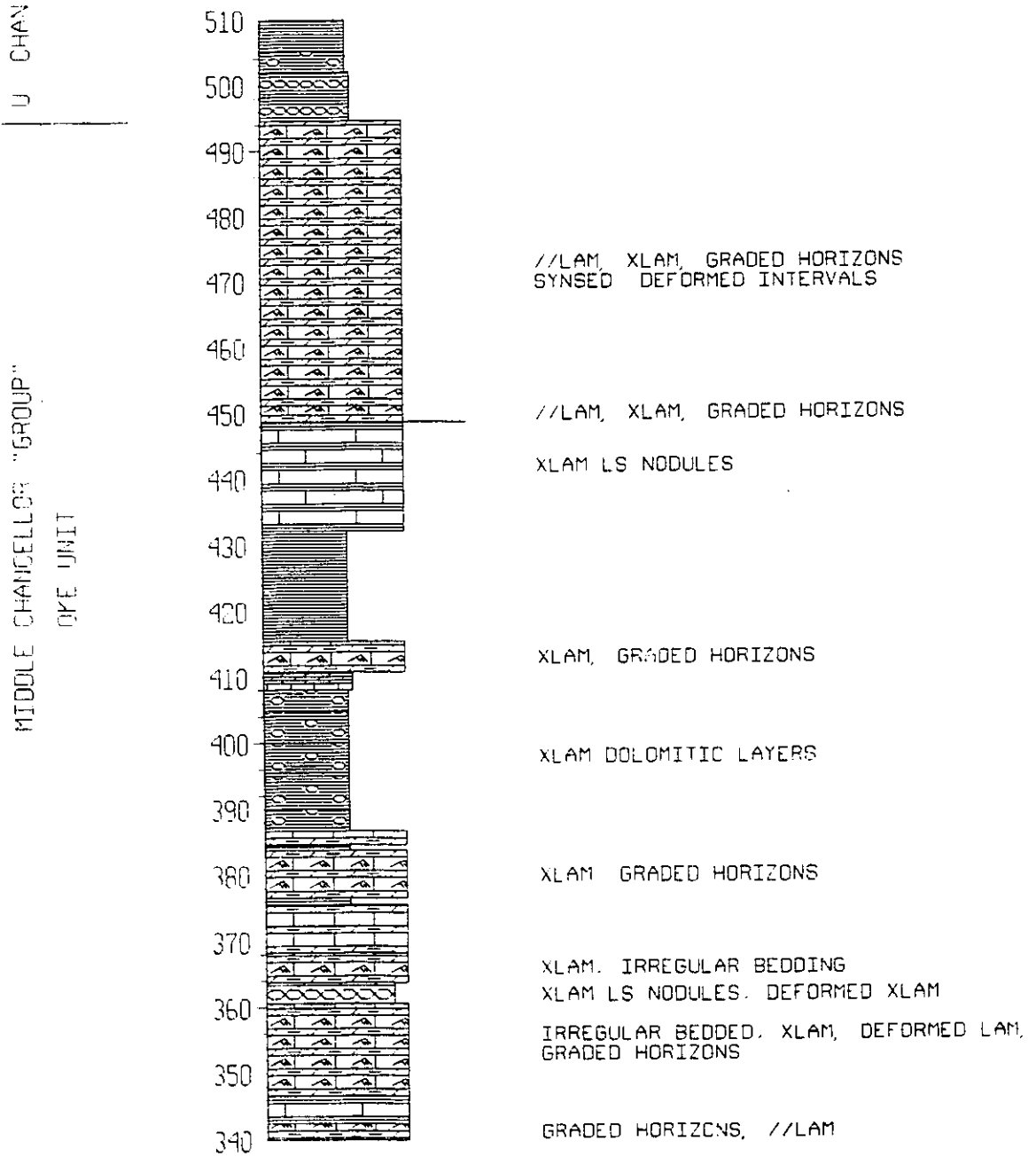
IRREGULAR BEDS, LENSES SS, SOME GRADED

SS LENSES, STRINGERS, SOME GRADED OR
XLAMINATED, SYNSED OVERFOLDS, CHLORITIC
SPOTS IN UPPER HALF

PLANAR BEDDED FINELY LAMINATED

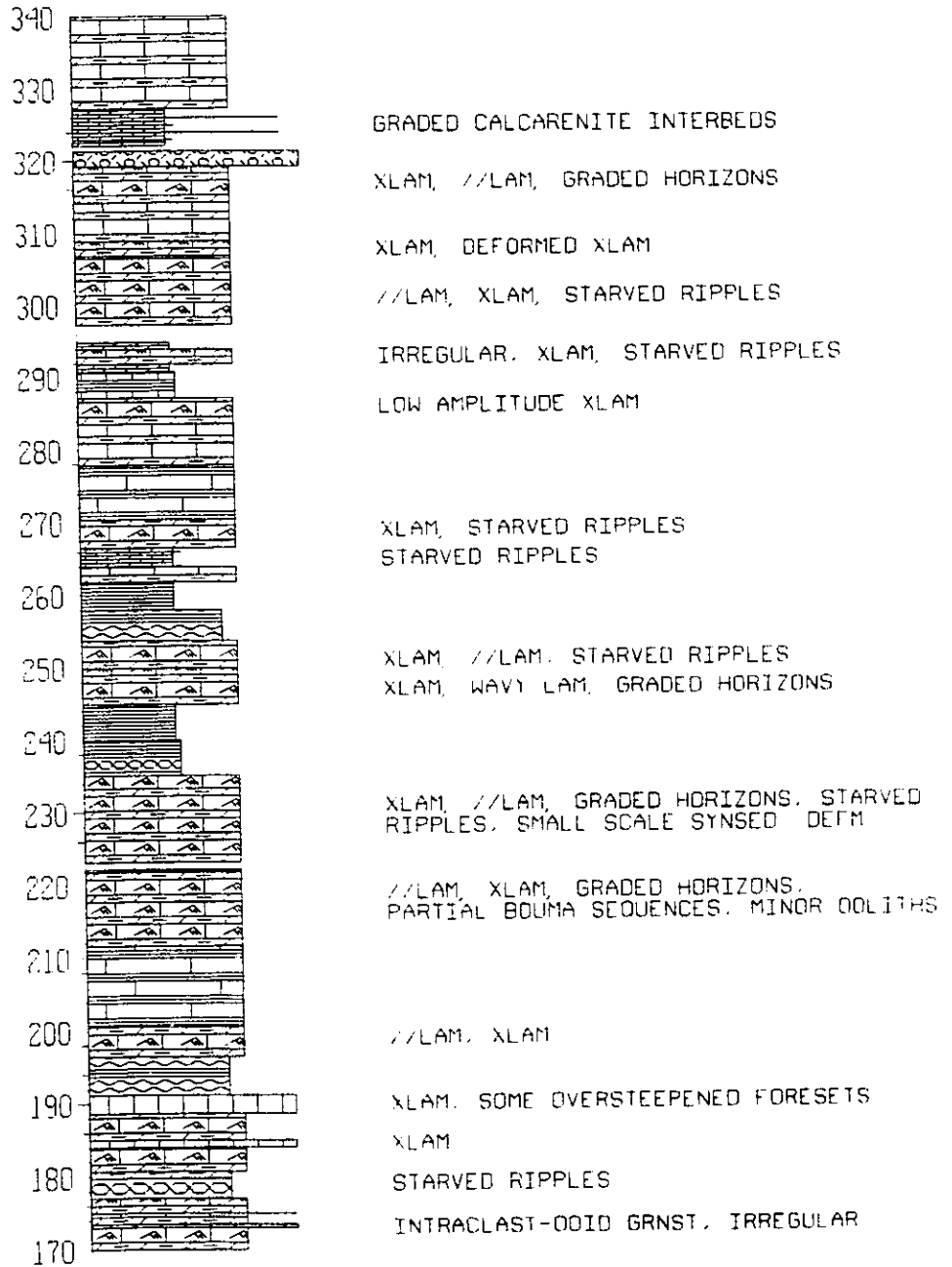
SHALE RIP-UPS, CHANNELS, GRADED BEDS
VERTICAL BURROWS
PLANAR CONTACT
XLAM, XBEDS

SECTION DS-16: MISKO MOUNTAIN



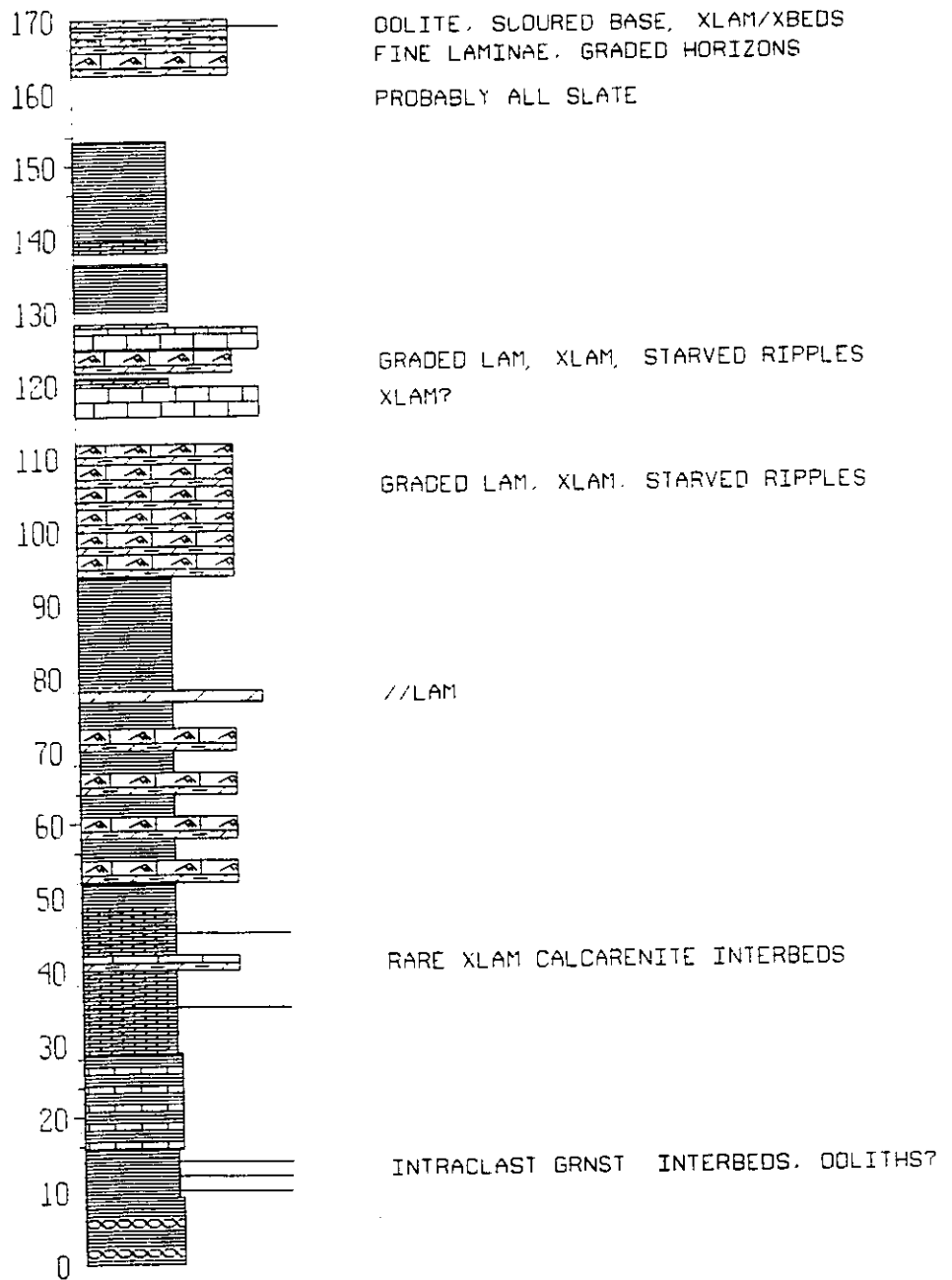
SECTION DS-16 (CONTINUED)

MIDDLE CHANCELLOR "GROUP"
OKE UNIT



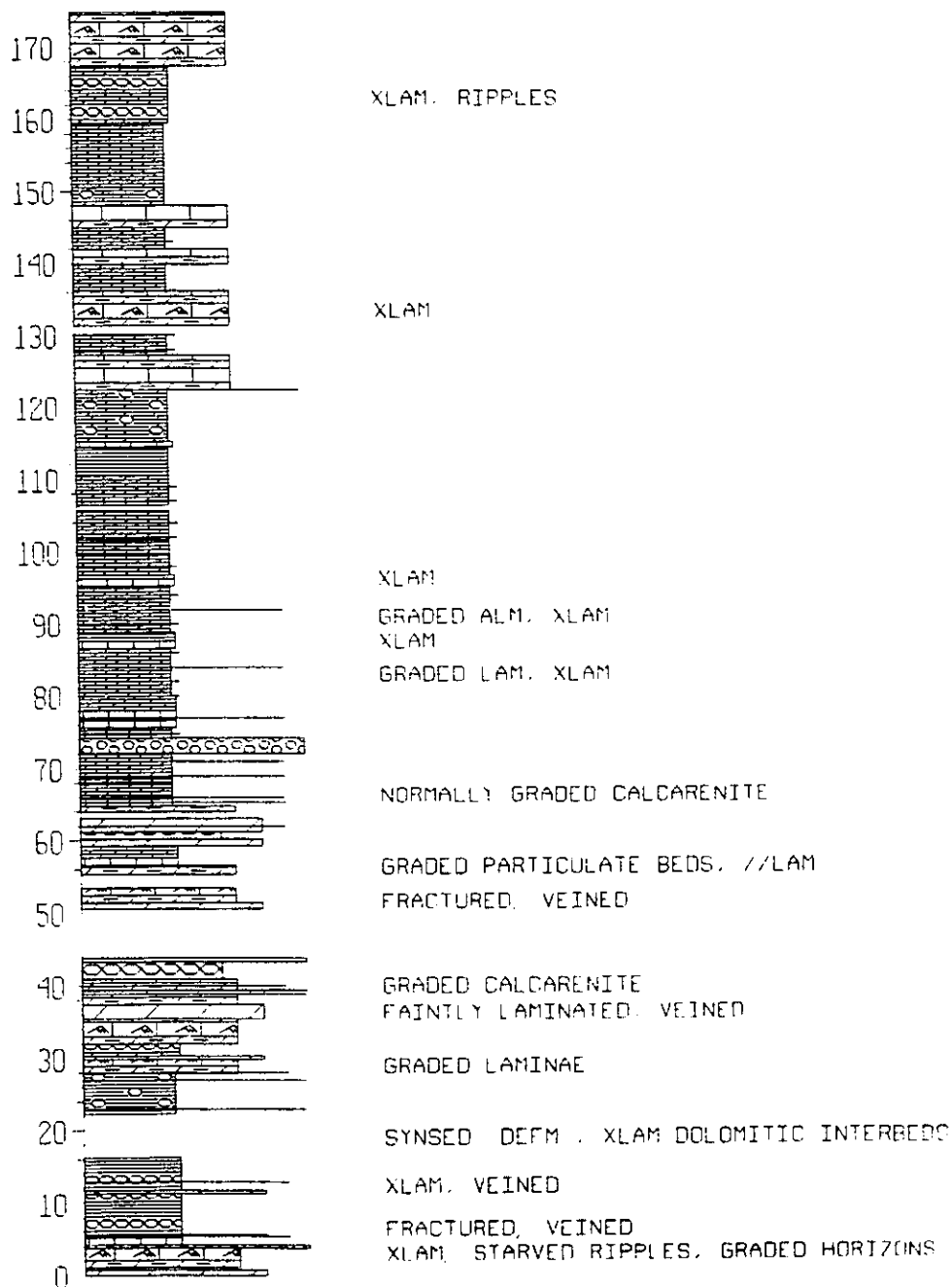
SECTION DS-16 (CONTINUED)

