

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

**Bell & Howell Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
800-521-0600**

UMI[®]

NOTE TO USERS

This reproduction is the best copy available.

UMI



Université d'Ottawa • University of Ottawa

**SEDIMENTOLOGY AND SEQUENCE
STRATIGRAPHIC FRAMEWORK OF THE LOWER
CRETACEOUS BLUESKY FORMATION, VALHALLA
AREA, WEST-CENTRAL ALBERTA**

by

Warren J.A. Walsh

**A thesis submitted to the School of Graduate Studies and
Research in partial fulfillment of the requirements
for the degree of M.Sc. in Earth Sciences**

**OTTAWA-CARLETON GEOSCIENCE CENTRE
AND
UNIVERSITY OF OTTAWA
OTTAWA, CANADA**

© Copyright by Warren J.A. Walsh, 1999



**National Library
of Canada**

**Acquisitions and
Bibliographic Services**

**395 Wellington Street
Ottawa ON K1A 0N4
Canada**

**Bibliothèque nationale
du Canada**

**Acquisitions et
services bibliographiques**

**395, rue Wellington
Ottawa ON K1A 0N4
Canada**

Your file Votre référence

Our file Notre référence

The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

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

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

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

0-612-52310-1

Canada

Abstract

The Lower Mannville (Aptian) Bluesky and underlying Gething formations of northwestern Alberta were deposited during the transgressive phase of a third order sequence. In west-central Alberta the Bluesky Formation forms a relatively thin succession of mostly shallow-marine strata that overlies a thick succession of non-marine to coastal plain coal, shale and sandstone of the Gething Formation. At the end of Bluesky time a marine basin covered much of Alberta, and in the study area this period of sea level highstand is characterized by a thick, generally northward prograding succession of marine shale and sandstone that make up the Wilrich, Falher and Notikewin formations of the Spirit River Group.

The study area is located in west central Alberta and is bounded north-south by Townships 74-76, and east-west by Ranges 7-9 west of the 6th meridian. Here the Bluesky Formation consists of a complex succession of marine and fluvial strata that were deposited during high order fluctuations of relative sea level (RSL). Seven lithofacies deposited in marginal marine to shoreface environments were deposited during transgressive and regressive phases. Based on paleoenvironment interpretations and cross cutting relationships strata of the Bluesky Formation are subdivided into three depositional sequences.

Sequence 1 comprises lowstand/transgressive fluvial sandstone of the Gething Formation in-filling number of northwest trending valleys incised into older coastal plain deposits of the Gething Formation. A single marine Bluesky Formation parasequence overlies a wave ravinement surface throughout most of the study area, and represents

deposition during the ensuing highstand. Subsequently, a fall of relative sea level shifted marine conditions northwest of the study area which led to a northwest-trending fluvial system incising the exposed strata of Sequence 1. During the ensuing rise of relative sea level fluvial deposits of Sequence 2 filled the valley system and a northeast-southwest trending barrier bar complex developed in the northern part of the study area. During a temporary stillstand of relative sea level an upward shoaling succession of marine shale to sandstone was deposited on a northwest prograding wave-dominated delta. This local progradation is interpreted as the result of a high sediment influx being supplied by the still active fluvial source. Nevertheless, rising RSL eventually overwhelmed the system and formed a wave ravinement surface across the study area which is marked by an erosional contact and coarse-grained lag generally less than 1m thick. Highstand strata overlie the transgressive lag and consist of distal marine shale that, in this study has been informally termed the Shale Break. The highstand shale is in turn abruptly overlain by a northwest prograding lower shoreface sandstone that was deposited following a fall of relative sea level. Deposition of Sequence 2 was terminated by a further fall of relative sea level. Transgressive barrier deposits of Sequence 3 were emplaced during the final (Bluesky) transgression of the Boreal Sea. Barriers were generally only partly preserved but locally in-place drowning have preserved an almost complete stratal record. Deposition during the ensuing highstand consists of distal marine shale of the Wilrich Formation that caps Bluesky strata across the study area.

The complex stratigraphy of the Bluesky Formation in the study area is most probably the result of short-term changes of relative sea level that were superimposed on a longer-term episode of rising relative sea level. Local variation in the thickness of

Bluesky strata, however, may be related to changes in accommodation space associated with movement along pre-existing faults. The study area is on the southern flank of the Peace River Arch, which during the Cretaceous was subsiding locally. Basement rooted faults noted from the Devonian, trending east-northeast and northwest and in places paralleling Early Carboniferous grabens, were likely reactivated having a profound effect on the distribution and preservation of Bluesky Formation lithofacies.

RESUME

La formation Bluesky du Mannville Inférieur (Aptien) et la formation sous-jacente de Gething dans la partie nord-ouest de l'Alberta ont été déposés pendant la phase transgressive d'une séquence de troisième ordre. Dans la partie du centre-ouest de l'Alberta, la formation Bluesky forme une succession relativement mince de couches marines de milieu peu profond qui recouvre la succession épaisse de la formation Gething caractéristique d'une plaine cotière constituée d'intercallations de charbon, d'argile et de grès. Durant la fin de la déposition du Bluesky, un bassin marin recouvrait une grande partie de l'Alberta. Dans la région de la présente étude, cette période marque un haut niveau de la mer qui est caractérisé par une épaisse succession d'argile et de grès marins qui généralement progradent vers le nord. Cette épaisse succession forme les formations Wilrich, Falher et Notikewin du groupe Spirit River.

La région étudiée est située dans la partie centre-ouest de l'Alberta et est limitée au nord et au sud par "Townships 74-76" et à l'est et à l'ouest par "Ranges 7-9" au sud du 6ème méridien. Dans cette région, la formation Bluesky consiste en une succession complexe de couches marines et fluviatiles qui ont été déposés pendant des fluctuations d'ordres supérieurs répondant à la hausse du niveau de la mer. Les sept lithofaciès qui ont été identifiés varient d'un milieu marin marginal à un environnement côtier. Les lithofaciès ont été déposés pendant les phases transgressives et régressives reliées à la fluctuation d'ordres supérieurs du niveau de la mer. Basées sur les interprétations de paléo-

environnements et de leurs interdépendances, les couches de la formation Bluesky ont été subdivisées en trois séquences distinctes de déposition.

La première séquence (1) est formée d'un grès fluviatil transgressif (lowstand) de la formation Gething qui a érodé et formé des vallées orientées nord-ouest dans les anciennes plaines côtières de la formation Gething. Une seule paraséquence marine de la formation Bluesky recouvre la surface de ravinement, formée par le remaniement des vagues associé à la montée du niveau marin, à travers la majeure partie de la région à l'étude. Par la suite, une baisse du niveau de la mer a modifié les conditions marines au nord-ouest de la région à l'étude donnant lieu à un système fluvial orienté vers le nord-ouest qui a érodé et exposé les couches de la première séquence.