MIDDLE CHANCELLOR "GROUP"
DUCHESNAY UNIT

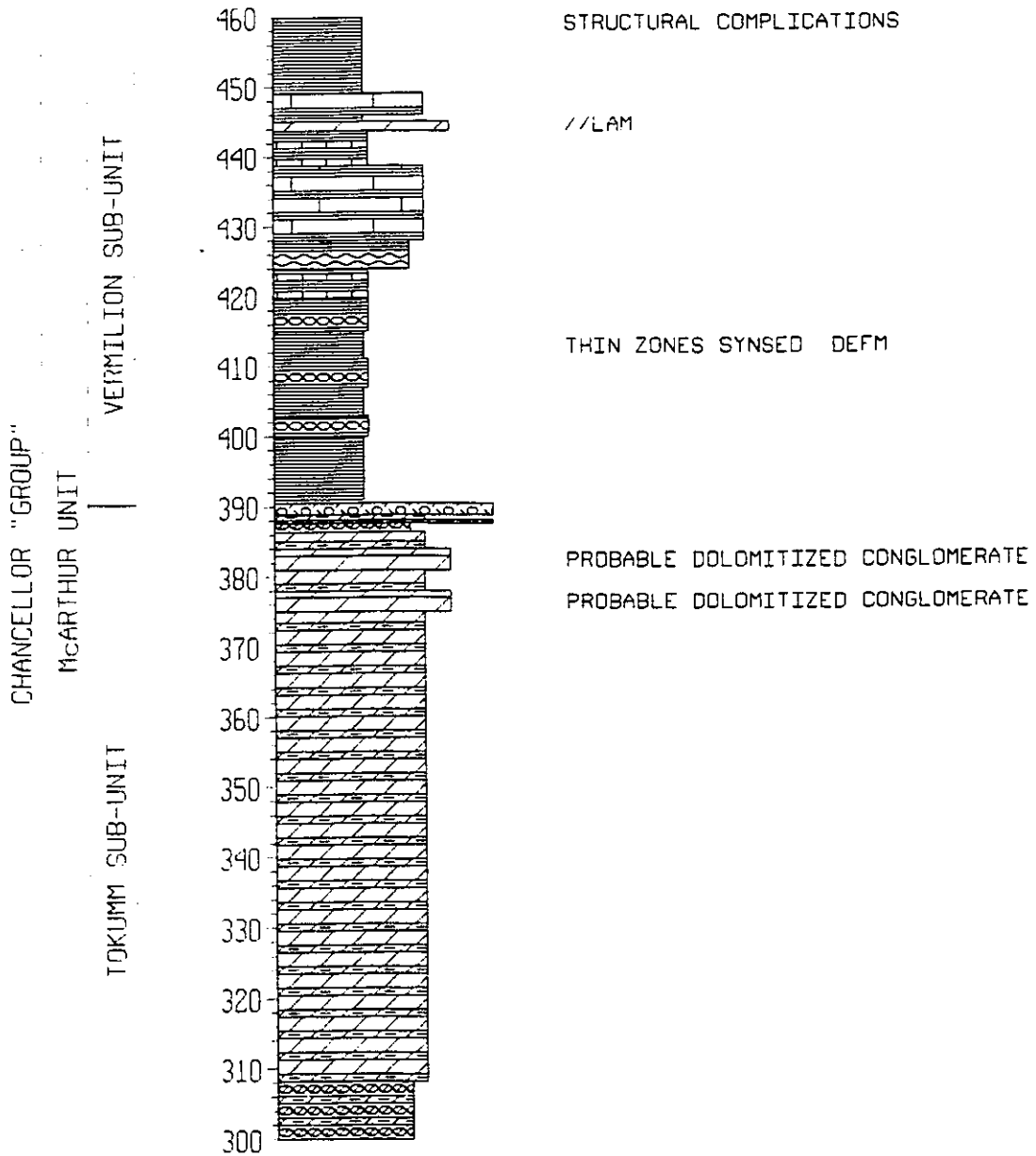


SECTION DS-16A: MISKO MOUNTAIN NORTH

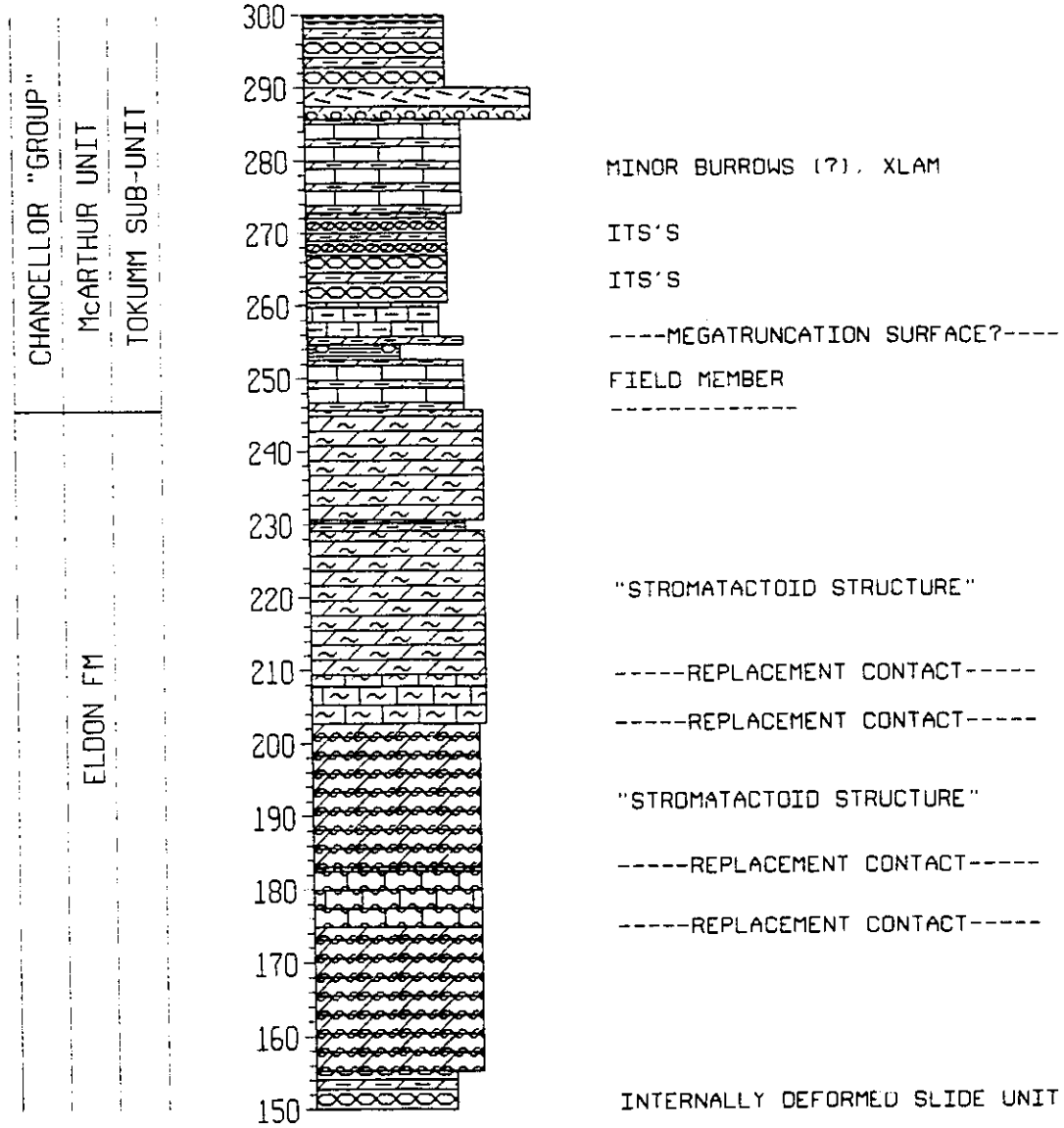
MIDDLE CHANCELLOR "GROUP"
DUCHESNAY UNIT



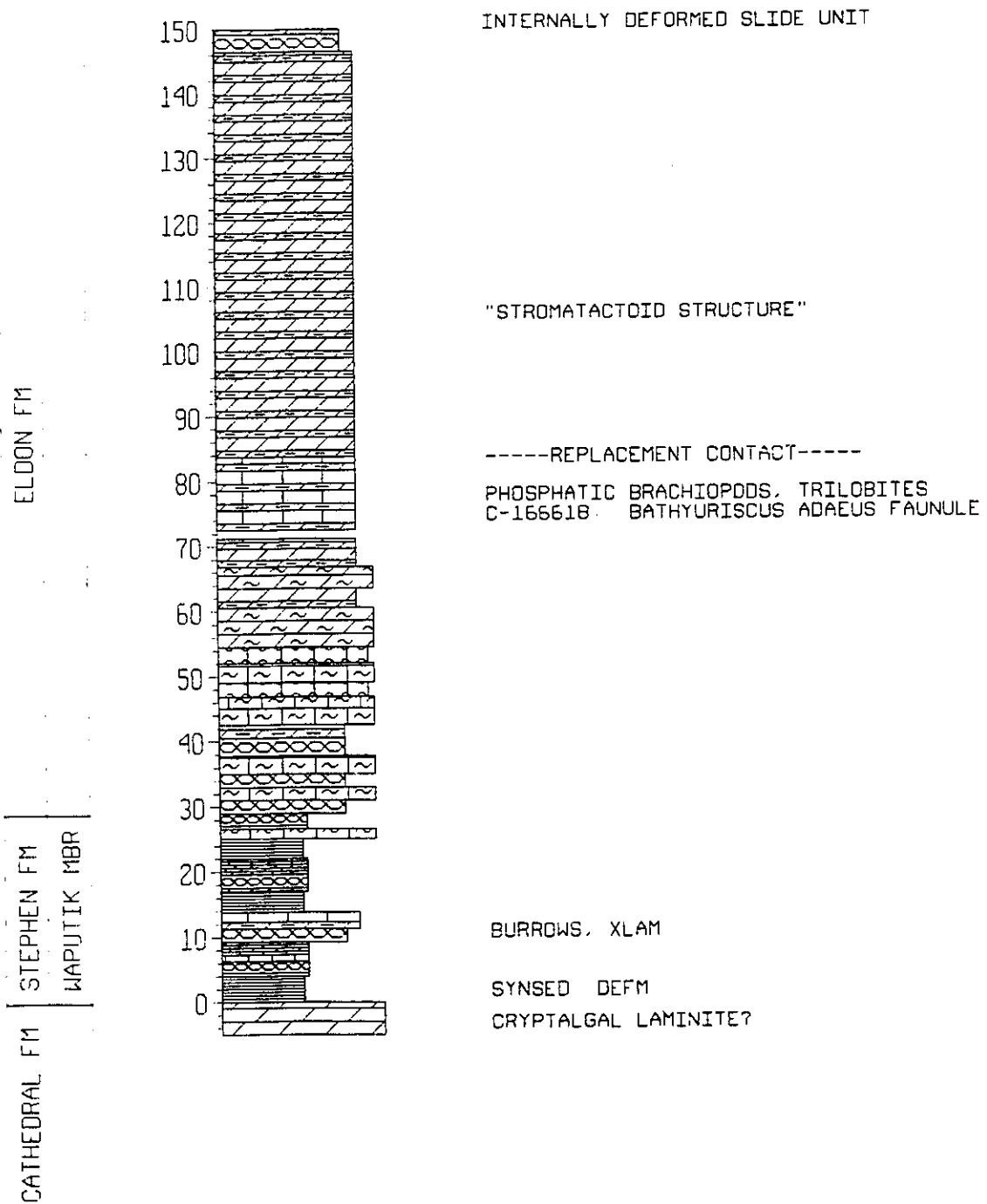
SECTION DS-17: TOKUMM HEADWATERS 1



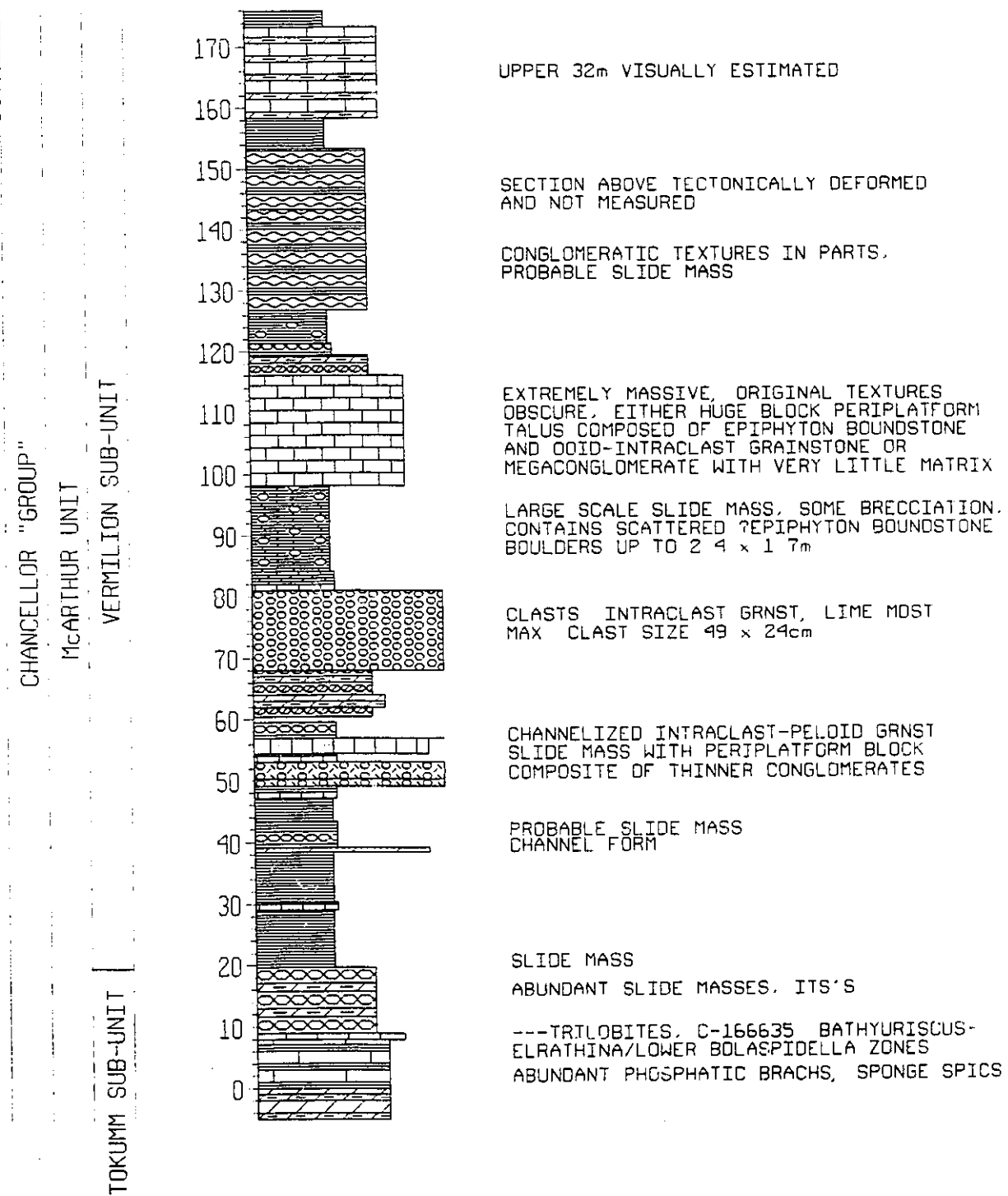
SECTION DS-17 (CONTINUED)



SECTION DS-17 (CONTINUED)

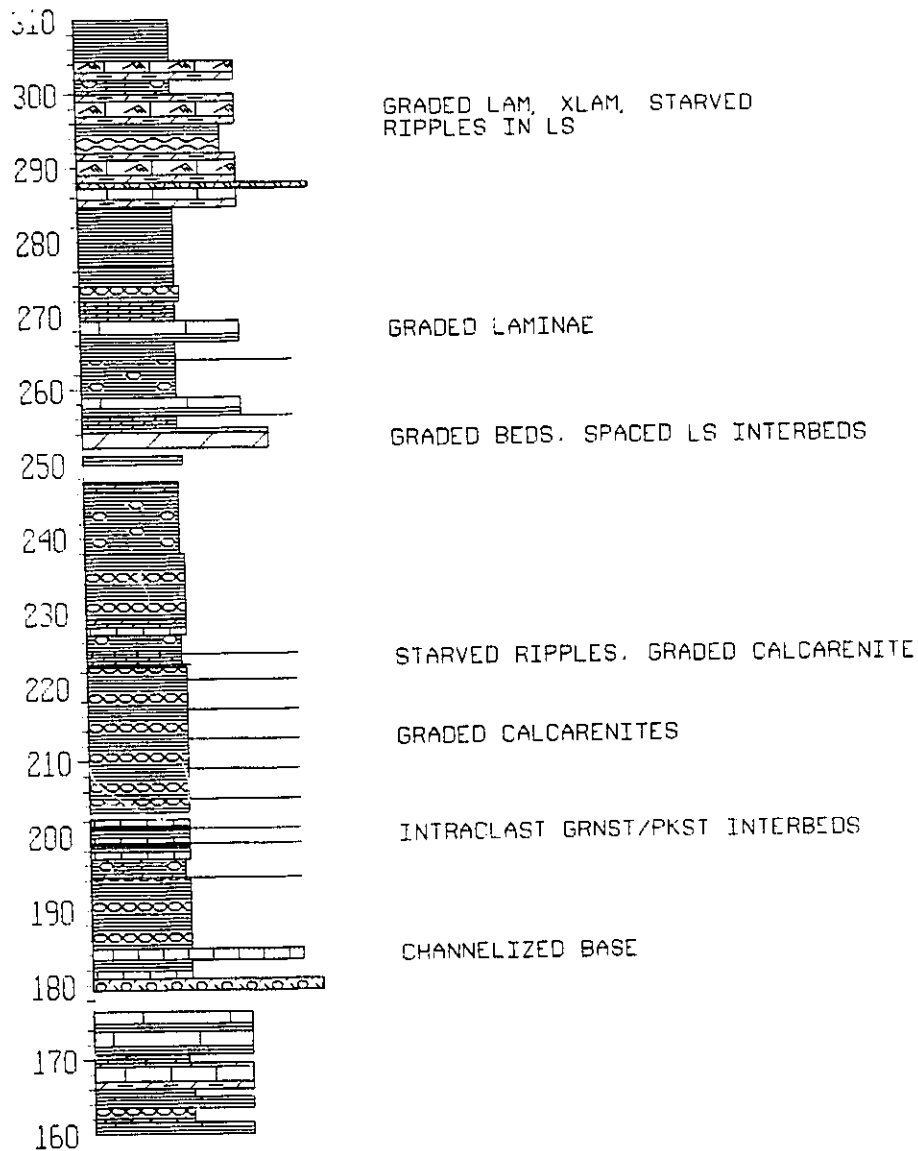


SECTION DS-18: TOKUMM HEADWATERS 2

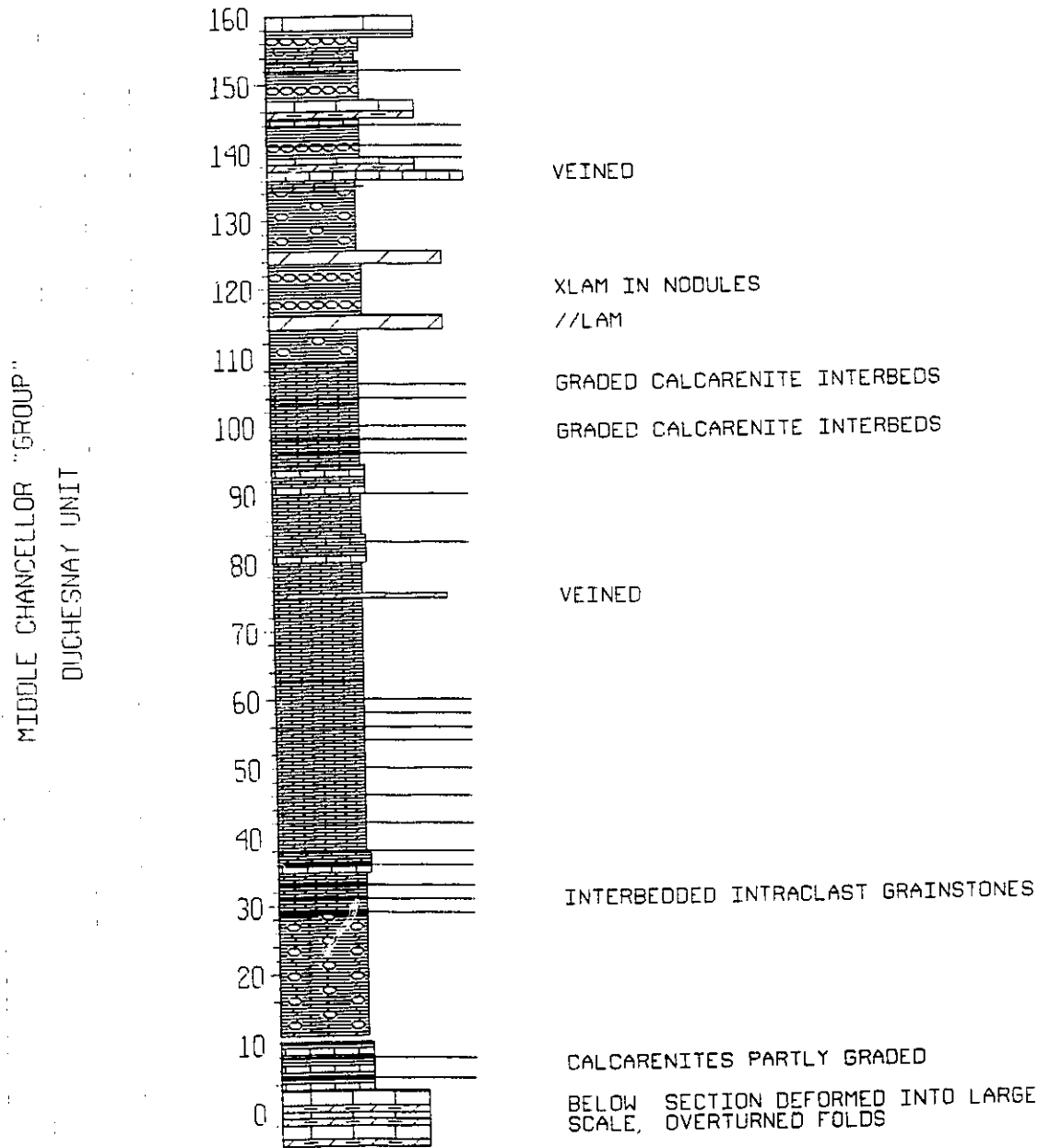


SECTION DS-19: MT. OKE SOUTH

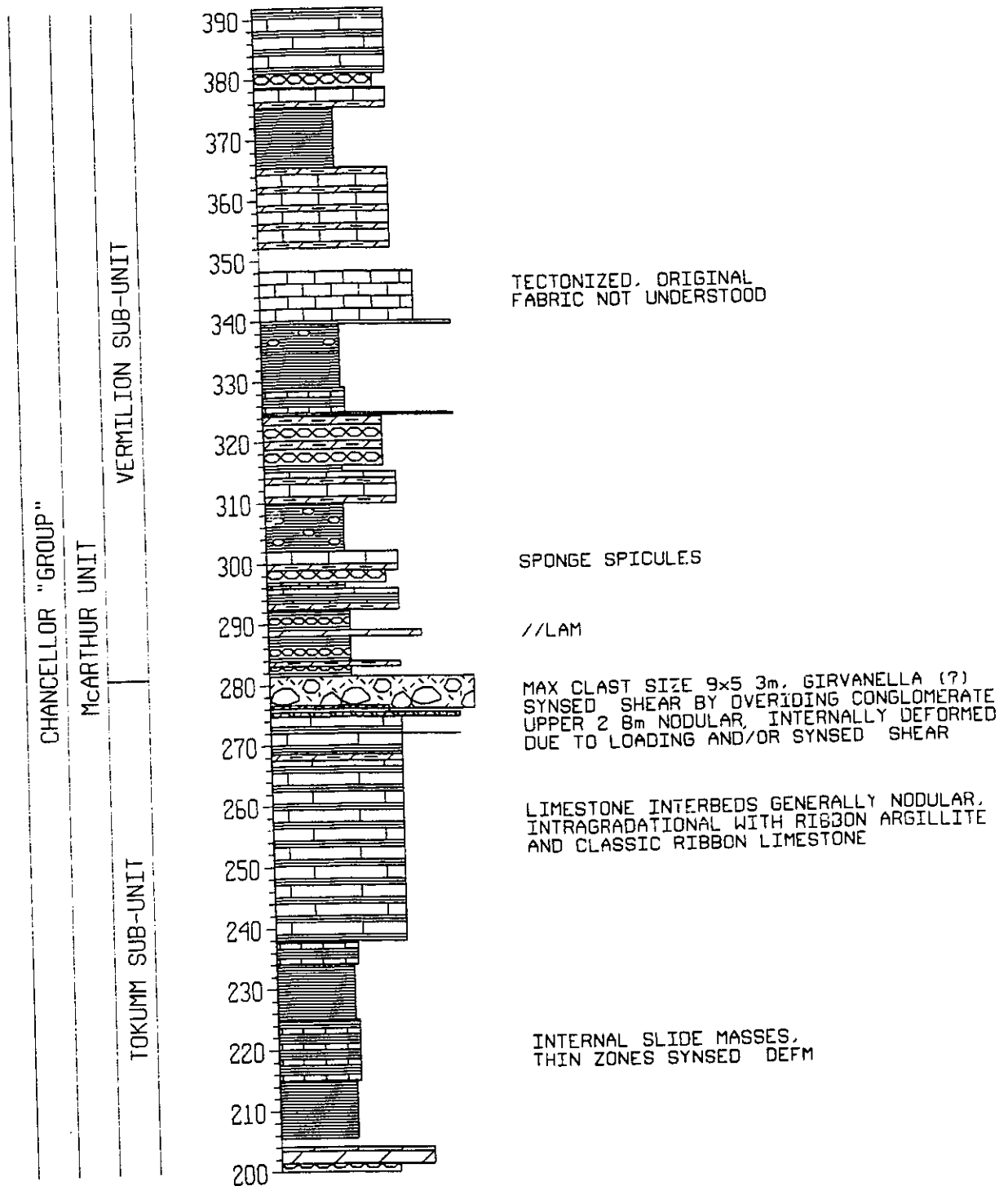
MIDDLE CHANCELLOR "GROUP"
DUCHESNAY UNIT



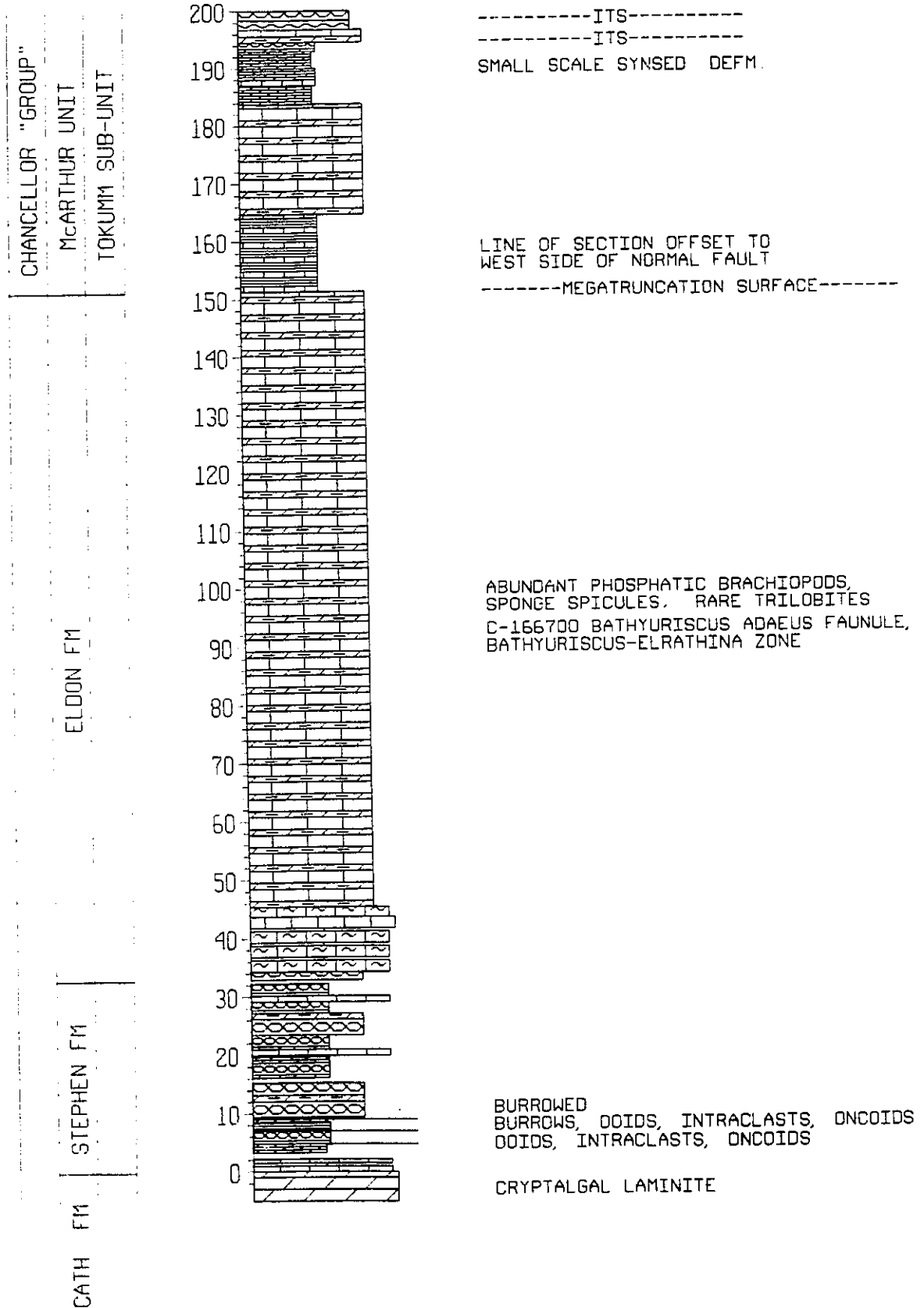
SECTION DS-19 (CONTINUED)



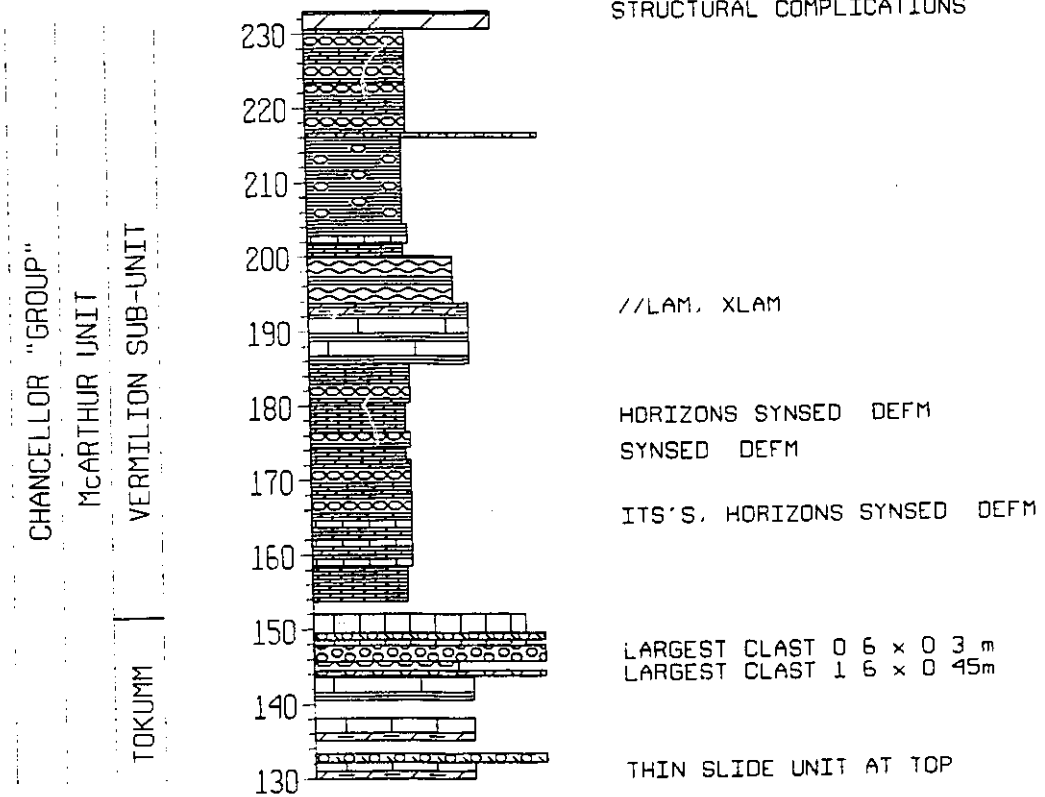
SECTION DS-20: MT. BIDDLE



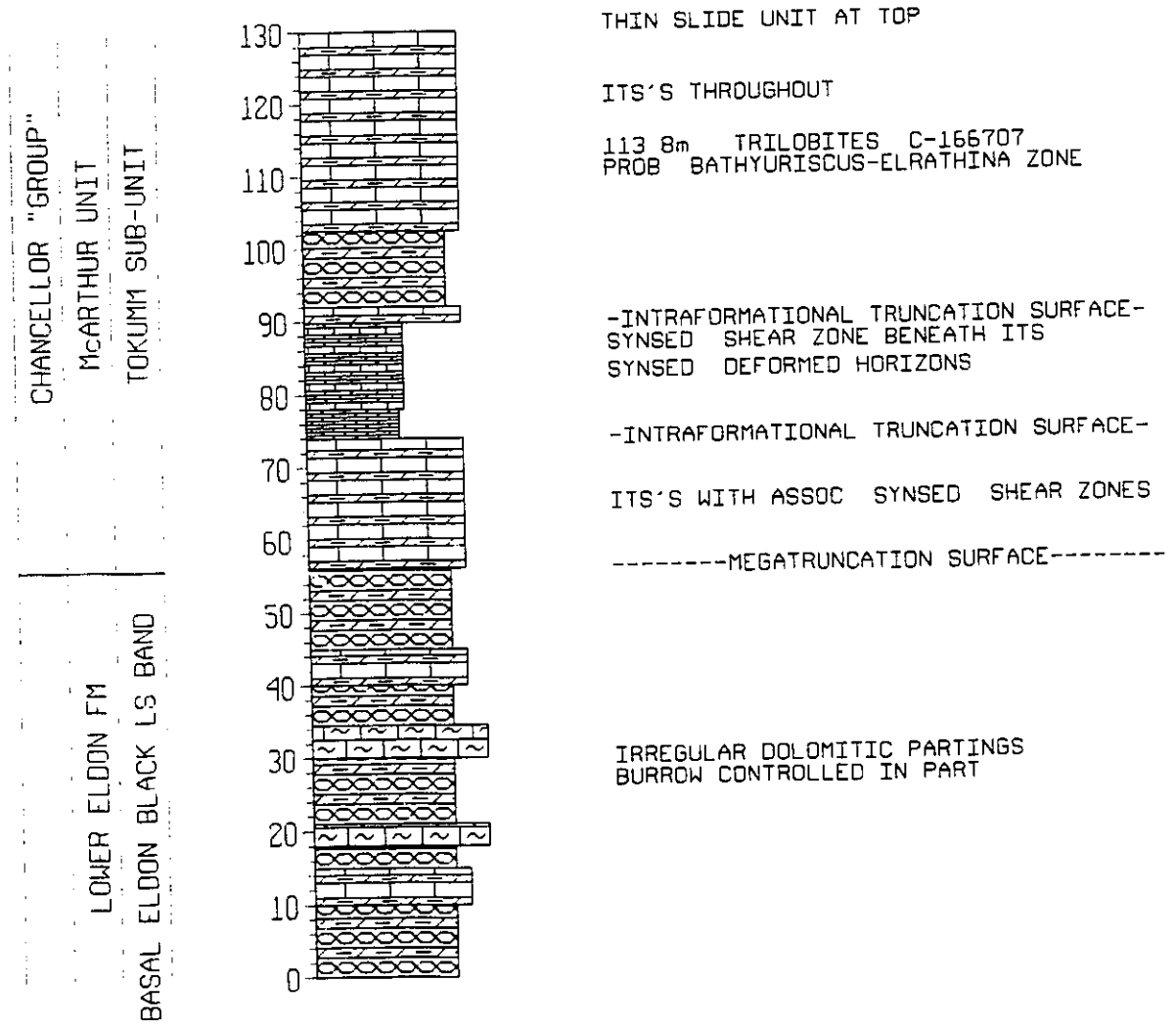
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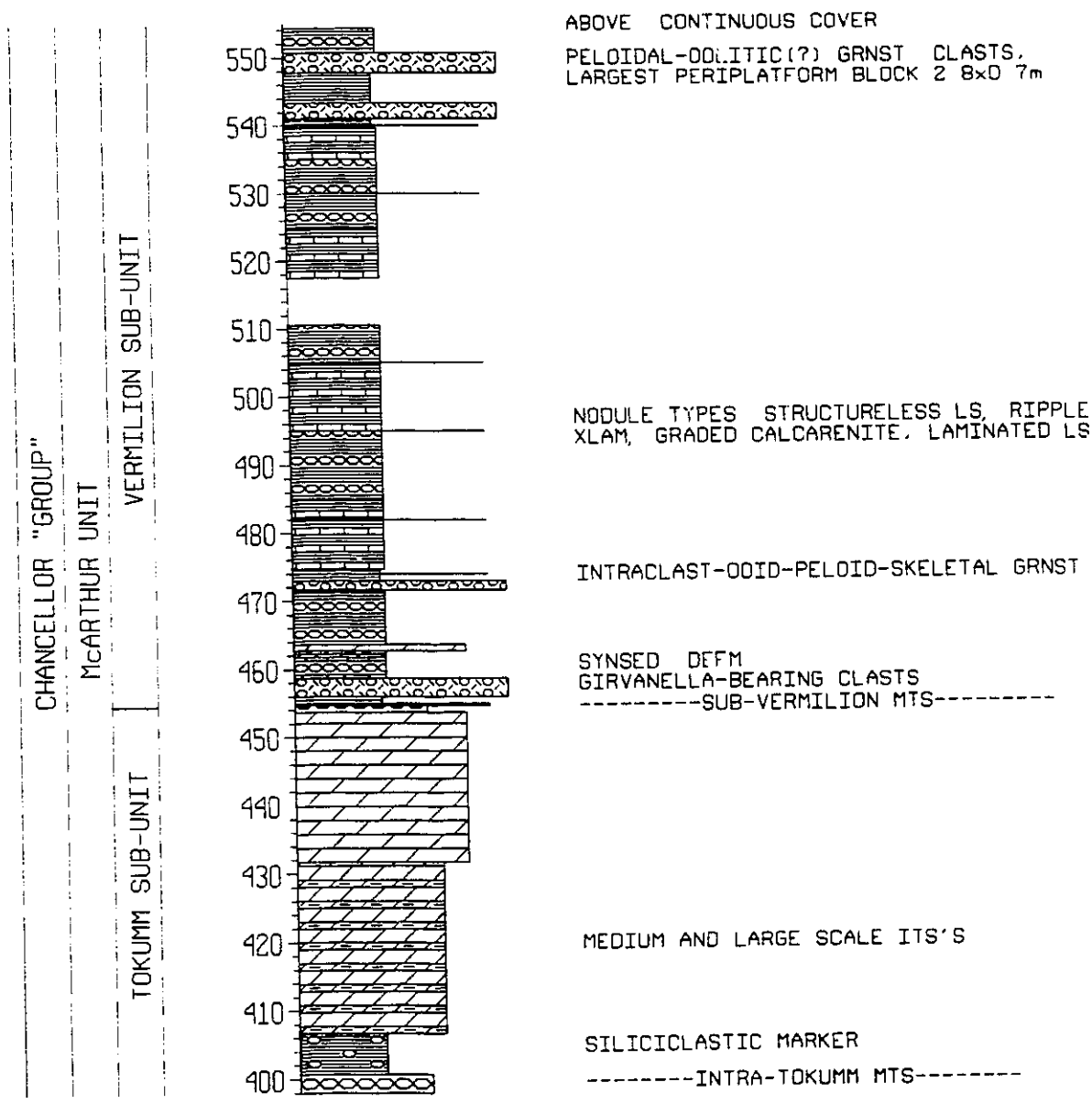
SECTION DS-21: CURTIS CIRQUE



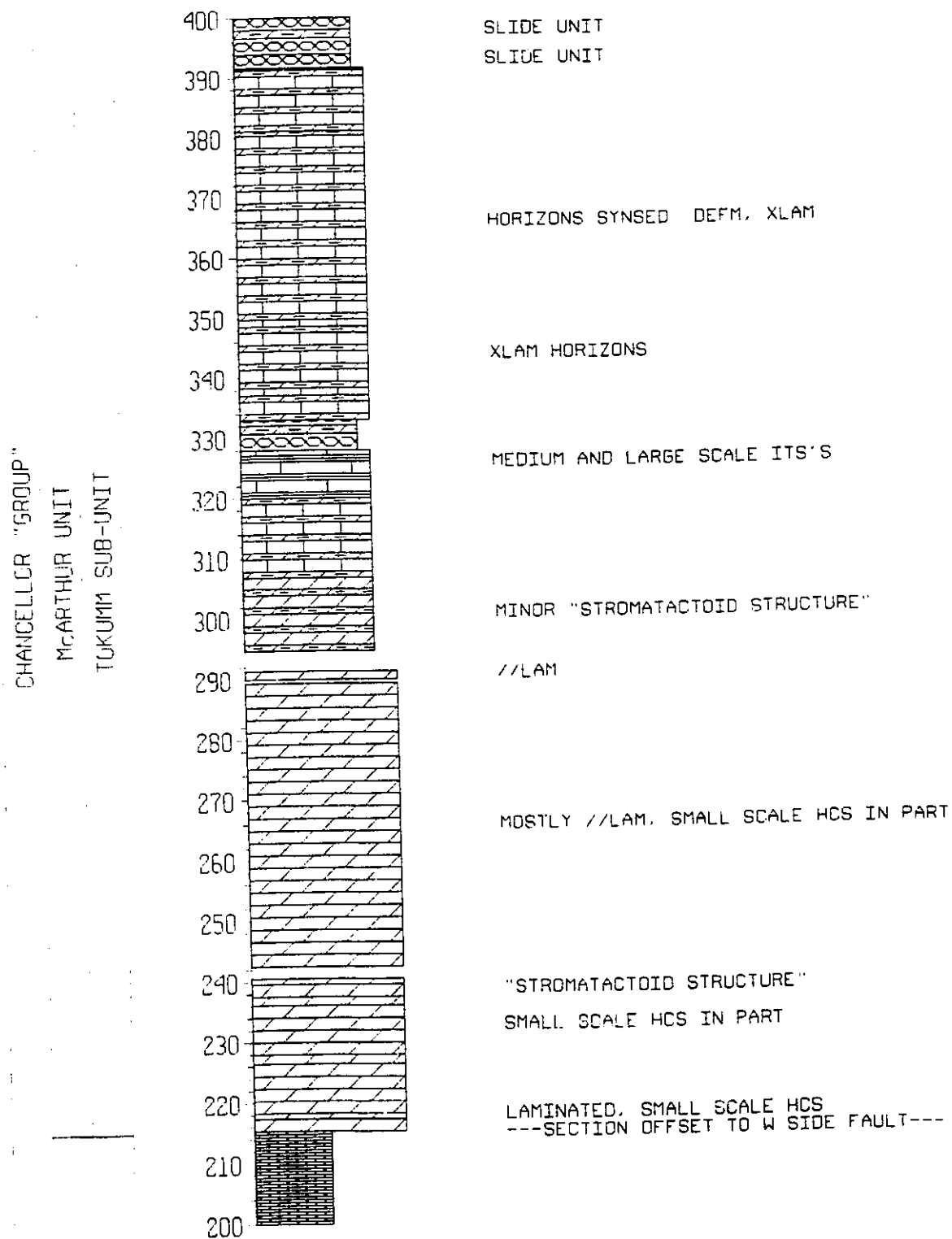
SECTION DS-21 (CONTINUED)