La deuxième séquence (2) est caractérisée par des dépôts fluviatiles qui ont rempli le système de vallées. Pendant la hausse du niveau de la mer qui suivit la déposition de la séquence 2, un système complexe de barrière orienté vers le nord-est/sud-ouest s'est développé dans la partie nord de la région étudiée. Durant la période de stagnation du niveau de la mer, une succession marine de caractère peu profond à un caractère de plage, constituée de sable et d'argile, a été déposée dans une direction nord-ouest sous forme de delta progradant sous l'influence des vagues. Localement, la progradation a été le résultat d'un afflux de sédiments important approvisionné par la source fluviale encore active. Néanmoins, la montée du niveau de la mer a éventuellement dominé le système et a formé une surface de ravinement, sous l'influence des vagues, à travers la région étudiée. Cette surface de ravinement est marquée par une surface

d'érosion et d'une accumulation d'un lit de sable à grain grossier d'une épaisseur de moins de 1 mètre. Des couches reliées au haut niveau marin recouvrent cette surface. Ces couches sont composées d'argile marine de milieu profond lesquelles dans cette étude sont dénommées "Shale Break". Les argiles marines sont brusquement recouvertes par des grès de plage progradant vers le nord-ouest et qui ont été déposés suite à une baisse du niveau de la mer. Une baisse plus accentuée du niveau de la mer a mis fin à la déposition de la séquence 2.

Les dépôts de barres transgressifs qui caractérisent la troisième séquence (3) ont été mis en place pendant la transgression (Bluesky) finale de la Mer Boréale (Boreal Sea). Les barrières ont généralement été partiellement préservées mais localement les couches ont été presque complètement préservées grâce à un enfouissement rapide (noyade) de la séquence. La formation Wilrich recouvre les couches du Bluesky à travers la région étudiée. Elle est caractérisée par une argile marine distale associée à une hausse du niveau de la mer.

La stratigraphie complexe de la formation Bluesky dans la région est très probablement le résultat de changements à court terme (rapides) du niveau de la mer qui ont été superposés sur un épisode à long terme de la hausse du niveau de la mer. La région à l'étude est située sur le flanc sud de l'arc Peace River, laquelle s'est affaissée localement pendant la période du Crétacé. La variation locale dans l'épaisseur des couches du Bluesky peut être cependant reliée aux changements de l'espace disponible le long des failles pré-existantes. Les failles profondément enracinées dans le Dévonien et

ré-activées sont vraisemblablement responsable de la distribution et de la préservation des lithofaciès de la formation Bluesky. Ces failles ont une orientation nord-est/est et nord-ouest et, dans quelques régions, elles sont parallèles avec les “grabens” du Carbonifère inférieur.

Table of Contents

ABSTRACT	III
RESUME	VI
ACKNOWLEDGEMENTS	XIV
SECTION 1.0 OVERVIEW	1
SECTION 1.1 INTRODUCTION	1
SECTION 1.2 THE STUDY AREA	1
SECTION 1.3 REGIONAL GEOLOGY	8
SECTION 1.4 THE WESTERN CANADA SEDIMENTARY BASIN	8
SECTION 1.5 DEVELOPMENT OF THE WESTERN CORDILLERA AND FORELAND BASIN	11
SECTION 1.6 THE MANNVILLE GROUP (APTIAN TO ALBIAN)	14
SECTION 1.7 PREVIOUS WORK	17
SECTION 1.8 OBJECTIVES AND METHODOLOGY	19
SECTION 2.0 FACIES DESCRIPTIONS	21
SECTION 2.1 METHODOLOGY	21
SECTION 2.2 LITHOFACIES 1: UPWARD FINING GLAUCONITIC CONGLOMERATE TO SANDY SHALE	21
SECTION 2.3 INTERPRETATION	25
SECTION 2.4 LITHOFACIES 2: SHALE	28
SECTION 2.5 INTERPRETATION	42
SECTION 2.6 LITHOFACIES 3: UPPER VERY FINE GRAINED, LOW-ANGLE CROSS-STRATIFIED SANDSTONE ..	43
SECTION 2.7 INTERPRETATION	44
SECTION 2.8 LITHOFACIES 4: UPWARD-COARSENING, FINE TO MEDIUM CROSS-STRATIFIED TO INTENSELY BIOTURBATED SANDSTONE	50
SECTION 2.9 INTERPRETATION	51
SECTION 2.10 LITHOFACIES 5: UPWARD FINING CARBONACEOUS COARSE TO FINE SANDSTONE.....	51
SECTION 2.11 INTERPRETATION	52
SECTION 2.12 LITHOFACIES 6: BLOCKY FINE OR MEDIUM SANDSTONE.....	53

SECTION 2.13 INTERPRETATION	56
SECTION 2.14 LITHOFACIES 7: CARBONACEOUS VERY-FINE SANDSTONE, MUDSTONE, AND COAL	60
SECTION 2.15 INTERPRETATION	61
SECTION 3.0 STRATIGRAPHY AND DEPOSITIONAL MODEL	63
SECTION 3.1 INTRODUCTION	63
SECTION 3.2 REGIONALLY CORRELATABLE SURFACES.....	63
SECTION 3.3 SEQUENCE 1 - UPPER GETTING CHANNELS AND PARASEQUENCE 1	67
SECTION 3.4 SEQUENCE 2.....	69
SECTION 3.5 SEQUENCE 3.....	80
SECTION 3.6 SUMMARY	100
SECTION 4.0 REGIONAL TECTONIC INFLUENCE	105
SECTION 4.1 DEPOSITIONAL AND STRUCTURAL TRENDS	105
SECTION 4.2 INTERPRETATION	116
SECTION 4.3 SUMMARY	119
SECTION 5.0 PETROLEUM GEOLOGY	125
SECTION 5.1 VALHALLA BLUESKY K POOL	125
SECTION 5.2 LA GLACE BLUESKY A POOL	132
SECTION 5.3 VALHALLA BLUESKY L AND U POOLS	137
SECTION 5.4. SUMMARY	141
SECTION 6.0. DISCUSSION.....	145
SECTION 7.0 CONCLUSIONS.....	151
SECTION 8.0 REFERENCES.....	151
APPENDIX A: CORE LOGS.....	158
APPENDIX B: SANDSTONE PETROGRAPHY	183

List of Figures

FIGURE 1.1 STRATIGRAPHIC TERMINOLOGY CHART	3
FIGURE 1.2 LOCATION OF THE STUDY AREA.....	5
FIGURE 1.3 WELLS WITHIN THE STUDY AREA CONTAINING BLUESKY CORE.....	7
FIGURE 1.4 CROSS SECTION OF THE WCSB.....	10
FIGURE 1.5 MORPHOLOGICAL BELTS OF THE CANADIAN CORDILLERA.....	13
FIGURE 1.6 CROSS SECTION OF THE LOWER CRETACEOUS MANNVILLE GROUP	16
FIGURE 2.1 LITHOFACIES 1 PHOTOGRAPH	23
FIGURE 2.2 BOX PHOTOGRAPH OF THE 6-10-75-8W6 CORE 1559.8-1557.5 M.....	27
FIGURE 2.3 BOX PHOTOGRAPH OF THE 6-10-75-8W6 CORE 1567.6-1563.0 M.....	30
FIGURE 2.4 ISOPACH MAP OF THE SHALE BREAK	34
FIGURE 2.5 BOX PHOTOGRAPH OF THE 02/14-7-75-8W6 CORE 1584.2-1573.0 M.....	37
FIGURE 2.6 LITHOFACIES 2B AND 3 PHOTOGRAPH.....	39
FIGURE 2.7 BOX PHOTOGRAPH OF THE 6-27-74-7W6 CORE 1587.3-1594.5 M.....	41
FIGURE 2.8 LITHOFACIES 3 PHOTOGRAPH	46
FIGURE 2.9 LITHOFACIES 3 PHOTOGRAPH	48
FIGURE 2.10 BOX PHOTOGRAPH OF THE 9-22-76-8W6 CORE 1467.5-1458.0 M	55
FIGURE 2.11 LITHOFACIES 6 PHOTOGRAPH	58
FIGURE 3.1 LOCATION OF CROSS SECTIONS.....	65
FIGURE 3.2 STRATIGRAPHIC CROSS SECTION A-A' TO E-E"	back pocket
FIGURE 3.3 DEPOSITIONAL ENVIRONMENTS OF SEQUENCE 1	71
FIGURE 3.4 ISOPACH MAP OF FLUVIAL SANDSTONE SEQUENCE 2	73
FIGURE 3.5 ISOPACH MAP OF TIDAL INLET SANDSTONE SEQUENCE 2	77
FIGURE 3.6 CORE LOG OF 14-3-76-7W6 WELL.....	82
FIGURE 3.7 ISOPACH MAP OF SEQUENCE 3 TRANSGRESSIVE DEPOSITS.....	85
FIGURE 3.8 CORE LOG OF 6-10-75-8W6 WELL.....	87
FIGURE 3.9 LITHOFACIES 6 PHOTOGRAPH	89

FIGURE 3.10 LOCATION OF THE VALHALLA SHOAL AND LA GLACE BARRIER COMPLEX	93
FIGURE 3.11 DEPOSITIONAL MODEL OF THE VALHALLA SHOAL AND LA GLACE BARRIER COMPLEX	99
FIGURE 3.12 STRATIGRAPHY OF THE BLUESKY FORMATION.....	103
FIGURE 4.1 EARLY CARBONIFEROUS GRABENS.....	107
FIGURE 4.2 BASEMENT ROOTED FAULTS IN THE STUDY AREA	109
FIGURE 4.3 ISOPACH MAP OF SEQUENCE 2 AND 3	112
FIGURE 4.4 STRUCTURAL CONTOUR MAP OF THE TOP OF THE BLUESKY.....	114
FIGURE 4.5 EFFECT OF COASTAL GRADIENT ON TRANSGRESSION.....	118
FIGURE 4.6 PRESERVATION OF THE SHALE BREAK.....	121
FIGURE 4.7 AXIS OF THE ALBIAN FORELAND BASIN	123
FIGURE 5.1 FIELDS AND BLUESKY POOLS WITHIN THE STUDY AREA	127
FIGURE 5.2 CORE LOG OF 02/6-19-75-8W6 WELL.....	129
FIGURE 5.3 LITHOFACIES 5 POROSITY-PERMEABILITY CROSS PLOT.....	131
FIGURE 5.4 LITHOFACIES 5 POROSITY-PERMEABILITY CROSS PLOT DIVIDED BY GRAIN SIZE.....	134
FIGURE 5.5 LITHOFACIES 6 POROSITY-PERMEABILITY CROSS PLOT.....	136
FIGURE 5.6 LITHOFACIES 1 POROSITY-PERMEABILITY CROSS PLOT.....	139
FIGURE 5.7 LITHOFACIES 1 AND 6 POROSITY-PERMEABILITY CROSS PLOT.....	143

Acknowledgements

I would like to thank Dr. Bill Arnott for supervising this thesis, helping me think like a sediment particle and most importantly being a friend. I would also like to acknowledge the financial support of NSERC grant to Dr Bill Arnott. Completion of this project would not be possible without the generous financial and technical support of Petro-Canada. Thanks are due to John Hogg who first suggested this project. Special thanks are due to Ken Saunders at Petro-Canada for acting as a liaison and his helpful discussions and suggestions. In addition, the drafting department at Petro-Canada is thanked for their preparation of the drafted figures and cross-sections.

Paul Arnott provided much needed assistance with core and log interpretation in the early days of this thesis. Christopher Collum, always willing to look at bits of shell, identified mollusk specimens. Germain Rodrique translated the abstract; John, Beth and Donna in the Petro-Canada lab are thanked for their assistance. Charles Henderson is thanked for the preparation and description of many microfossil samples. I would like to also thank the administrative staff, especially Helene DeGouffe for assistance throughout my studies.

Finally, I must acknowledge the Rosterie Café where most of this thesis was written and edited and Mike Bell and his Six Guinness Afternoon for insightful commentaries of the human mind.

Oh yes, M & P, thank you.

Section 1.0 Overview

Section 1.1 Introduction

In the Peace River Arch Region of northwestern Alberta the Bluesky Formation occurs between coastal plain deposits of the Gething Formation and marine shale of the Wilrich Formation (Figure 1.1). Marine strata of the Bluesky Formation represent the initial transgression of the Boreal Sea into Alberta and northwest British Columbia during the latest Aptian earliest Albian (110-113 Ma), which in large part was because of regional subsidence related to the Laramide orogeny.

The Bluesky Formation has been subdivided into three high order sequences comprising transgressive and regressive deposits. Transgressive deposits include tidally influenced fluvial successions, locally preserved barrier complexes and thin lags of glauconitic sandstone. Progradational shoreface deposits of marine sandstone and shale represent deposition during relative sea level stillstand and highstand. Local accommodation space and the reactivation of older fault systems controlled distribution of the Bluesky Formation.

Section 1.2 The Study Area

The study area is located in west-central Alberta and is bounded north-south by Townships 74-76, and east-west by Ranges 7-9 west of the 6th meridian (Figures 1.2 and 1.3). Two major gas fields, the Valhalla and La Glace fields, occur in the area. A total of 18 pools with an initial established reserve of $3212 \times 10^6 \text{m}^3$ produce from the Bluesky Formation in the Valhalla field. Within the La Glace field the Bluesky Formation

Figure 1.1 Stratigraphic correlation chart of the Lower Cretaceous strata of the Western Canadian Sedimentary Basin. The Bluesky Formation (Bullhead Group) in northwestern Alberta lies between coastal plain deposits of the Gething Formation and marine shale of the Wilrich Formation. After Cederwall (1989).

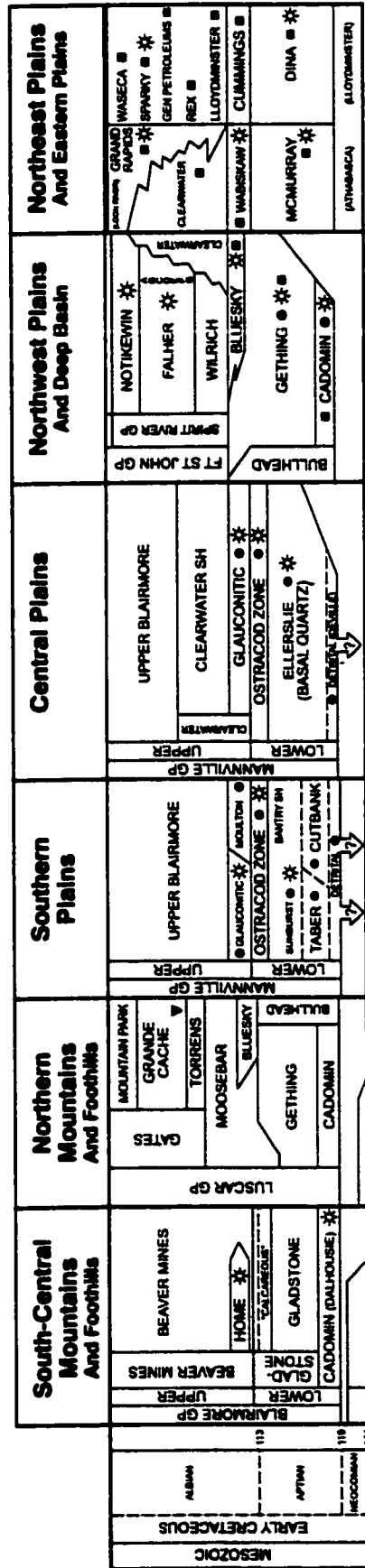


Figure 1.2 Location of study area; outline of the Peace River Arch modified from Reinson et al. (1993).