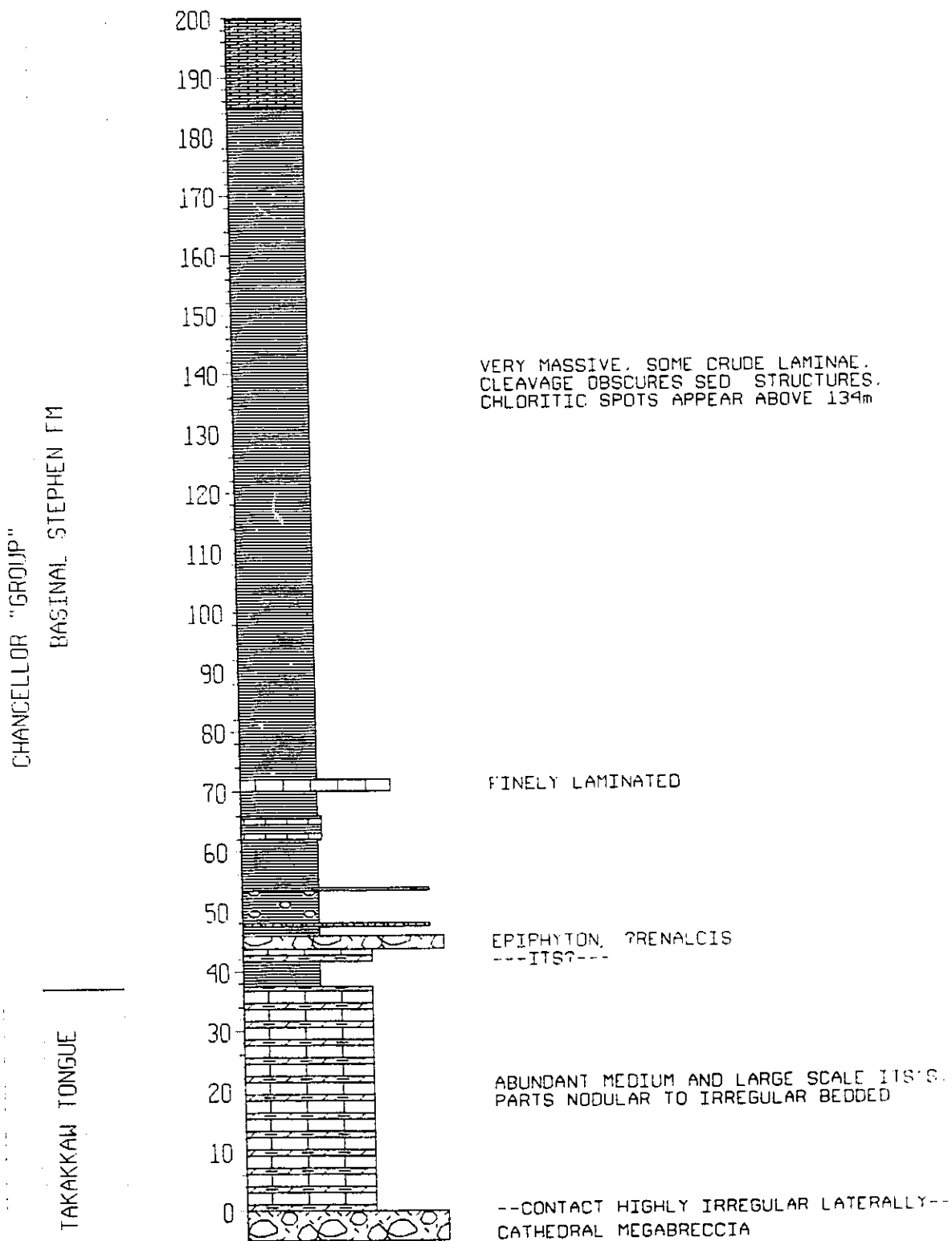
SECTION DS-22: THE MONARCH (NORTH FACE)



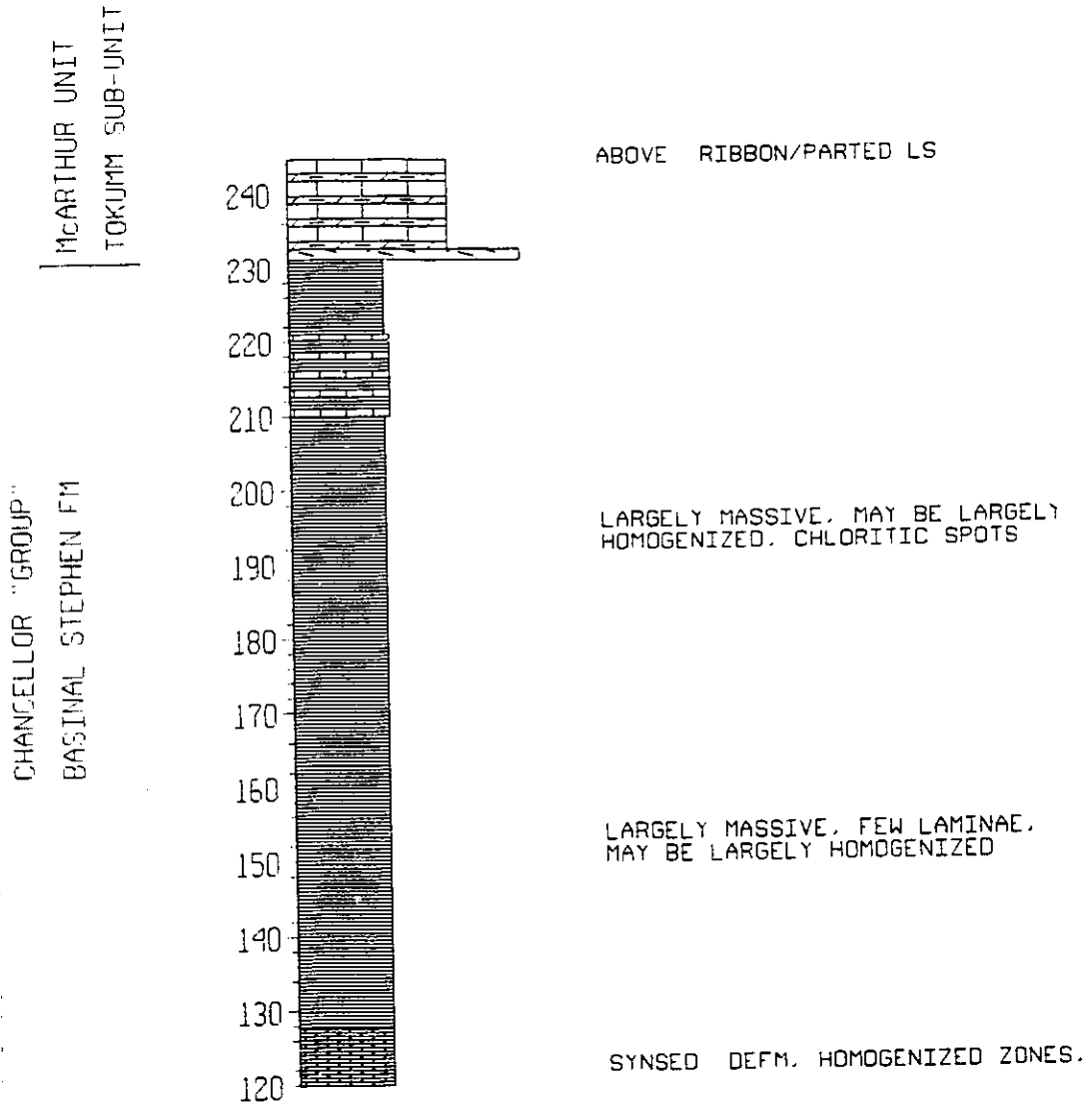
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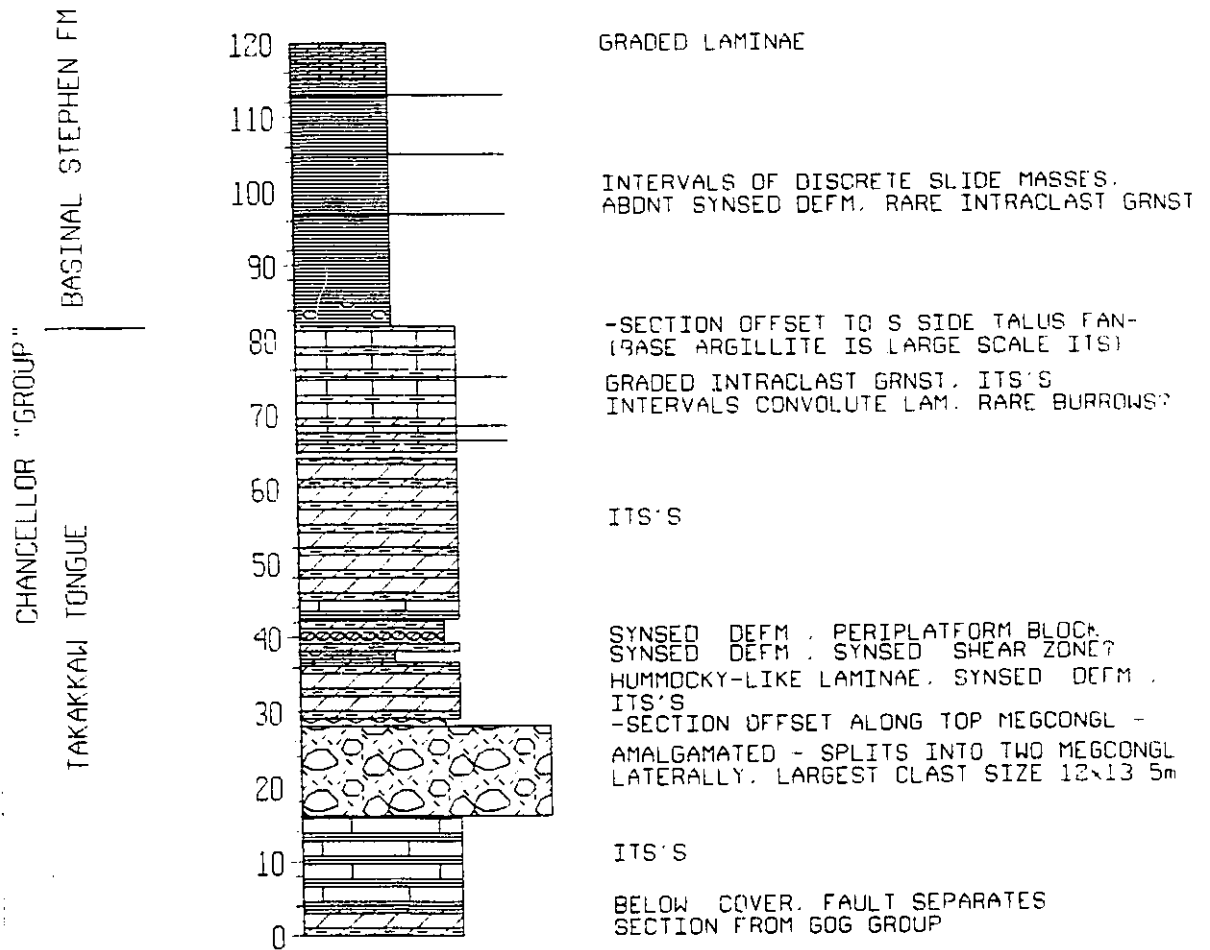
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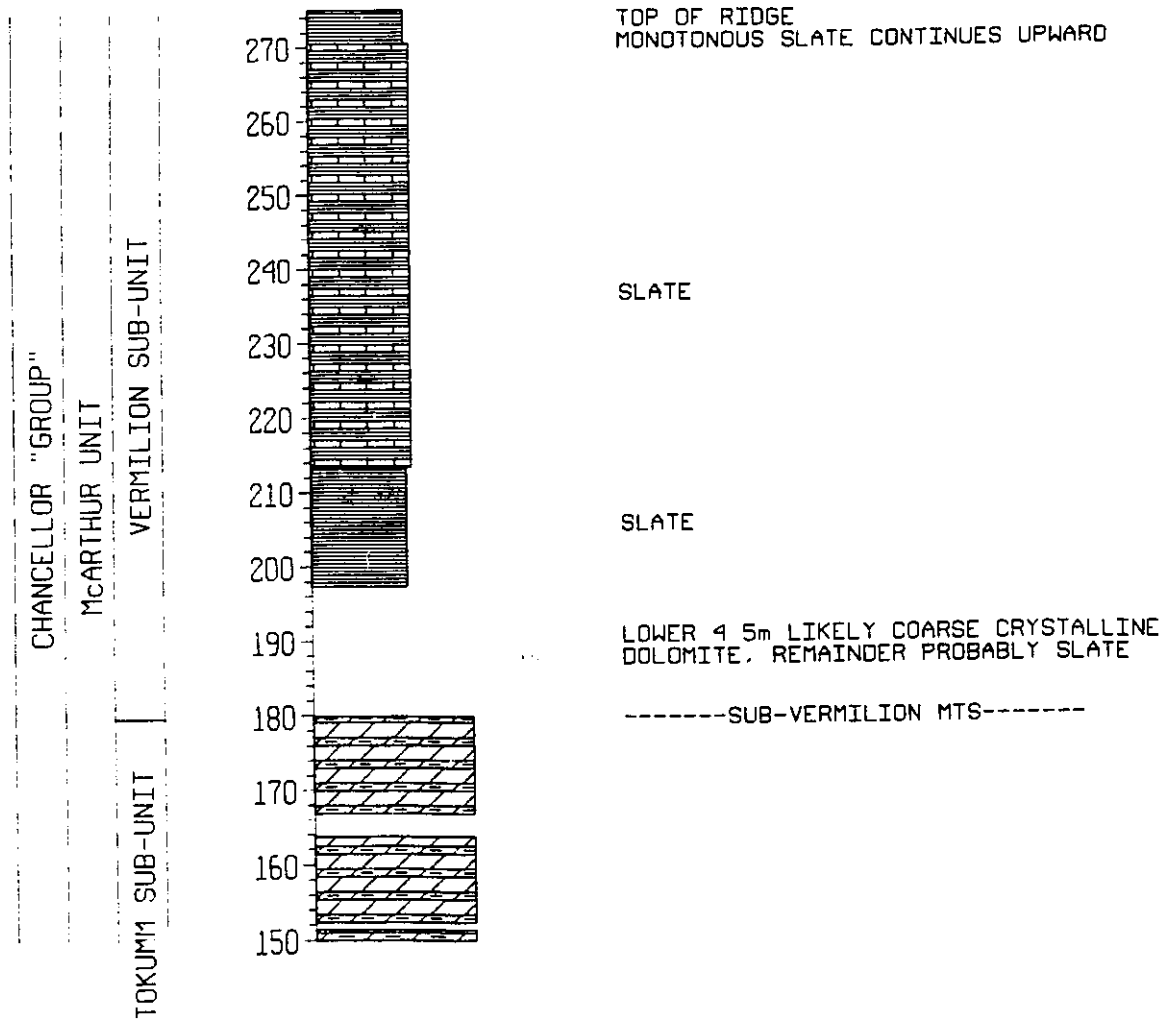
SECTION DS-23: NATALKO LAKE



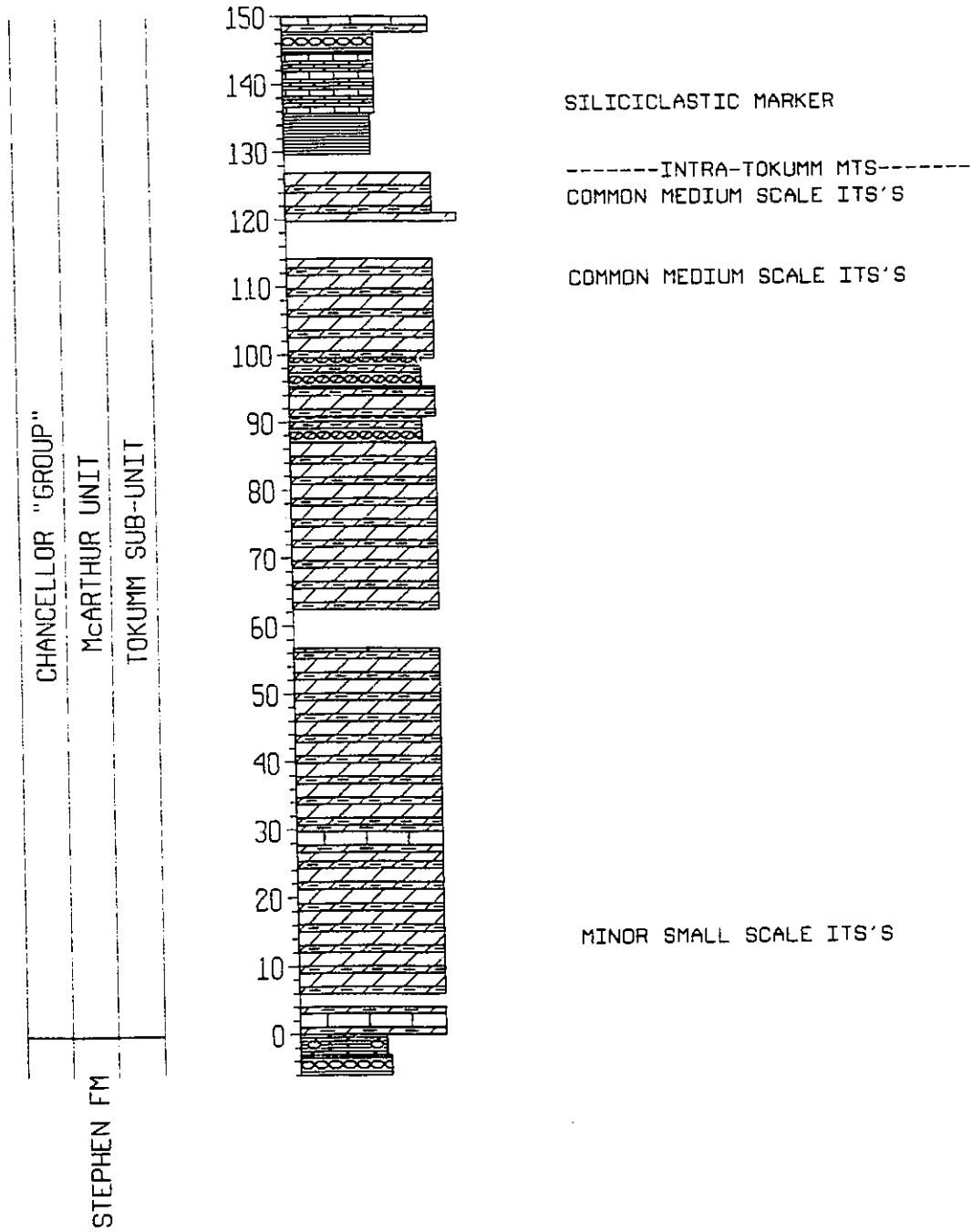
SECTION DS-23 (CONTINUED)