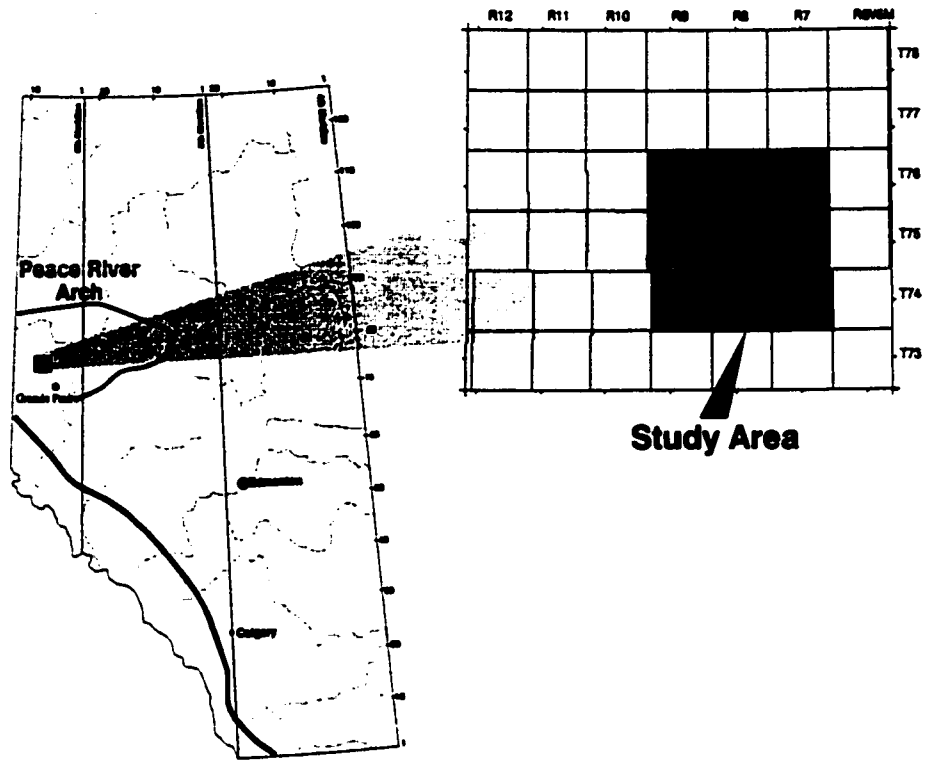
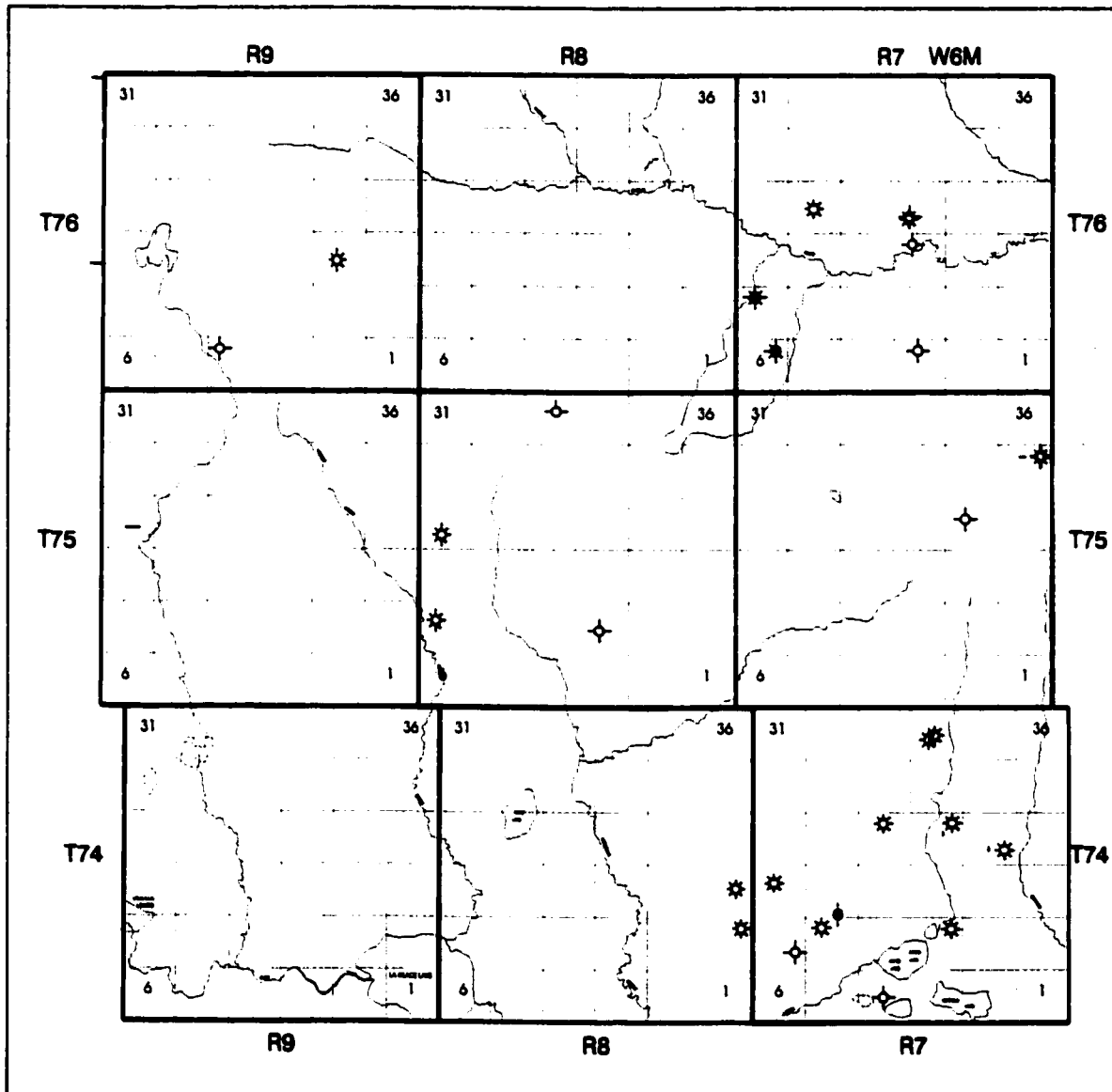


Figure 1.3 Location of cores within the Bluesky Formation described for this study.



Well Legend

○ Location	● Oil	☆ Gas
◊ Suspended	◆ Abandoned Oil	☆ Abandoned Gas
◊ Abandoned	◐ Suspended Oil	☆ Suspended Gas
		☆ Oil Prev Gas

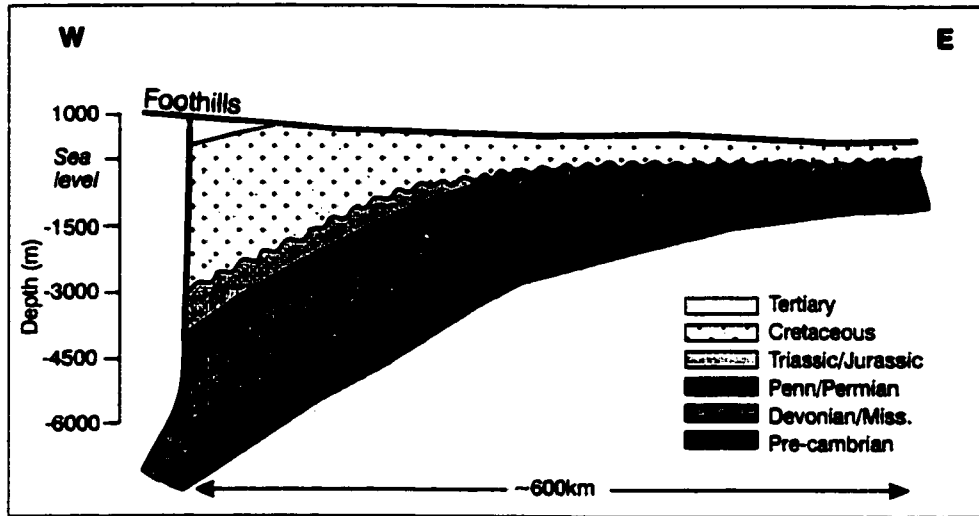
produces from 4 pools with an initial established reserves of $1502 \times 10^6 \text{m}^3$.

Section 1.3 Regional Geology

Section 1.4 The Western Canada Sedimentary Basin

The Western Canada Sedimentary Basin (WCSB) consists of a wedge of sedimentary rocks that range in age from mid-Proterozoic to Lower Tertiary. At its thickest point, near the eastern margin of the Western Cordillera, the wedge is approximately 5,800 meters thick and then thins progressively eastward to zero in the interior of Manitoba (Figure 1.4). From south to north the basin extends from the US/Canada border to the Yukon and Northwest Territories in the north. Strata within the basin are subdivided into two main depositional phases that are separated by a basin-wide unconformity (Figure 1.4). The early phase consists primarily of Paleozoic carbonates. During much of the Paleozoic North America straddled the Equator and the western paleo-margin was at approximately the position of the present-day Rocky Mountain Trench. Reef, back reef and shelf sediments accumulated along the essentially passive western continental margin. Paleo-topographic highs, for instance the Peace River Arch, were exposed and flanked by pinnacle and barrier reefs (Moore, 1989). The later phase of deposition occurred from the Early Mesozoic to the Early Cenozoic and is made up of a thick succession of clastic sedimentary rocks. In comparison to the Paleozoic, North America had moved far to the north (close to its present-day position). In addition, its western margin had been transformed into a tectonically active zone characterized by collisional tectonics and pericontinental and exotic terranes accretion. Overthrusting of

Figure 1.4 Cross section of the Western Canada Sedimentary Basin in central Alberta modified from Masters (1984). A basin wide unconformity separates Paleozoic passive margin carbonates from Mesozoic foreland basin deposits. Two main phases of the foreland basin associated with orogenies (Columbian and Laramide-Cordilleran) are separated by a major unconformity



Paleozoic rocks and the consequent formation of the Cordillera downwarped the underlying and adjacent crust, which in turn lead to the formation of a foreland basin to the east. Sediment eroded from the developing Cordillera were transported eastward and deposited in the foreland basin.

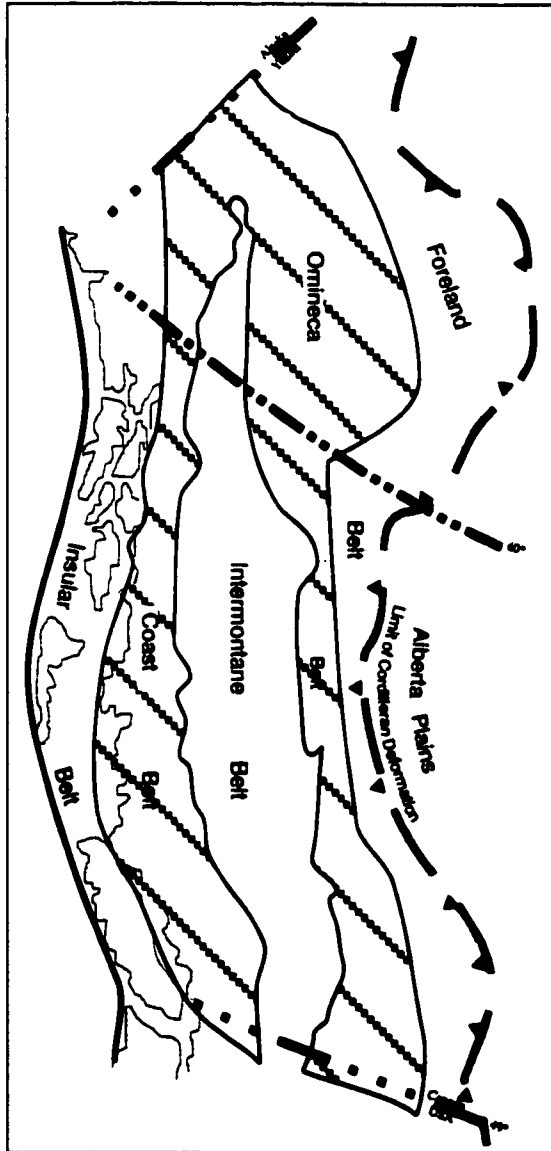
Section 1.5 Development of the Western Cordillera and Foreland Basin

The Western Cordillera is a collage of subparallel, north-south-trending terranes that accreted onto the North American craton during the Mesozoic to Early Cenozoic. The terranes are arranged into 5 morphogeological belts, which from east to west are: the Foreland, Omineca, Intermontane, Coast and Insular belts (Figure 1.5) (Monger, 1989). The development of these five belts have been interpreted to be a record of three separate orogenic events, the Columbian, Laramide and Cordilleran.

The Columbian Orogeny (Middle Jurassic to Earliest Cretaceous) marks the accretion of terranes of the Intermontane Belt and metamorphism in the Omineca Belt. A narrow foreland basin formed on the east side of the deformation front and was filled with marine shale and sandstone of the Jurassic Fernie Group and the Nikanassin Formation or Kootenay Group (Leckie and Smith, 1992; Stott, 1993).

The Laramide orogeny commenced in the Early Cretaceous and continued through the Middle Cretaceous. Terranes associated with the Insular Belt were accreted to the western margin of North America at this time. Associated heat and pressure formed metamorphic and igneous rocks that formed the present-day Coast Mountains. The third orogeny, the Cordilleran orogeny, began in the Late Cretaceous and ended in the early

Figure 1.5 Generalized morphological belts of the Canadian Cordillera modified from Monger and Hutchinson (1971). Terranes of the Intermontane Belt were accreted and metamorphism in the Omineca Belt occurred during the Columbian Orogeny (Middle Jurassic to Earliest Cretaceous). During the Laramide orogeny (Early Cretaceous to Middle Cretaceous), terranes associated with the Insular Belt were accreted to the western margin of North America, in addition, metamorphic rocks, plutonic and volcanic rocks formed the Coast Mountains.