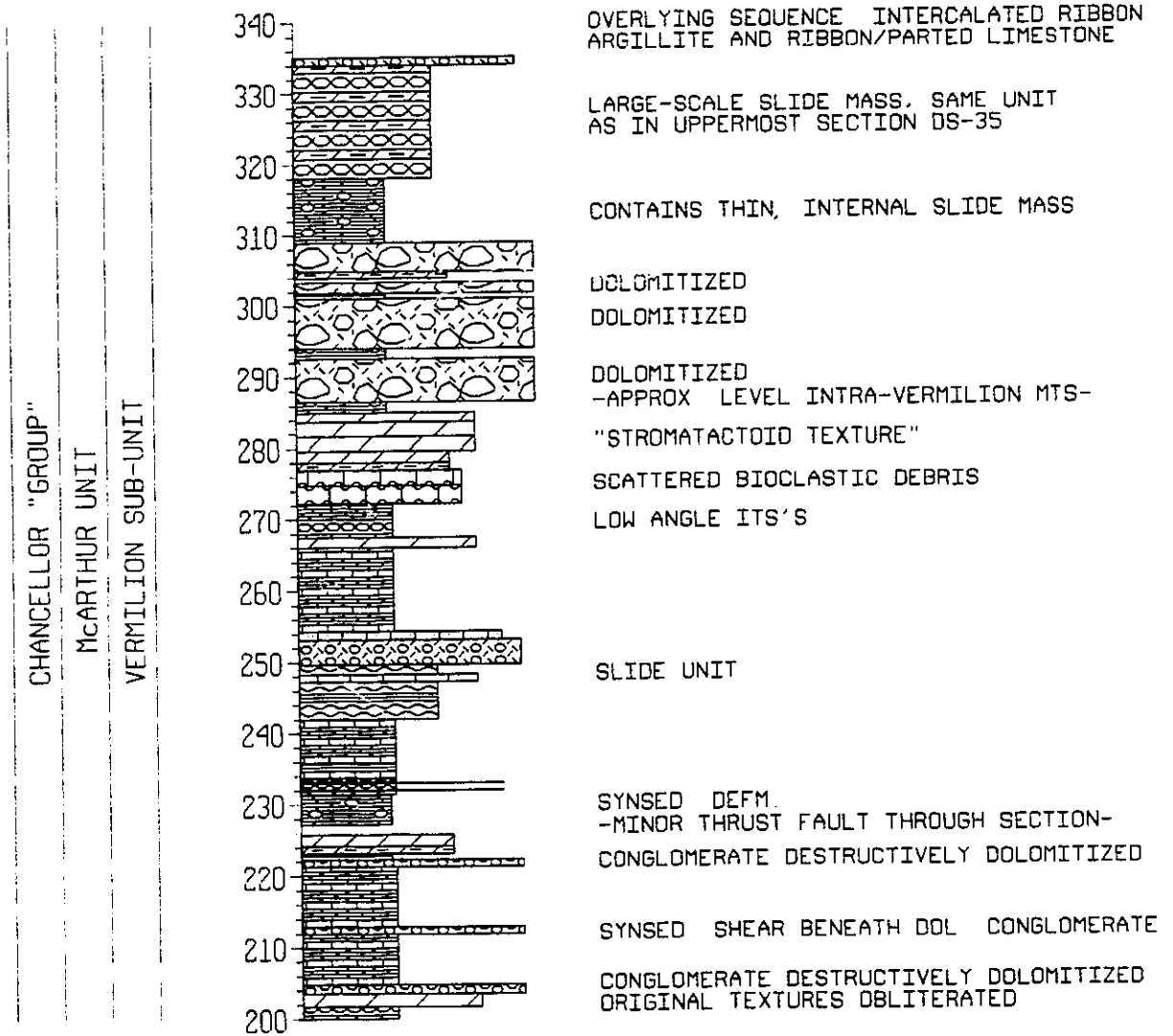
SECTION DS-24: STEPHEN CIRQUE WEST



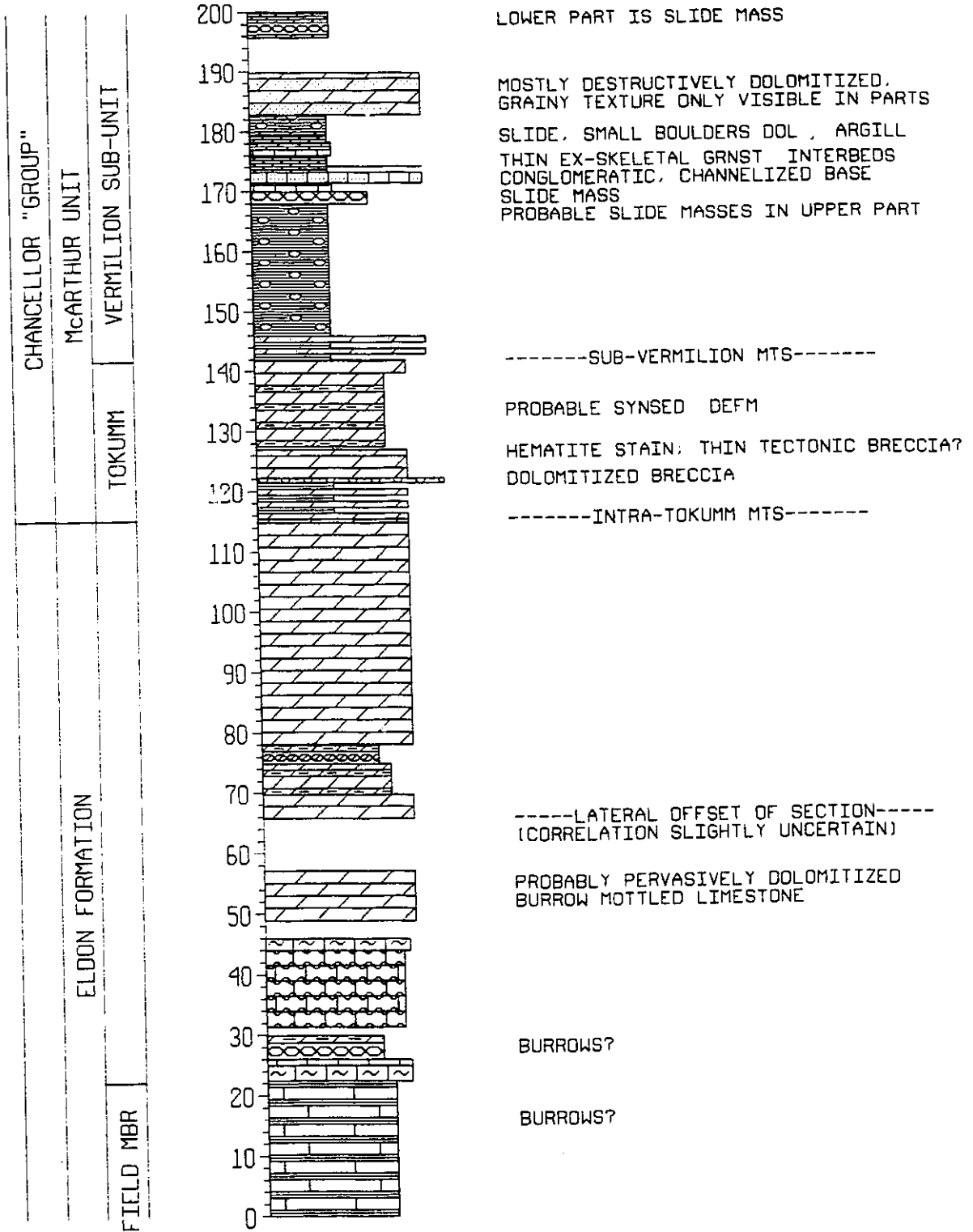
SECTION DS-24 (CONTINUED)



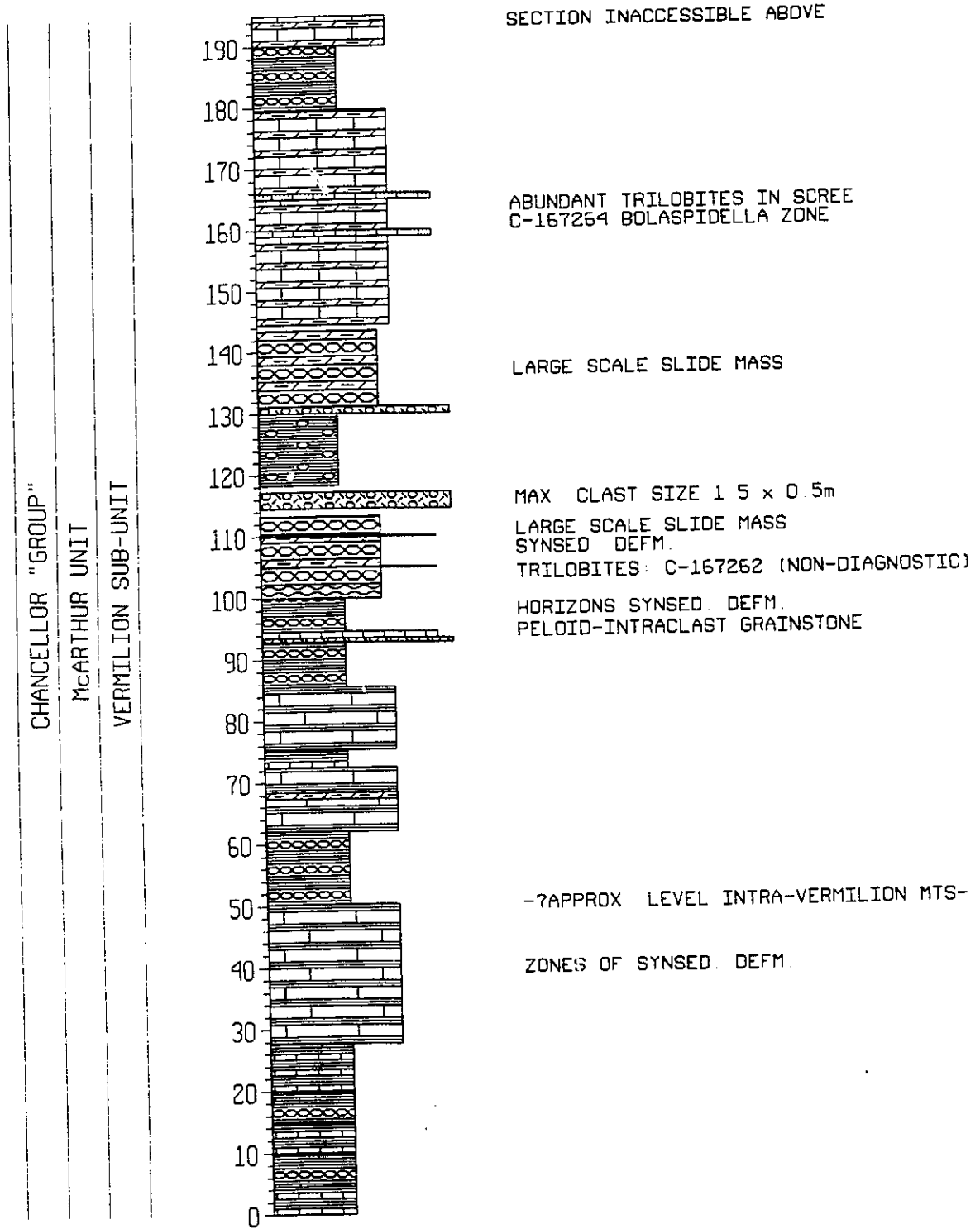
SECTION DS-25: STEPHEN CIRQUE EAST



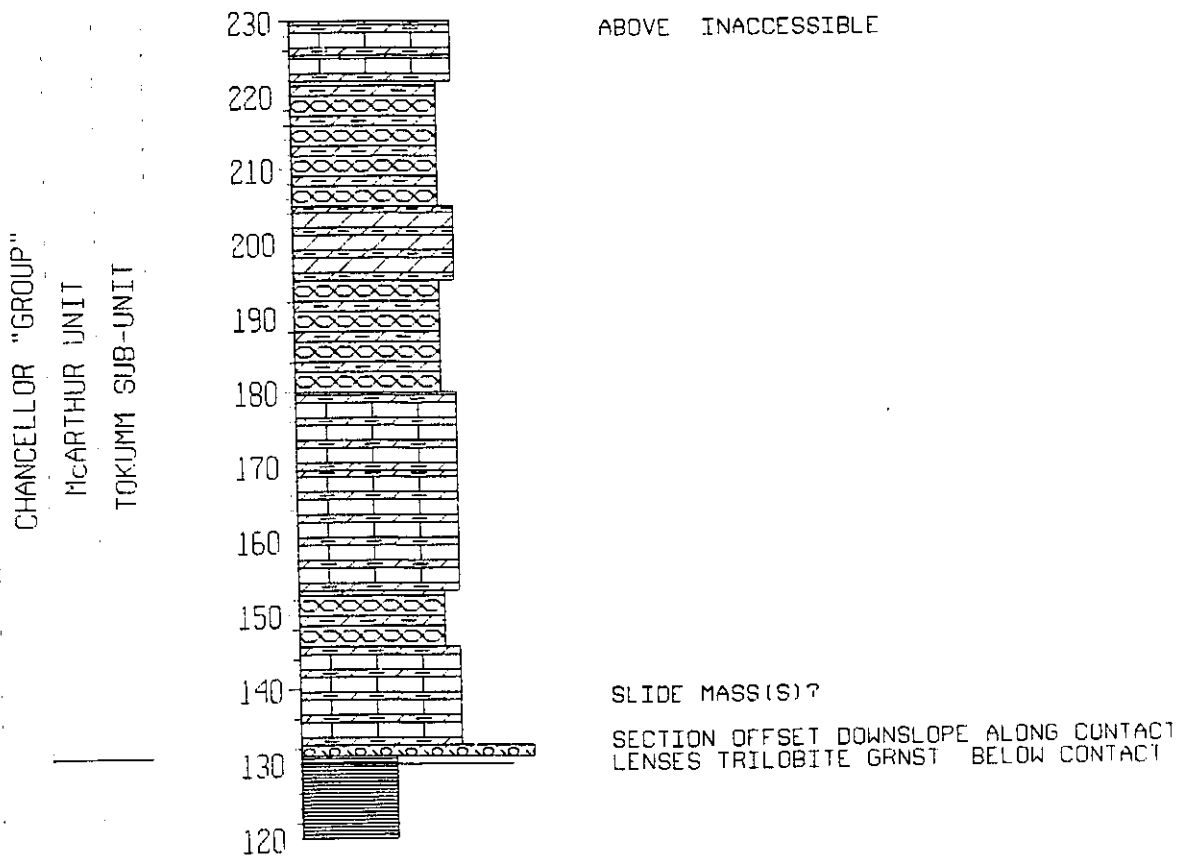
SECTION DS-25 (CONTINUED)



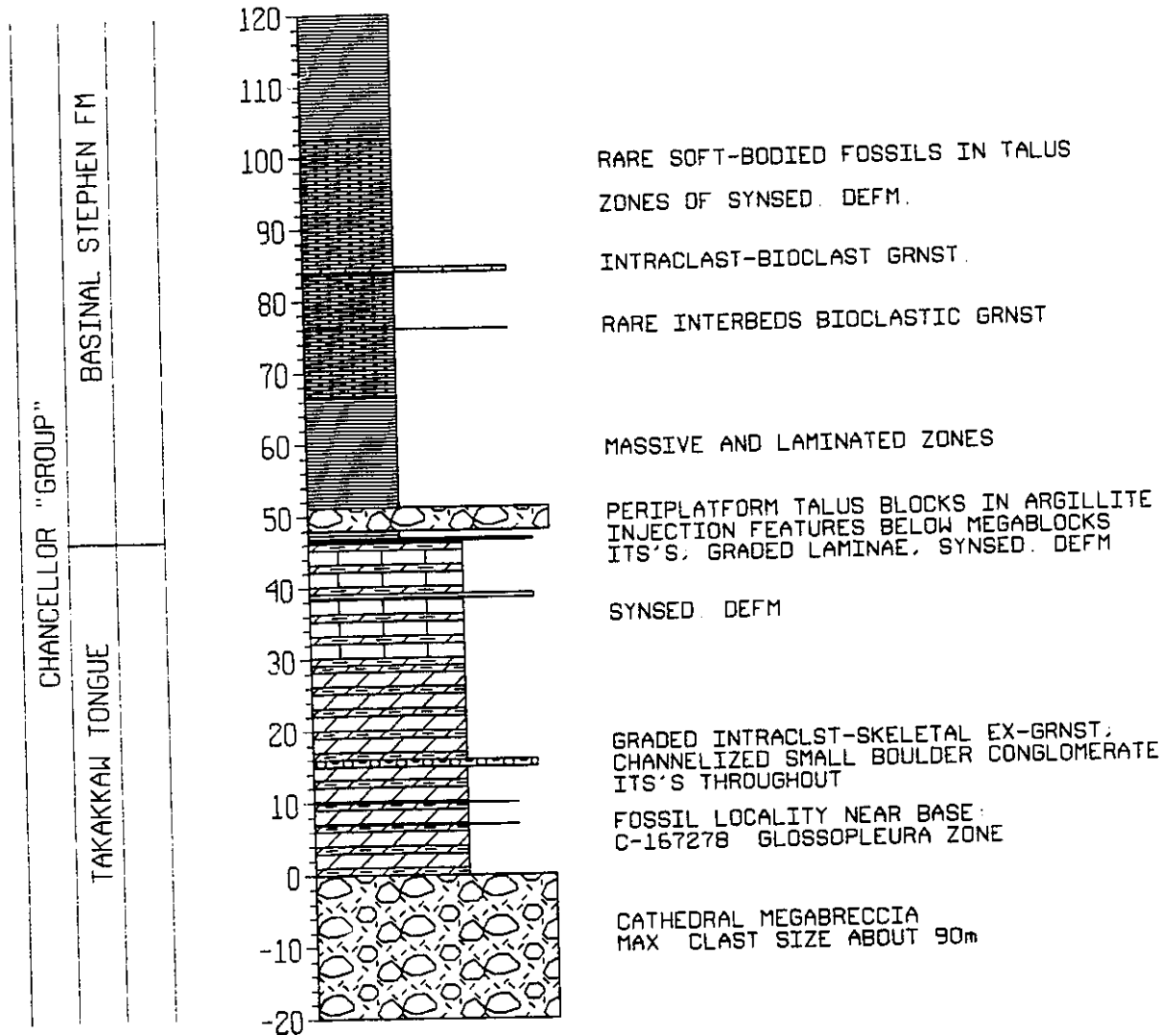
SECTION DS-26: STEPHEN CIRQUE CENTRE 1



SECTION DS-27: MONARCH CIRQUE 1

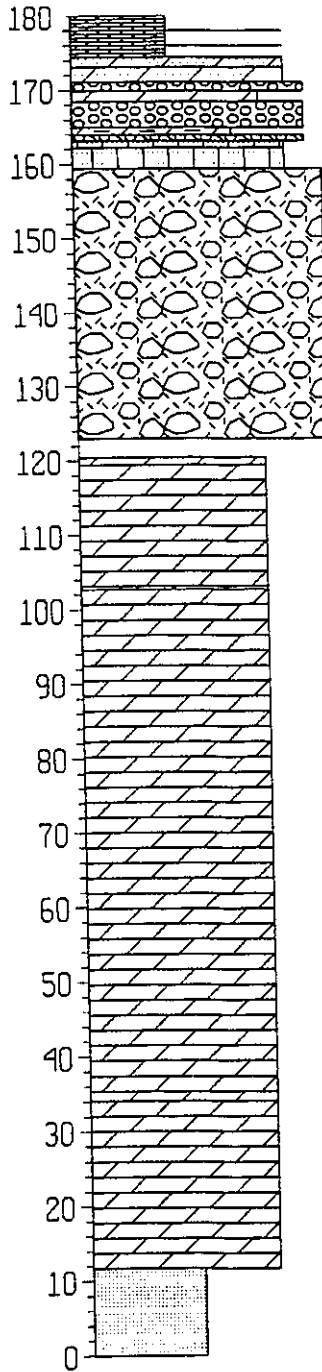


SECTION DS-27 (CONTINUED)