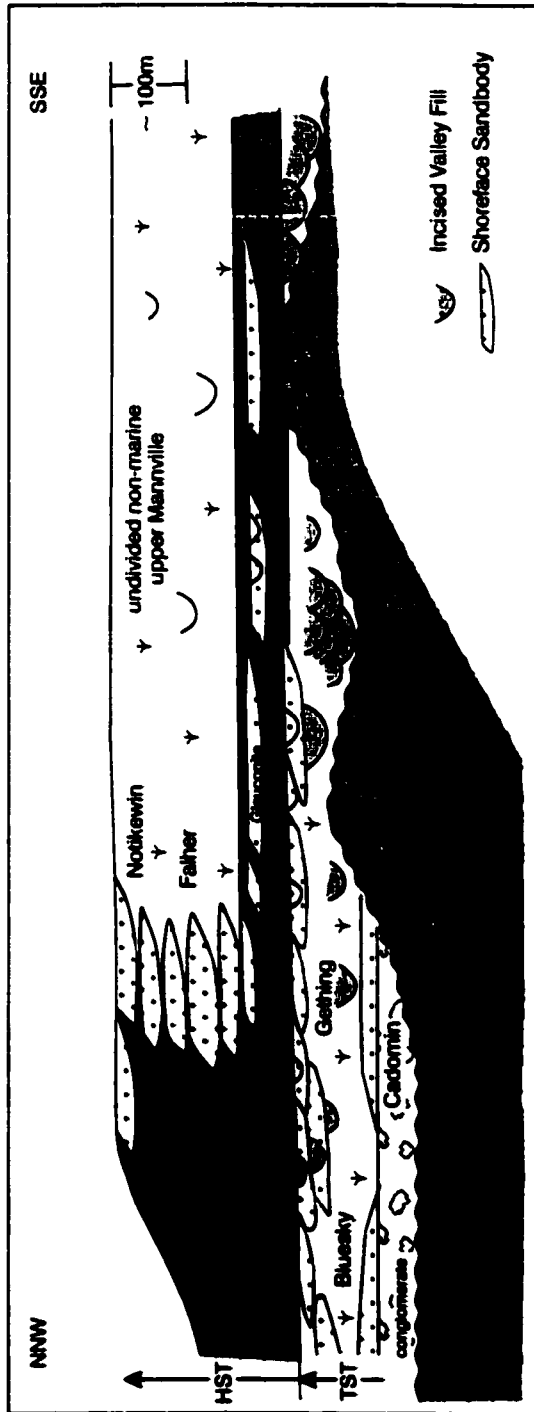


Tertiary. The foreland belt experienced nearly continuous subsidence through the Laramide and Cordilleran orogenies. The foreland basin and similarly its coeval stratigraphy that formed represents a second order sequence of Vail (1977) and is separated from the basin deposits of the Late Jurassic by a 10 – 20 My unconformity produced by uplift and erosion as the basin relaxed between orogenic events (Cant and Abrahamson, 1996). Initial deposition within the foreland basin is represented by non-marine to marine strata of the Mannville Group and its temporal equivalents.

Section 1.6 The Mannville Group (Aptian to Albian)

The Aptian to Albian Mannville Group is a third order sequence that records the initial development of the Cretaceous foreland basin (Cant and Abrahamson, 1996; Vail, 1977). Based on sequence stratigraphic principles the Mannville Group has been subdivided into lower transgressive and upper highstand successions (Figure 1.6) (Jackson, 1984; Hayes et al, 1994; Cant and Abrahamson, 1996). The transgressive succession consists of the non-marine Gething Formation and marine shale and sandstone of the Bluesky Formation. The highstand succession, on the other hand, consists of northwest prograding shoreface and shelf deposits of the Wilrich, Glauconite, Falher and Notikewin formations. The maximum flooding surface (MFS) that separates the transgressive and highstand successions occurs in the lowermost Wilrich Formation in the north and in calcareous sandstone of the Ostracod Formation in the south (Cant and Abrahamson, 1996). The Ostracod Formation has been dated to be Aptian to Earliest Albian (Finger, 1983).

Figure 1.6 Cross section of the Lower Cretaceous Mannville from southern Alberta to northeastern British Columbia. The 3rd order transgressive and highstand systems tracts are indicated. The Bluesky Formation caps the 3rd order transgressive system tract and is overlain by the Maximum Flooding Surface. After Cant and Abrahamson (1996).



Section 1.7 Previous Work

The first reference to the Bluesky Formation was a study of the Lower Cretaceous in Central Alberta by Badgley (1952). He described the stratigraphy of the Bluesky Formation and interpreted it to have been deposited as a number of offshore bars. Furthermore, he suggested that the Bluesky Formation in the Peace River Arch area correlated with the Wabiskaw and Islay members of the Clearwater Formation in central and east-central Alberta. Subsequently, marine sandstone between the continental Gething Formation and the marine shale of the Wilrich Formation in the Peace River region was formally named the "Bluesky Formation" by the Alberta Study Group (1954). The type locality is located at Shell-British America Bluesky No. 1 at 4-29-81-1W6, and occurs between 834.5 and 857 m (2736 and 2810 ft). The Bluesky Formation was described as a relatively porous, glauconitic and pebbly sandstone with minor interbeds of shale (Alberta Study Group, 1954)

A regional study of Lower Cretaceous stratigraphy, integrating previously published outcrop and subsurface data, was completed by Glaister (1959). The study correlated the Bluesky Formation in the Peace River region with the Calcareous Member in Central Alberta and the Glauconitic Sandstone and Islay Member of the Mannville Group in east-central Alberta. Similar to Badgley, Glaister also interpreted the Bluesky Formation to be a series of offshore bars that formed during a major transgression.

Later, Pugh (1960) correlated the Bluesky Formation from Alberta into British Columbia. Correlations were made using drill cuttings, core and well logs. Pugh interpreted that the contact between the Bluesky and Gething formations was erosional to the north of the Peace River Arch. He described the Bluesky Formation as a thin lag,

deposited in a nearshore marine environments during the transgression of the Moosebar Sea (Pugh, 1960).

North of the Peace River Arch correlations by Stott (1975) suggested that the Bluesky Formation thinned irregularly and eventually pinched-out. Where absent marine shale of the lower Wilrich Formation disconformably overlay the strata of the Gething Formation.

In the Peace River Arch area thin coarser-grained lag deposits commonly bound marine shale and shoreface and non-marine fluvial and estuarine deposits. This succession has been described by various authors to represent regressive pulses during an overall transgression of the Moosebar or Boreal sea from the north (Clark, 1978; Jackson, 1984; Smith et al. 1984; O'Connell, 1988; Oppelt, 1989; LeDrew, 1992; Male 1992; Brekke 1995). Deposition and distribution of the Bluesky Formation have been variously attributed to: pre-Bluesky topography and wave and current activity of the Boreal Sea (Clark, 1978); continuous sediment supply during transgression (Smith, 1984); and structural reactivation of older graben systems (O'Connell, 1988).