SECTION DS-28: MONARCH CIRQUE 2

GOG GP	CHANCELLOR "GROUP"
	TAKAKKAW TONGUE
CATHEDRAL FM	CATHEDRAL MEGABRECCIA



LENSES, LAM SKELETAL GRNST, PHOSPHATIC BRACHIOPODS, HYOLITHIDS, TRILOBITES
 EX-PELOID-INTRACLAST-OOID GRNST
 FENESTRAL DOLOMITE, ALLOCH BLOCK?
 DOLOMITIZED
 INTRACLAST GRAINSTONE

CATHEDRAL MEGABRECCIA
 MASSIVE, REDDISH-WEATHERING DOLOMITE WITH LOCALLY RECOGNIZABLE FABRIC AS IN UNDERLYING UNITS. COMPOSED OF ENORMOUS MEGABLOCKS AND SMALLER, ANGULAR MATERIAL. MEGABLOCKS VARIABLY ORIENTED, UP TO 90x90m IN SIZE

-----MEGATRUNCATION SURFACE-----

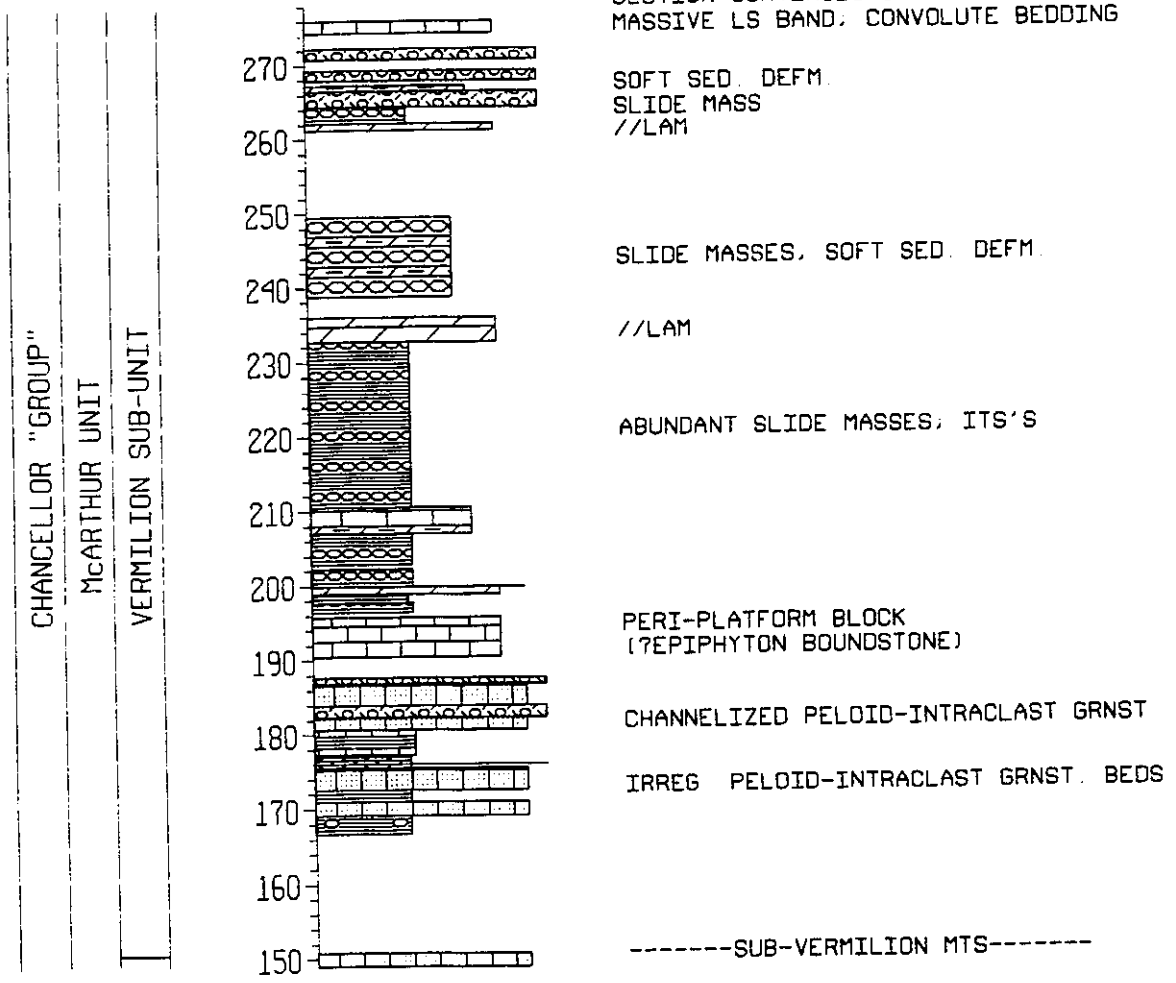
"YOHOLAMINITES" AND FENESTRAL DOLOMITE IN PARTS, MOSTLY MASSIVE DOLOMITE

INTERBEDDED AND INTERCALATED FENESTRAL DOLOMITE, OOLITIC-PISOLITIC DOLOGRNST, AND "YOHOLAMINITES" WHERE ORIGINAL SEDIMENTARY FABRICS VISIBLE. OTHERWISE MASSIVE DOLOMITE

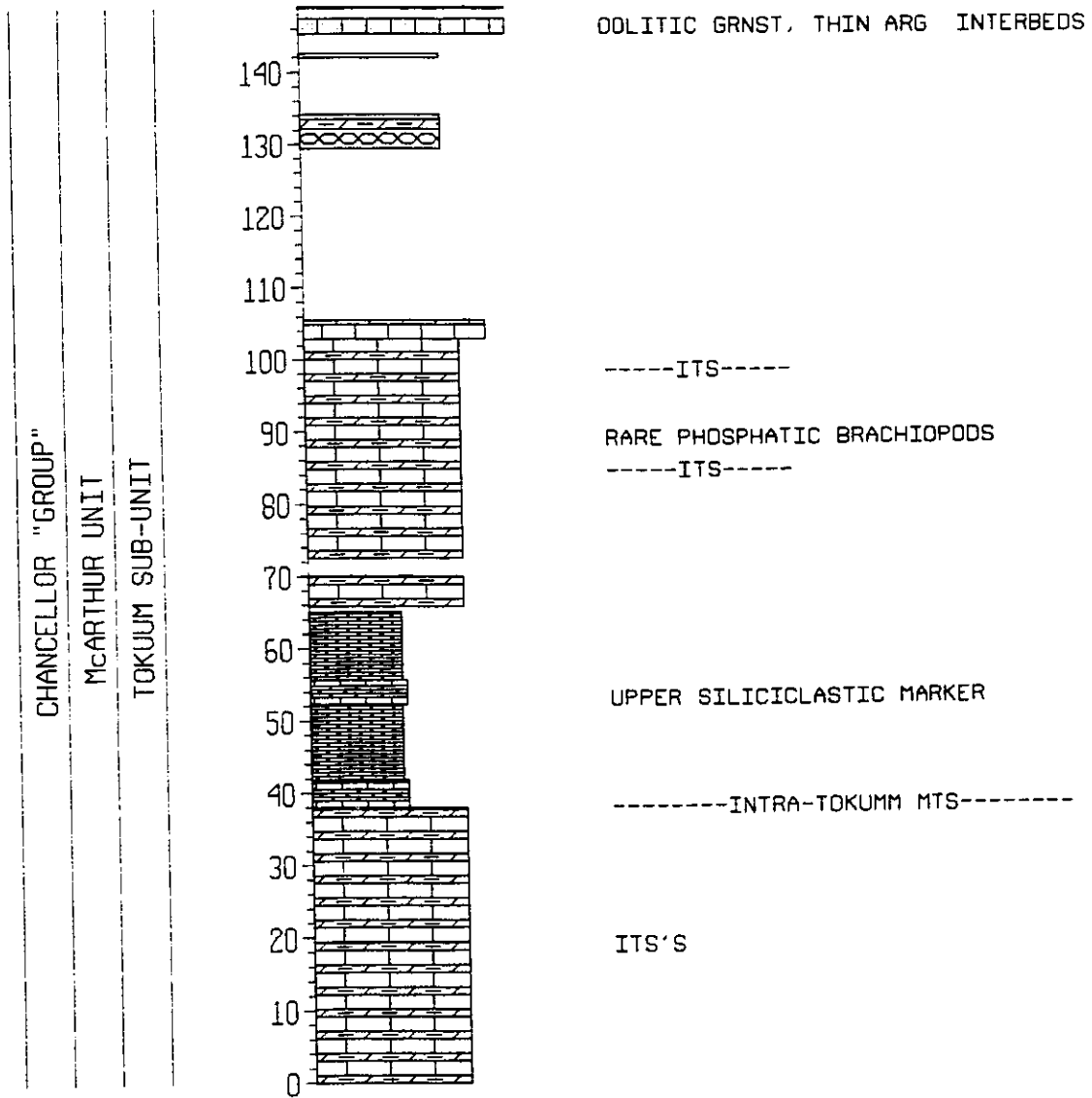
UNIT HEAVILY ALTERED TO REDDISH WEATHERING, CLAY-LIKE MATERIAL, WITH LARGE, REMNANT MASSES PERITIDAL DOLOMITE AS IN OVERLYING UNIT, "YOHOLAMINITES", OOLITIC-PISOLITIC GRNST

FINE GRAINED, WELL SORTED, SILICA CEMENTED, MED TO THICK PLANAR BEDDED

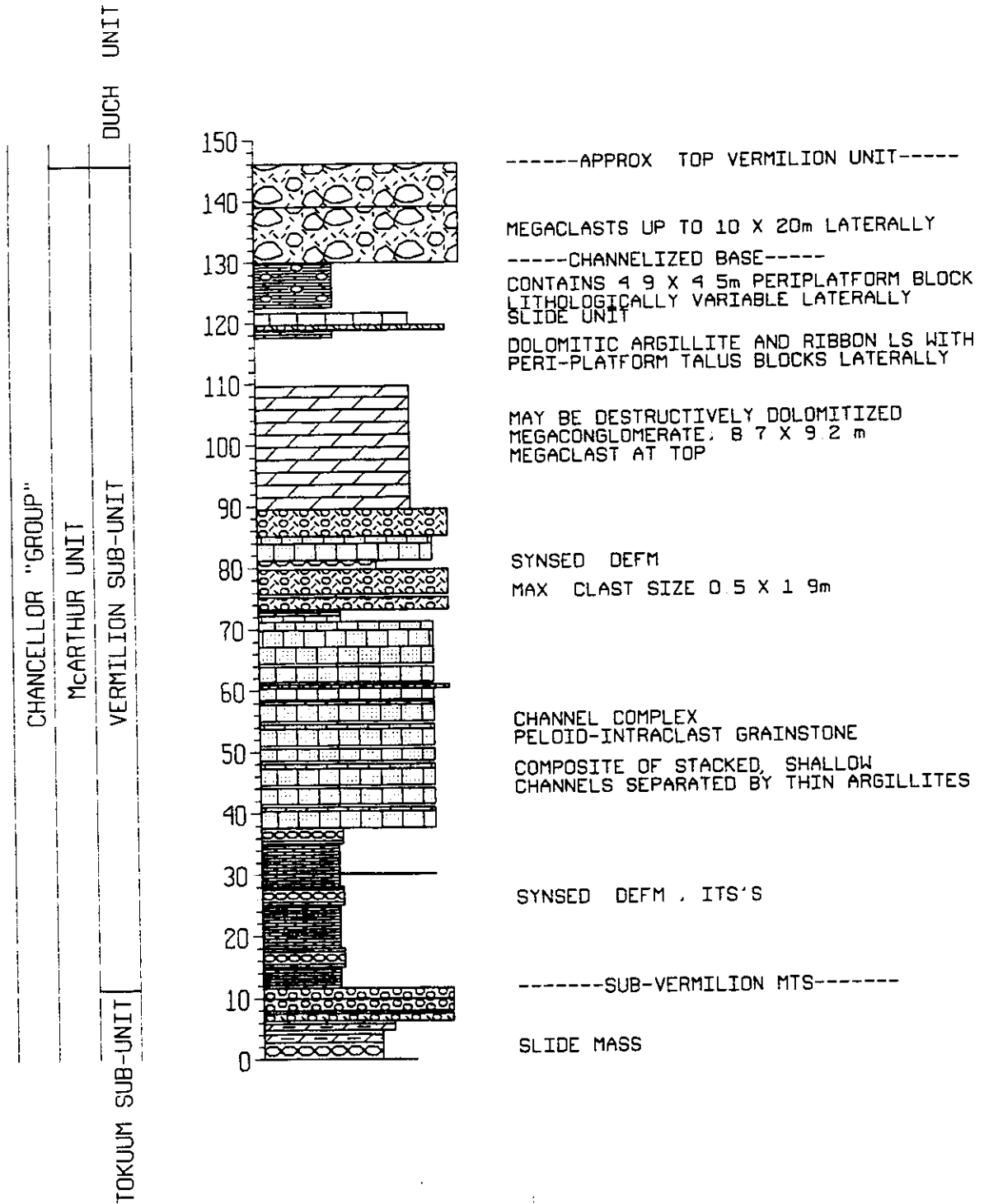
SECTION DS-29: HAFFNER CREEK SOUTH



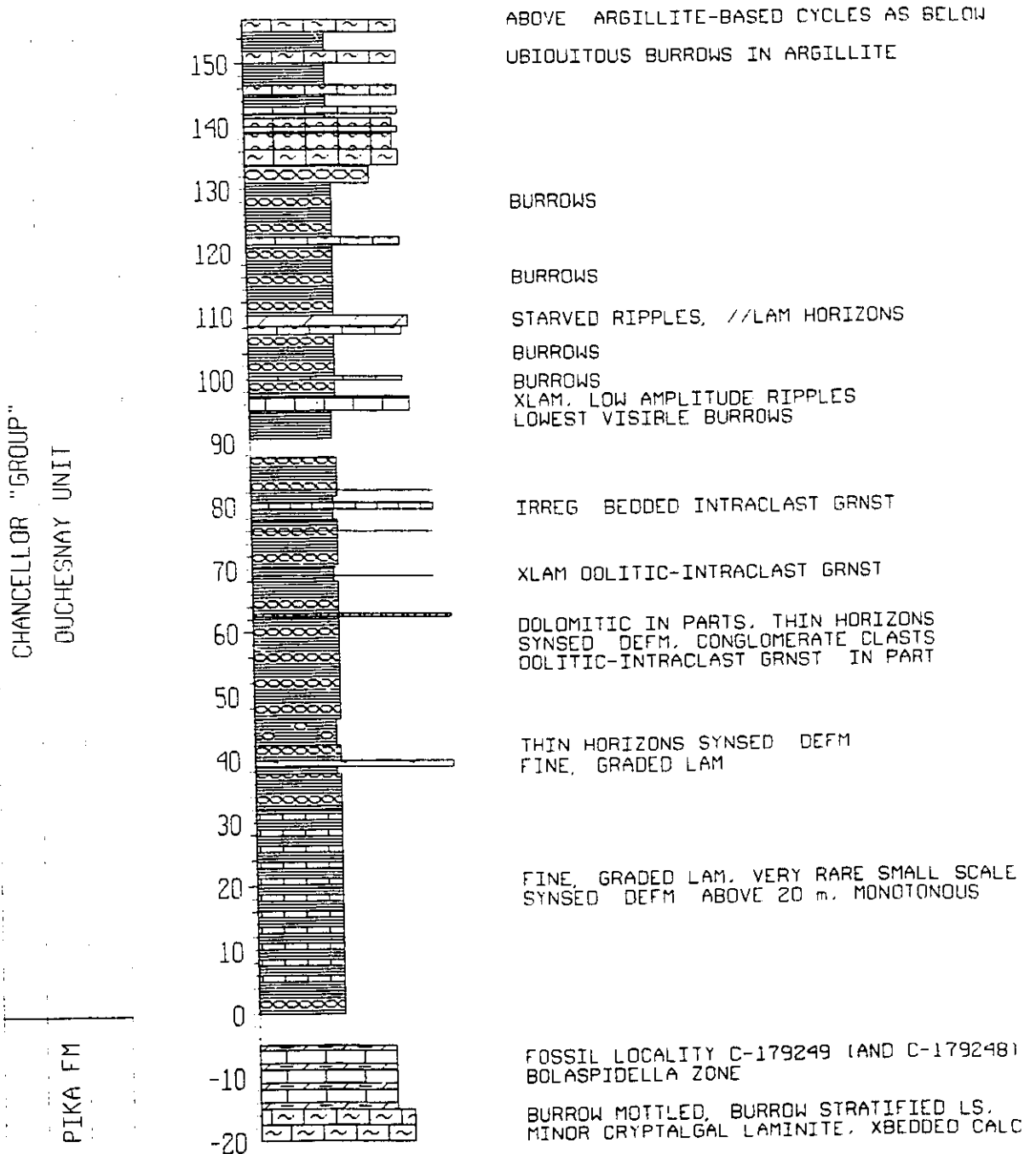
SECTION DS-29 (CONTINUED)