Recently, Cant and Abrahamson (1996) reviewed the sedimentology and stratigraphy of the Mannville Group. They suggest that the Mannville consists of a number of 4th order sequences, and that the Gething and Bluesky formations of the Lower Mannville Group formed as a result of short term relative sea level fluctuations that were superimposed on a long-term rise of RSL (Cant and Abrahamson, 1996).

Further work by O'Connell (1997) in the Sexsmith area (La Glace field) on the southern flank of the Peace River Arch, interpreted the Bluesky Formation to consist of a number of stacked shoreface successions. Reservoir strata, however, was interpreted to

represent fluvial/estuarine deposits that overlie a lowstand unconformity and in turn are overlain by highstand shoreface deposits (O'Connell, 1997).

Section 1.8 Objectives and Methodology

The primary objective of this study was to decipher the paleoenvironments of sediment deposition based on sedimentological data. The second objective was to develop a sequence stratigraphic framework and depositional model for the Bluesky Formation in the study area. The third objective was to determine the controls that influenced the development of Bluesky stratigraphy and also the distribution of hydrocarbon reservoirs.

Paleoenvironment interpretations are based on observations from 32 cores, which were logged during the summer of 1996 (Figure 1.3). Lithofacies and significant surfaces observed in core were correlated to geophysical logs of approximately 300 wells within the study area. From this data base stratigraphic cross sections and facies distribution and isopach maps were constructed to summarize correlations through the study area.

Section 2.0 Facies Descriptions

Section 2.1 Methodology

The lithofacies described below are based on the detail bed-by-bed sedimentological and ichnological description of 26 cores within the study area (Figure 1.3). An additional 7 cores from the area around the study area were described to supplement the data set (Figure 1.3). Based on grain-size, physical sedimentary structures, and ichnofossil assemblage and abundance, six unique lithofacies were identified. Cross-stratified sets <5 cm thick are considered small-scale, medium-scale sets are 5 - 50 cm thick, and sets >50 cm thick are considered large-scale. Intensity of bioturbation was assessed using the six ichnofacies classes defined by Droser and Bottjer (1986) -- none, low, moderate, high, very high and intense.

Section 2.2 Lithofacies 1: Upward Fining Glauconitic Conglomerate to Sandy Shale

Lithofacies 1 forms thin, areally extensive units across the study area that have a distinctive dark green colour in core. Strata of Lithofacies 1 are generally 0.25-1.0 m thick, but can be as much as 3 m thick. The base is commonly marked by an erosion surface with long (up to 75 cm), vertical, unlined *Skolithos*, *Diplocraterion*, *Arenicolites* burrows (Figure 2.1). These burrows penetrate into the underlying strata and commonly are filled with glauconitic sandstone that is coarser grained than the surrounding strata. Overlying the basal contact is a 5 to 20 cm-thick conglomerate that consists of rounded chert pebbles and rock fragments ranging from 0.5 – 2 cm in diameter with a medium-grained, commonly glauconitic sandstone matrix. Where the conglomerate is absent,

Figure 2.1 Unlined *Skolithos* burrow penetrating lower shoreface sandstone. The burrow has been passively filled with glauconitic sandstone from the overlying unit of Lithofacies 1. Core is approximately 10 cm wide.

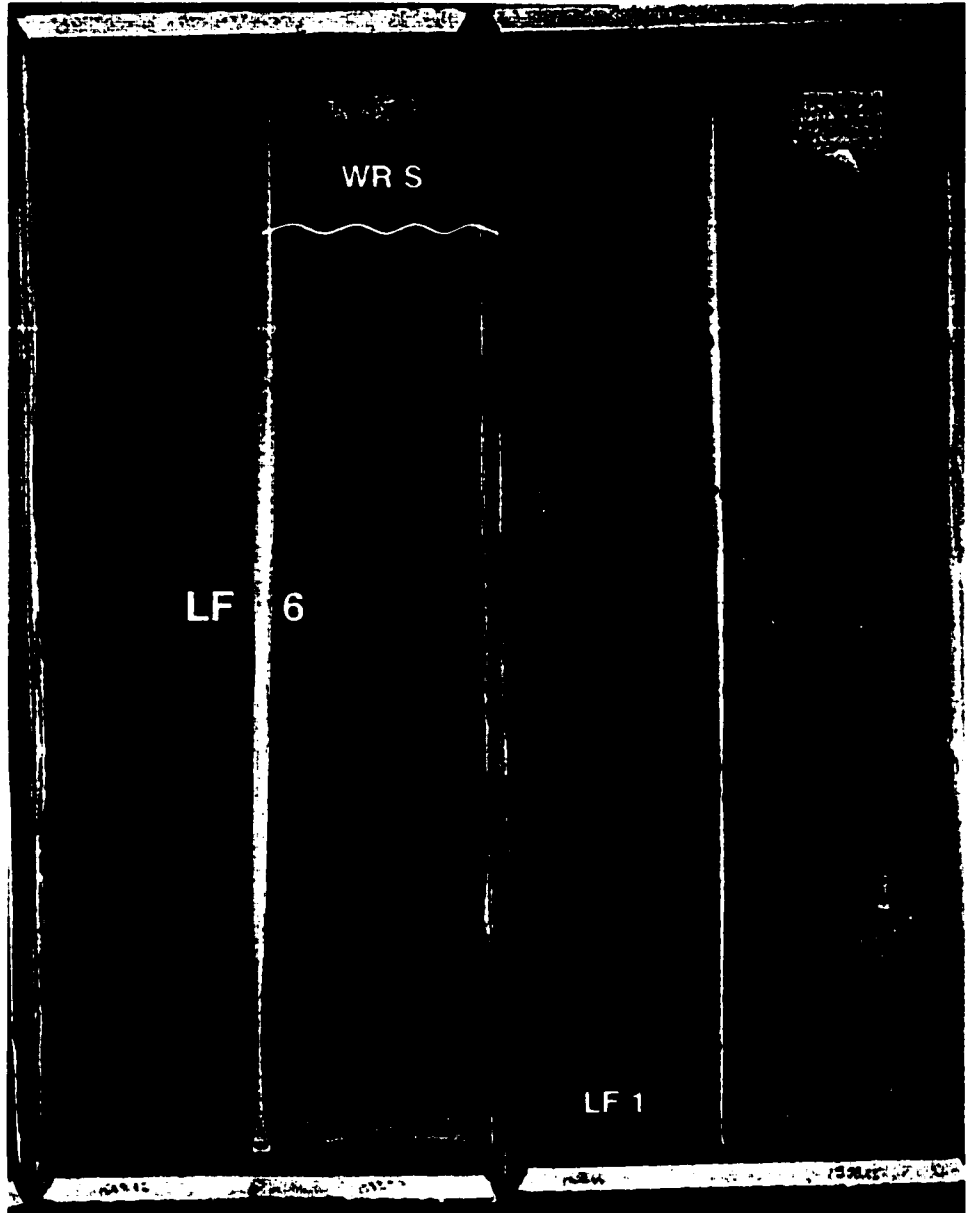


however, the basal contact is overlain by medium-grained, glauconitic sandstone. Because of intense bioturbation (*Teichichnus*, *Planolites*, *Skolithos*, *Rosselia*) primary physical sedimentary structures are generally poorly preserved, although medium-scale cross-stratification is observed locally. Sideritized mud clasts, broken bivalve shells and pyrite blebs are present locally. The basal layer of conglomerate or sandstone is gradationally overlain by dark grey fissile shale with dispersed grains of medium grained sand and glauconite (Figure 2.2).