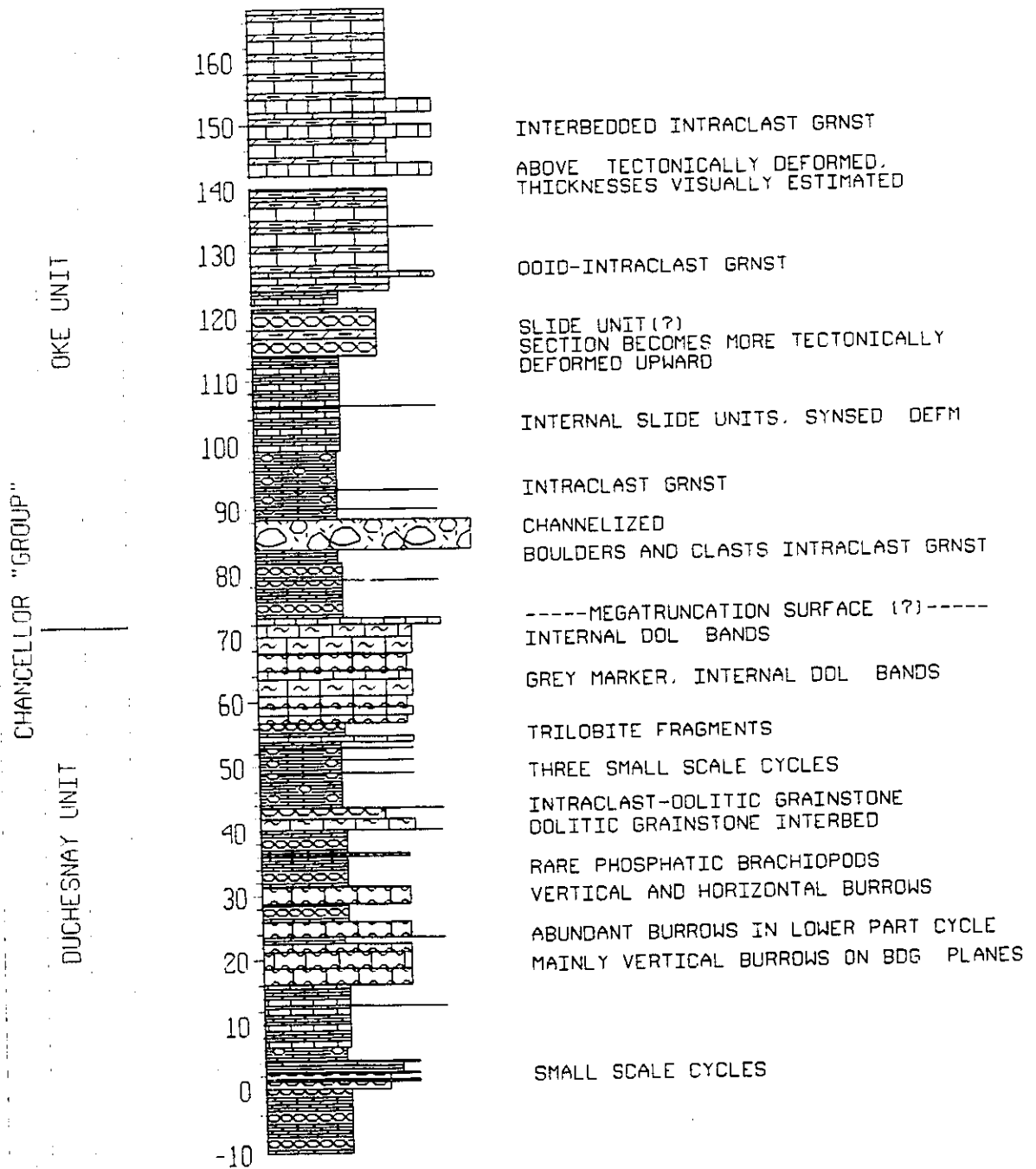
SECTION DS-30: PROSPECTORS VALLEY 4



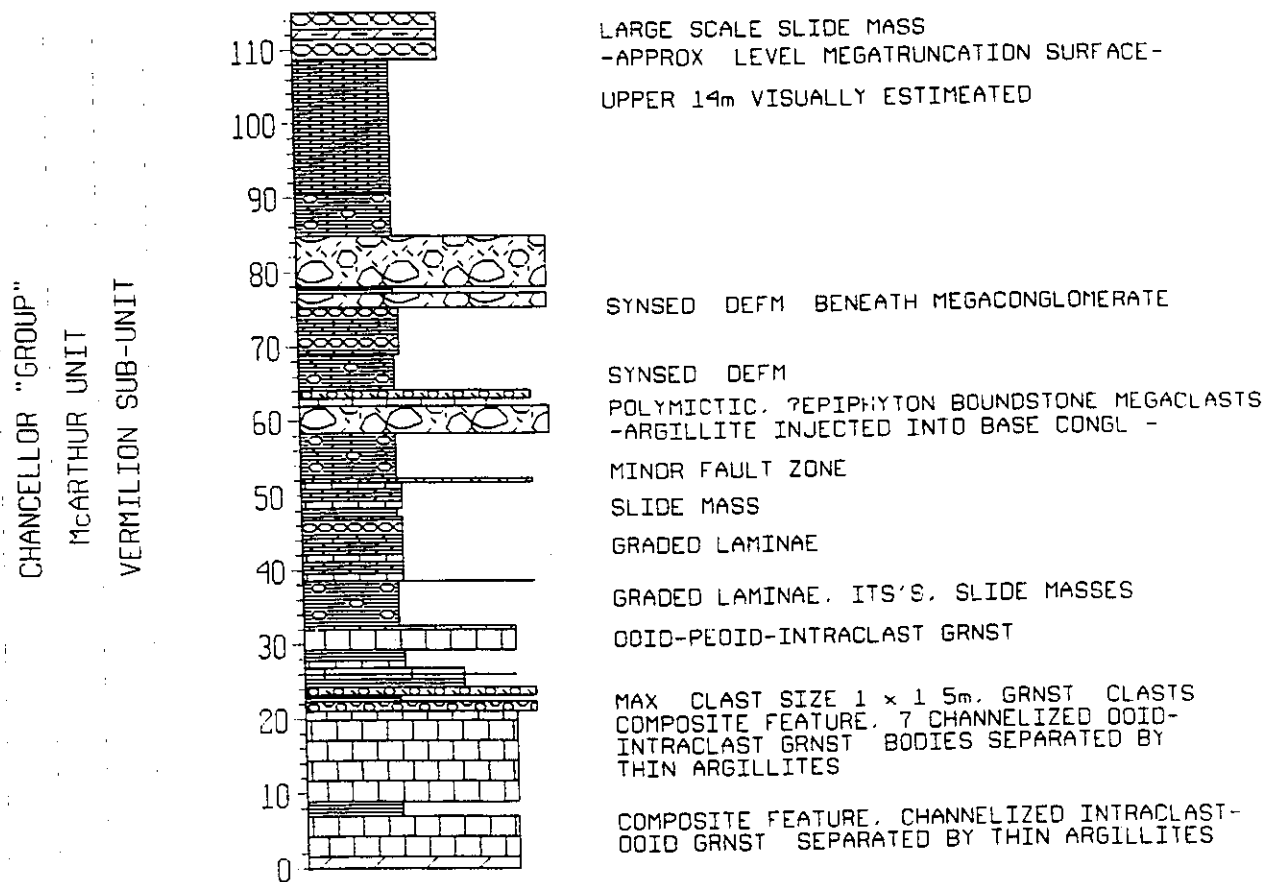
SECTION DS-31: HAMILTON LAKE NORTH



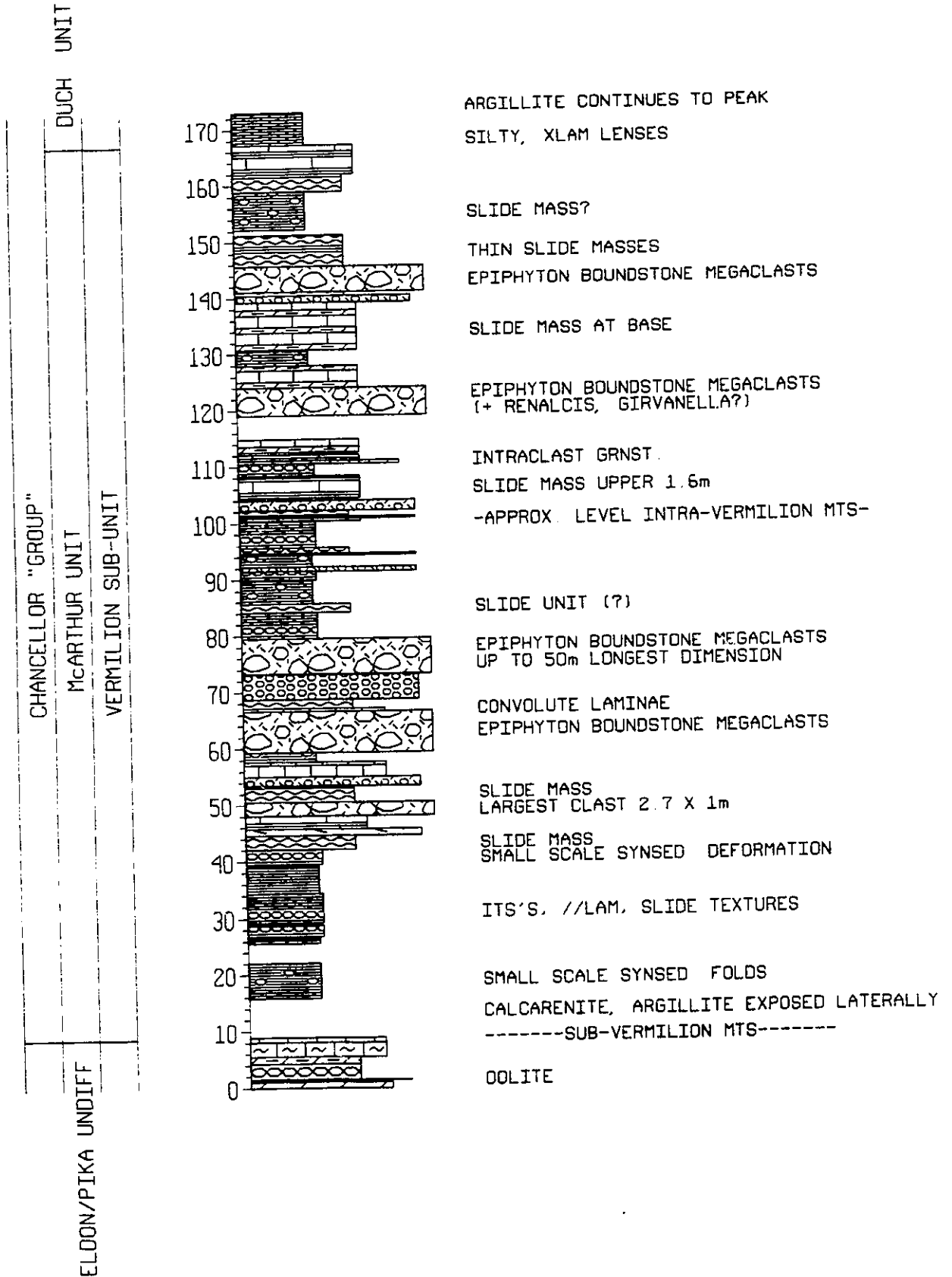
SECTION DS-32: HAMILTON LAKE SOUTH



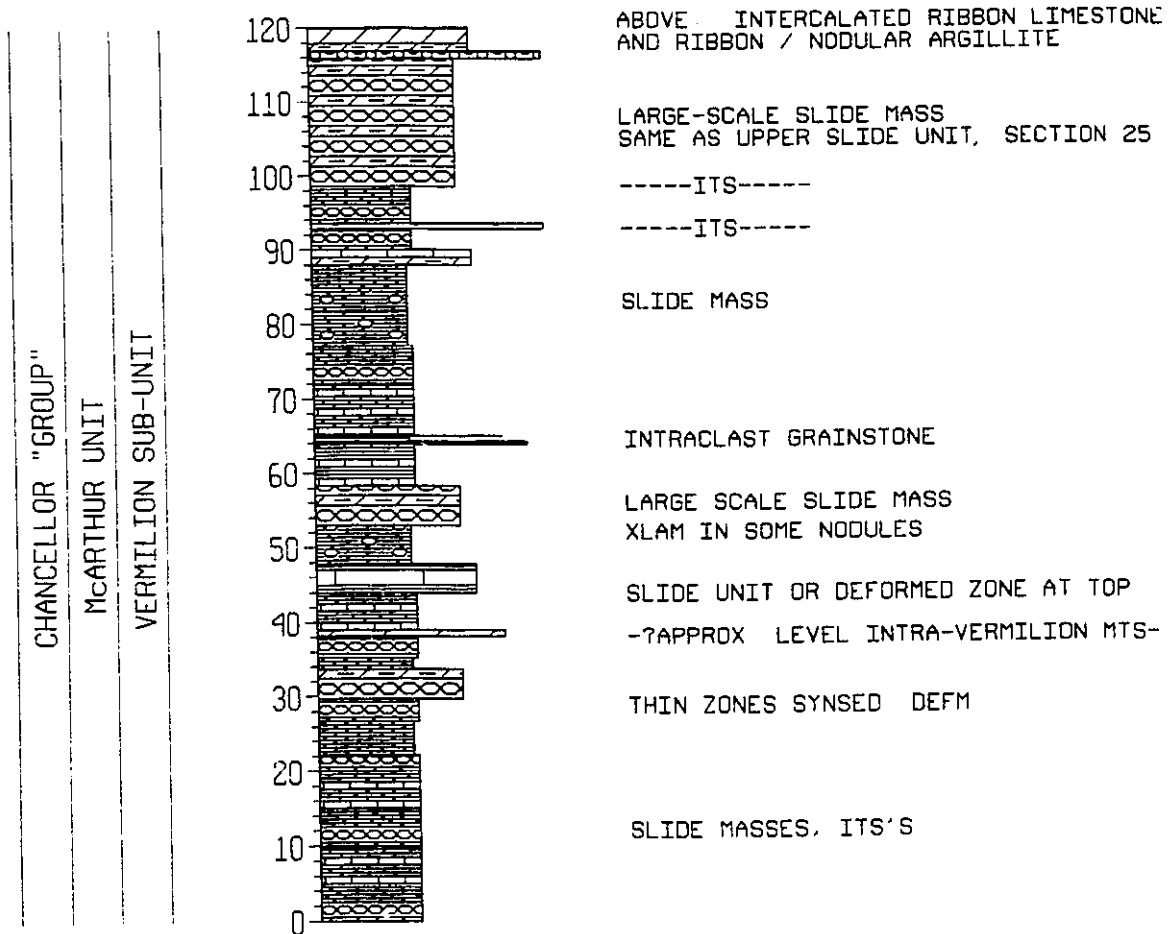
SECTION DS-33: VERDANT HEADWATERS SOUTH



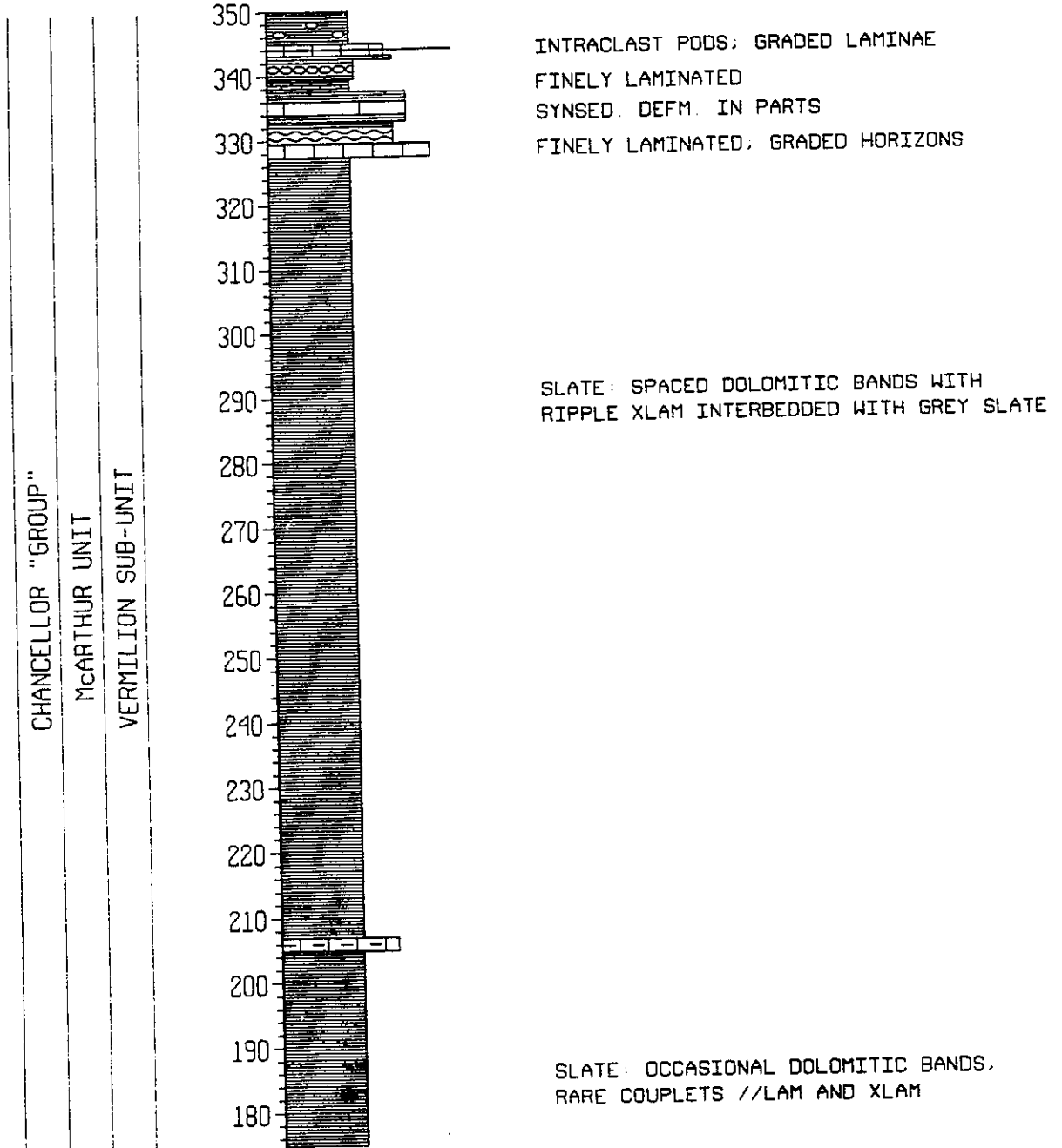
SECTION DS-34: VERDANT HEADWATERS NORTH



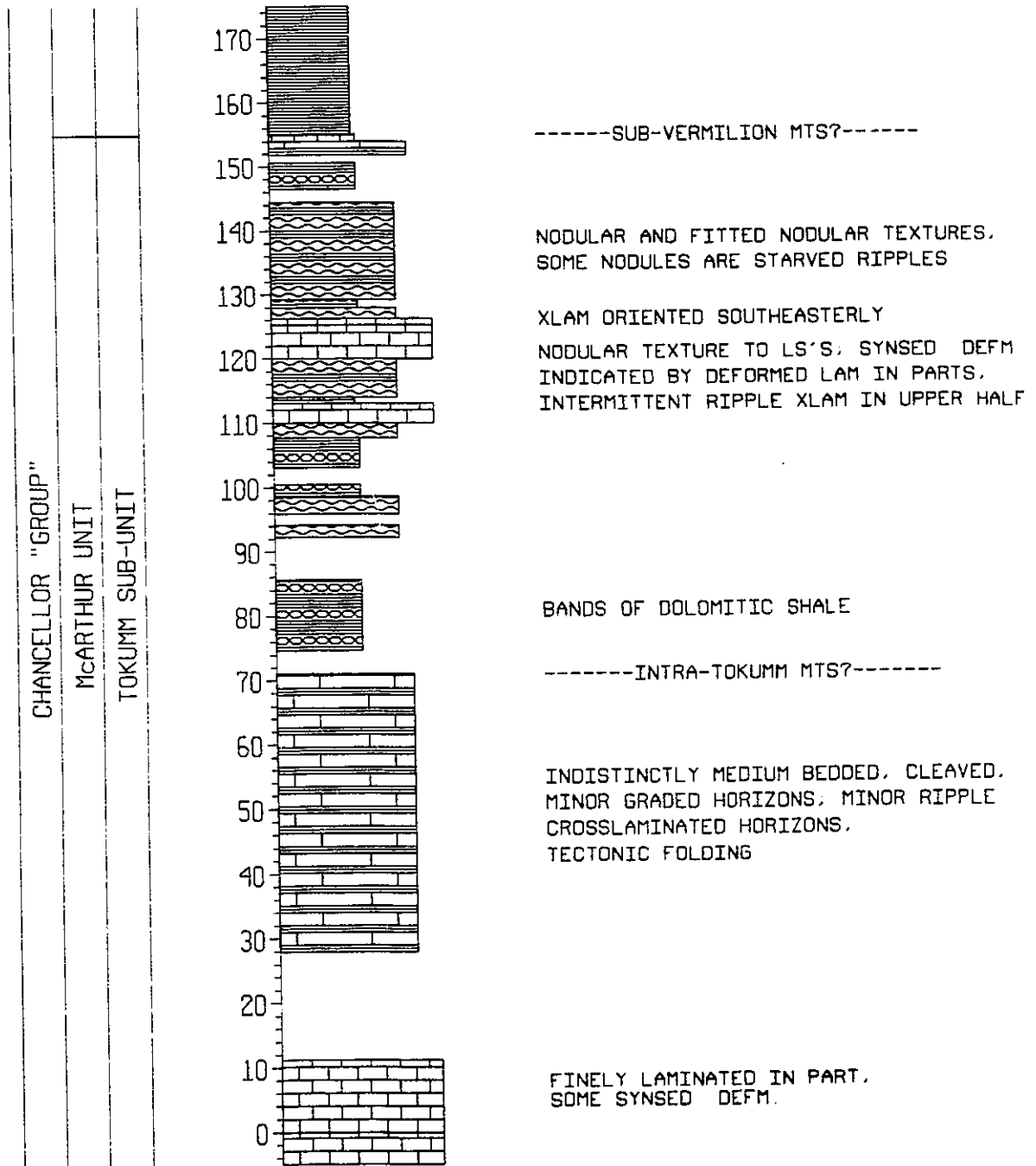
SECTION DS-35: STEPHEN CIRQUE CENTRE 2



SECTION DS-36: NUMA MOUNTAIN SOUTH



SECTION DS-36 (CONTINUED)



APPENDIX 3

APPENDIX 3

EVALUATION OF AN ALTERNATIVE CATHEDRAL MARGIN MODEL

A3.1 INTRODUCTION

In 1989, Rolf Ludvigsen wrote the first detailed arguments refuting the classical interpretation of the Cathedral Escarpment advocated by W.H. Fritz (Fritz, 1971), I.A. McIlreath (McIlreath, 1977a,b), and J.D. Aitken (Aitken, in press, a). An alternative interpretation had long been rumored, but had not previously been published except in abstract form (Beales et al., 1986).

The arguments advanced by Ludvigsen (1989) have been forcefully rebutted by Fritz (1990) and Aitken and McIlreath (1990). This appendix further evaluates Ludvigsen's ideas from the viewpoint of the writer.

A3.2 BASIS FOR THE MODEL

The basic arguments presented by Ludvigsen (1989, 1990) are as follows:

1. The trilobite zonation scheme utilized by Fritz (1971) is obsolete, as it ignores the profound influence of facies control on the paleogeographic distribution of trilobites. A "dual" model utilizing facies-specific zones is more appropriate, as

exemplified by Robison's (1976) lithofacies-specific zonation for the Middle Cambrian of the Great Basin (Fig. 25).

2. The sole evidence for the existence of a Cambrian submarine escarpment is a 200 m high "step" in the boundary between the Glossopleura and Bathyriscus - Elrathina zones (Fig. 24). This boundary is instead considered by Ludvigsen (1989, 1990) to be a markedly diachronous interface between a high diversity, Bathyriscus-Elrathina biofacies in deep-water shales, and a low diversity, Glossopleura biofacies in shallow-water carbonate rocks.
3. No debris apron or periplatform talus blocks have been found in the "basinal" Stephen Formation to substantiate the claim that a carbonate margin stood high over the adjoining slope during late Cathedral time. This stands in contradiction to the extensive debris aprons shown in published depositional models of bypass margins (e.g. McIlreath and James, 1984).
4. The escarpment-like interface between carbonate and shale is in fact an abrupt, vertical facies change, the sharpness of which has been enhanced by diagenetic factors and minor fault movement.
5. The Cathedral carbonate and Stephen siliciclastic sediments were deposited contemporaneously on a muddy ramp. The Burgess shale, situated about 20 m basinward of the present-day carbonate-shale interface, consists of distal storm beds deposited immediately below storm wave base in moderately shallow-water (water depths of perhaps 50 m).

A3.3 EVALUATION OF THE PALEONTOLOGICAL EVIDENCE

The paleontological arguments raised by Ludvigsen (1989, 1990) focused on facies control of trilobite distribution. This problem was also raised by Aitken (in press, a) in his discussion of "basinal" Stephen Formation biostratigraphy. In the Middle Cambrian of the Great Basin, for example, the lateral displacement of sedimentary environments resulted in the intertonguing of different lithofacies and associated biofacies, causing phylogenetically unrelated faunas to succeed one another vertically (Robison, 1976, p. 95). The Field Member of the Eldon Formation is a good example of this in the study area.

The chronocorrelation of "restricted shelf" and "open shelf" zones suggested by Robison (1976) appears to be a rational approach to the problem of facies control of trilobite distribution (Fig. 25). However, the stratigraphic and sedimentological implications of the model in the case of the Cathedral margin are subject to interpretation. Ludvigsen (1989) has selectively applied **one** possible interpretation, but there are others.

Under the "Dual Model" advocated by Ludvigsen, the range of the "restricted shelf" Glossopleura Zone overlaps with part of Robison's (1976) proposed "open shelf" Oryctocephalus Zone (Fig. 25). The entire "basinal" Stephen Formation lies within the range of the latter zone. Ludvigsen's redrawn correlation chart, which is consistent with (but not dictated) by this model, shows "temporal alignment of the Cathedral carbonates and most of the Stephen shales even though the zones are entirely distinct" (Ludvigsen, 1989, his Fig. 10). Ludvigsen also concluded (p. 55) that "according to the Dual Model, the Burgess Shale was deposited on a gently inclined ramp, not at the base of a high escarpment."

Ludvigsen (1989) ignored the fact that a gently inclined ramp is only **one** of many possible depositional configurations compatible with the Dual Model. Implicit in his correlation chart is the assumption that the sedimentation rates of the upper Cathedral and "basinal" Stephen formations were approximately equal throughout. This assumption is made more explicitly in his diagrammatic stratigraphic cross section (Ludvigsen, 1989, his Fig. 11), which shows a time line passing through the zone of facies change with very little downward deflection. With the poor biostratigraphic resolution available, it is unclear how Ludvigsen managed to correlate individual stratigraphic horizons in the platformal Cathedral and "basinal" Stephen formations to produce this "time line" and substantiate his ramp model.

Virtually any depositional configuration can be accommodated in the context of the Dual Model. If, at the opposite extreme, the platform aggraded rapidly relative to the adjoining slope, the corresponding time line would have significant relief. This is essentially the scenario advocated by McIlreath (1977a) and Aitken (in press, a). Thus, Ludvigsen's (1989) gentle ramp hypothesis is simply an end-member of a range of possible depositional configurations. At the other end of the spectrum is a high-relief carbonate margin, largely abutted by younger sediments. The Dual Model does not prove, or even imply, that the Cathedral margin configuration conformed to either end-member.

If Robison's (1976) revised trilobite zonation scheme is both correct and applicable to the Field area, the biostratigraphic evidence would seem to favour the latter configuration. In his zonation of the "restricted shelf" trilobite genera in the Great Basin, the Glossopleura Zone is succeeded temporally by the Ehmaniella Zone, which is dominated by species of Ehmaniella (Robison, 1976, p. 100). Ehmaniella first appears in strata bearing the Ogygopsis klotzi faunule, a short distance above the Boundary Limestone (Fritz, 1971, his

Fig. 6). The presence of this genus is evidence that virtually the entire "basinal" Stephen Formation above the Boundary Limestone must be younger than the Glossopleura-bearing, carbonate platform strata they abut. Significantly, the top of the Cathedral carbonate platform, from which Glossopleura Zone fossils have been recovered, lies about 180 m above the lowest occurrence of Ehmaniella in the adjacent slope sequence. Thus, the biostratigraphic evidence supports the concept of a high relief margin abutted by younger sediments. Whether this was a depositional or a collapse margin must be determined from other lines of evidence.

Another issue not addressed by Ludvigsen pertains to the presence of Glossopleura and its affiliates in deeper water strata. Glossopleura Zone fossils have been found in the lower Boundary Limestone and upper Takakkaw Tongue near the Cathedral Escarpment on Mt. Stephen (Fritz, 1971; Fritz in McIlreath, 1977a, his Appendix I), and in the upper Takakkaw Tongue in Monarch cirque (C-167278; Appendix 1). They also occur in association with Burgess Shale-like fossils in a more distal setting near the Fossil Gully Fault on Mt. Stephen (Briggs and Collins, 1988). With rare exceptions, the Glossopleura Zone fossils are disarticulated specimens, and are probably allochthonous (McIlreath, 1977b, p. 119). This is consistent with Robison's (1976) view that these fossils were confined to the "restricted shelf" facies, but contradicts Fritz's (1990, p. 108) view that Glossopleura had the capacity "to live within more than one bottom condition in a basin edge (slope) environment."

Regardless of who is correct, Glossopleura and its affiliates either had the capability to live in deep-water environments, or were transported into them from the adjacent platform in sufficient numbers to be recognized and collected from these sections. Thus, if the post-Boundary Limestone siliciclastic muds and Glossopleura-bearing Cathedral carbonate

sediments really did accumulate contemporaneously, there is every reason to expect Glossopleura and its affiliates at higher levels in the "basinal" Stephen Formation. On the contrary, they are absent.

A3.4 PROBLEM OF MISSING PERIPLATFORM TALUS

Ludvigsen (1989, 1990) was greatly troubled by the lack of a debris apron or individual periplatform talus blocks in the "basinal" Stephen Formation adjacent to the Cathedral Escarpment. He invited direct comparison with the reef-dominated bypass margin model proposed by McIlreath and James (1984), who stated that "the most characteristic and spectacular style of accumulation [adjacent to this type of margin] is the wedge of periplatform talus" (McIlreath and James, 1984, p. 254). The utter lack of such debris stands as evidence against a 200 m high submarine cliff, and in favour, Ludvigsen implies, of a ramp model.

Ludvigsen's (1989, 1990) comparison with the reef-dominated bypass margin model is either a misunderstanding or a misrepresentation of the Cathedral Escarpment model advocated by McIlreath (1977a). McIlreath distinguished between a vertically aggrading escarpment during a period of active reef growth, and a drowned, inactive, carbonate wall in the process of being buried by fine-grained, siliciclastic sediments. In his interpretation, periplatform blocks and allochthonous calcarenites were being shed basinward during growth of the escarpment. They were incorporated in deep-water carbonate strata of the upper "thin" Cathedral Formation (Takakkaw Tongue of Aitken, in press, a). Following an inferred deepening event (Aitken, 1989), the platform top was inundated by fine-grained, siliciclastic sediment, and escarpment growth ceased. The escarpment then acted as a bypass margin in a siliciclastic setting, analogous (though much smaller in scale) to the drowning

unconformities described by Schlager (1989). As a stable, well lithified carbonate wall facing a deep, quiet basin, it did not shed any more debris during its entombment by Stephen sediments. Hence, while the shallow-water, reef-dominated, bypass margin model is fully applicable to the initial active stage of escarpment development, Ludvigsen's (1989, 1990) attempt to apply it to the second, inactive stage is both erroneous and misleading.

It is an open question as to whether even small amounts of carbonate debris would be shed by an inactive escarpment undergoing passive entombment. Documented analogues appear to be lacking. As the Cathedral Escarpment is an order of magnitude smaller than the modern Florida and Blake-Bahama escarpments, direct comparisons with many of the erosional processes affecting these large-scale features would be misleading. For example, the modern escarpments are affected by dissolution and undercutting by corrosive bottom waters and boundary currents (Paull and Dillon, 1980), and by acids produced from seeping brines (Paull and Neumann, 1987). Undercutting and oversteepening of the lower slope by the same processes is reported to be the main cause of slumping and rocksliding on the upper (<2500 m) Bahama Escarpment slope (Freeman-Lynde and Ryan, 1985). These processes act at much greater depths than are indicated for the Cathedral Escarpment, and thus are not applicable.

Other possible factors that could have resulted in debris being shed are physical erosion by sediment gravity flows, and bioerosion. The escarpment may well have been vulnerable to erosion by sediment gravity flows early in its history. However, this would have ceased to be a factor once the platform top was buried by fine-grained siliciclastic sediments. Bioerosion remains an unknown factor. It has a minor influence on the Bahama Escarpment, where the dense, carbonate substrate appears to have been a factor in reducing the number of boring organisms to an insignificant level (Freeman-Lynde and Ryan, 1985).

If bioerosion was active at all during the Middle Cambrian, it may have caused local dissolution, but is unlikely to have caused major blocks to spall off.

In summary, it is conceivable that the Cathedral Escarpment stood as a stable, high, carbonate wall during Stephen deposition. It would have to be assumed, however, that violent seismic events did not occur during the early stages of slope aggradation, when the margin stood at its highest and was most vulnerable to collapse. This risk would have lessened with time, as the escarpment progressively diminished in height.

A3.5 ESCARPMENT VERSUS RAMP: SEDIMENTOLOGICAL EVIDENCE

Ludvigsen (1990, p. 117) denied the sedimentological evidence presented by Aitken and McIlreath (1990), stating that none of it ". . . demonstrated that the outer edge of the carbonate platform stood vertically above the muddy basin during deposition of the Burgess Shale." It is puzzling, therefore, why Ludvigsen (1989, 1990) failed to present any sedimentological evidence in support of his own ramp model.

Ludvigsen did not attempt to clarify his ramp concept, other than by providing a few sketches. He does not seem to be suggesting a carbonate ramp in the original sense of Ahr (1973), or a distally steepened ramp, as described by Read (1982). Instead, Ludvigsen (1989) appears to be proposing a depositional margin model (McIlreath and James, 1984), which essentially corresponds to the accretionary rimmed shelf margin illustrated by Read (1982). He should therefore be able to cite sedimentological grounds to defend this model, which would, in his own words, make "predictions . . . which then become the basis for confirmation or falsification" (Ludvigsen, 1990, p. 117).

It is undeniable that predominantly fine-grained siliciclastic sediments of the "basinal" Stephen Formation terminate abruptly at a near-vertical wall of dolomite up to 223 m high on Mt. Field and Mt. Stephen (Section 7.2.1). The same is true at the new localities near Natalko Lake and The Monarch (Section 7.2.3). The contact between the carbonate and siliciclastic lithofacies, as emphasized by Aitken and McIlreath (1990), is sharp, with absolutely no evidence of intertonguing. Above the Boundary Limestone, the Amiskwi Member of the "basinal" Stephen Formation lacks interbeds of allochthonous calcarenite or hemipelagic lime mudstone.

These observations are consistent with the concept of an escarpment-type margin abutted by younger siliciclastic sediments. The contact is vertical, either because it records rapid vertical aggradation of a margin attempting to keep up with an accelerated rate of relative sea level rise (Aitken and McIlreath, 1990), or because it is the headwall of a collapse feature (this thesis). The contact is sharp, because the siliciclastic sediments were deposited passively against a pre-existing, lithified carbonate wall. The upper Amiskwi Member shales lack carbonate interbeds, because there was no contemporaneous shallow-water carbonate sedimentation on the adjoining shelf.

The same observations cannot be explained in the context of a depositional margin. Intertonguing at the margin-slope interface is implicit in the models by McIlreath and James (1984) and Read (1982). None is in evidence at the upper Cathedral margin. The margin-slope transition zone should be marked by a band of periplatform debris (carbonate sand and/or early-lithified blocks; McIlreath and James, 1984, their Figs. 12, 13). It is not. At least some of the carbonate mud generated on the platform should have been carried basinward by storms or tidal exchange. None is in evidence in the supposedly coeval siliciclastic sediments.

The last point is of the utmost importance, and can be reinforced by simply looking at the underlying Takakkaw Tongue. This unit was demonstrably deposited on a reef-dominated depositional margin adjoining a healthy carbonate platform. Copious quantities of lime mud, sand and larger debris were shed down the slope, as predicted by the depositional model by McIlreath and James (1984). This is essentially the same depositional configuration proposed by Ludvigsen (1989) for the upper Cathedral, yet he provided no explanation for the abrupt change in the character of the allegedly coeval siliciclastic slope sediments. To eliminate periplatform carbonate sediments entirely from the slope would require a total and irrevocable reversal of sediment transport from off-platform to on-platform. A strong on-platform, physical energy flux is possible in open windward settings (Hine *et al.*, 1981), such as the northeastern side of the Little Bahama Bank (Mullins *et al.*, 1984). However, even in these settings, carbonate mud still continues to reach the slope via storm and tidal currents (Heath and Mullins, 1984), although perhaps in reduced quantities. Thus, the contemporaneity of essentially pure siliciclastic slope sediments and equally pure carbonate platform sediments only metres apart is very difficult to accept.

The only means by which Ludvigsen (1990) has been able to eliminate these deficiencies in his model has been to propose that the dolomite wall is an artifact of diagenesis, and that straightening of this diagenetic front occurred during minor compactional fault movement. As evidence for the diagenetic mobility of carbonate, he cited Whittington's (1980) observation that chlorite and illite had completely replaced a calcium carbonate *Olenoides* exoskeleton in the Burgess Shale. Similar replacement of carbonate peloids and bioclasts has also been observed by the writer elsewhere in the "basinal" Stephen Formation (Section 4.3.2.6).

It is difficult to defend the concept of a mass calcium carbonate remobilization that simultaneously decalcified the Stephen argillites, and created a sharp, vertical, carbonate-shale interface over 200 m high. Remobilization and local precipitation of calcium carbonate in argillaceous sequences is an important part of the depositional/diagenetic models proposed by Einsele (1982), Eder (1982), Hallam (1986), and Coniglio and James (1990). According to these models, remobilized calcium carbonate often enhances primary depositional rhythms to produce the familiar ribbon limestones and ribbon argillites. The models are backed by a wealth of observational and analytical data (e.g. Coniglio and James, 1990). They are far more realistic than the scenario proposed by Ludvigsen (1990), who presented no field or laboratory evidence to support his claim. Moreover, had a vertical diagenetic front been created, it would presumably have been quite irregular in form, in contrast to the sharp, smooth walls observed in the field. Minor compactional faulting would have only displaced, and not otherwise physically modified, this putative diagenetic boundary.

A3.6 CONCLUSION

Stratigraphic and sedimentological observations in the Field and Nataiko Lake/Monarch areas are fully consistent with the concept of a dormant, paleobathymetric feature towering over a rapidly aggrading siliciclastic slope. Ludvigsen (1989, 1990) attempted to discredit the classical interpretation of this feature through the use of equivocal biostratigraphic evidence and a "carbonate ramp" model utterly unsupported by sedimentological evidence. His revised depositional scenario for the Burgess Shale is therefore rejected. He did, however, raise legitimate concerns about paleoenvironmental controls on the distribution of trilobites in carbonate margin and slope settings. These concerns will have to be addressed in future biostratigraphic studies in the region.