Section 2.3 Interpretation

In core, because of its distinctive colour and coarse grain size, this lithofacies contrasts markedly the sub- and superjacent strata. The basal contact was burrowed by tracemakers that formed robust, unlined, passively-filled burrows, and therefore, are similar to those that make up the *Glossifungites* ichnofacies (Frey and Pemberton, 1985; Pemberton and Frey, 1985). Commonly these surfaces are interpreted to represent surfaces of erosion that exposed previously-deposited and now semi-lithified sediment in a submarine setting (cf. Vossler and Pemberton 1988; Pemberton and Frey, 1985; Pemberton et al., 1992). Marine conditions are also suggested by the abundance of glauconite, which commonly forms by the maturation of organic matter, typically fecal pellets, under marine conditions (Amorosi, 1995). The basal (erosion) surface of Lithofacies 1, therefore, is interpreted to represent a wave ravinement surface related to rising relative sea level (Swift, 1968; Walker, 1995). Organisms colonized the surface and formed large, unlined, vertical burrows. Sedimentation rates were also most probably low, primarily because

Figure 2.2 Bioturbated glauconitic sandstone of Lithofacies 1 sharply overlying planar laminated sandstone of Lithofacies 6 at 6-10-75-8W6 between 1559.8 – 1557.5 m. Glauconitic sandstone forms a transgressive lag as a result of reworking in the upper shoreface of backbarrier washover sandstones. The contact between the two facies is a wave ravinement surface (WRS).



sediment was being preferentially trapped in marginal-marine sedimentary environments. As a result, the large volume of fecal material being generated locally was able to mature and be transformed into glauconite grains. These grains then became mixed with coarse sediment left behind by the landward-advancing wave-ravinement front, and together formed a thin, areally-extensive lag deposit. In turn, these strata are overlain by dispersed sandy shale, suggesting even lower sedimentation rates in a more distal shelf setting (as a result of the ongoing transgression).

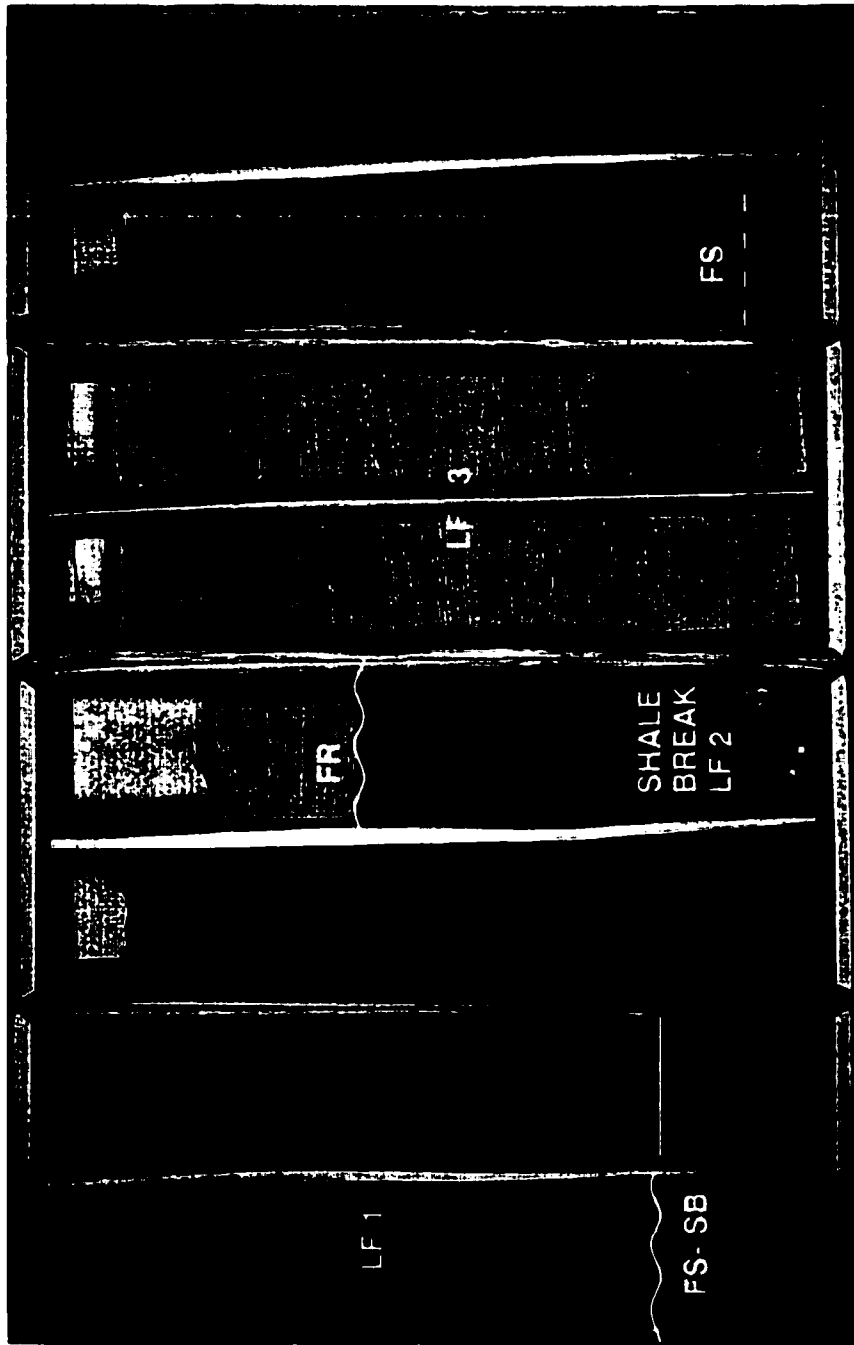
Section 2.4 Lithofacies 2: Shale

This lithofacies can be subdivided into three subfacies. All three subfacies are present in the Bluesky Formation, however, only Subfacies 2a and 2b were observed in the Wilrich Formation. Subfacies are differentiated from one another based on the intensity and type of bioturbation, microfossil assemblage and geophysical log character.

Subfacies 2a: Black Shale

In core these strata overlie glauconitic sandstone of Lithofacies 1. The contact is gradational over 20- 50 cm and is marked by a change to dark grey fissile shale with little to no silt or sand grains. In turn, Subfacies 2a is overlain sharply by Subfacies 2b or Lithofacies 3 (Figure 2.3). It is present throughout the study area at the base of the Wilrich Formation and within the Bluesky Formation forms an areally extensive marker unit informally termed the Shale Break (Sh Brk). The Shale Break is present throughout the southern half of the study area and ranges from less than 1 metre to greater than 3 metres thick (reconnaissance work suggests that it extends east- and westward of the

Figure 2.3 Lithofacies 2a (the Shale Break) gradationally overlying glauconitic sandstone of Lithofacies 1 at 6-10-75-8W6 between 1567.6 – 1563.0 m. Lithofacies 2a shale is intensely bioturbated, however, the lack of silt and sand coupled with the small size of traces makes observation of traces difficult. Sharp based Lithofacies 3 sandstone overlying the shale break is dominated by low angle cross-stratification interpreted to be hummocky cross-stratification. The sharp contact with underlying distal marine shale represents a fall of relative sea level and is interpreted to be a forced regression.



study area) (Figure 2.4).

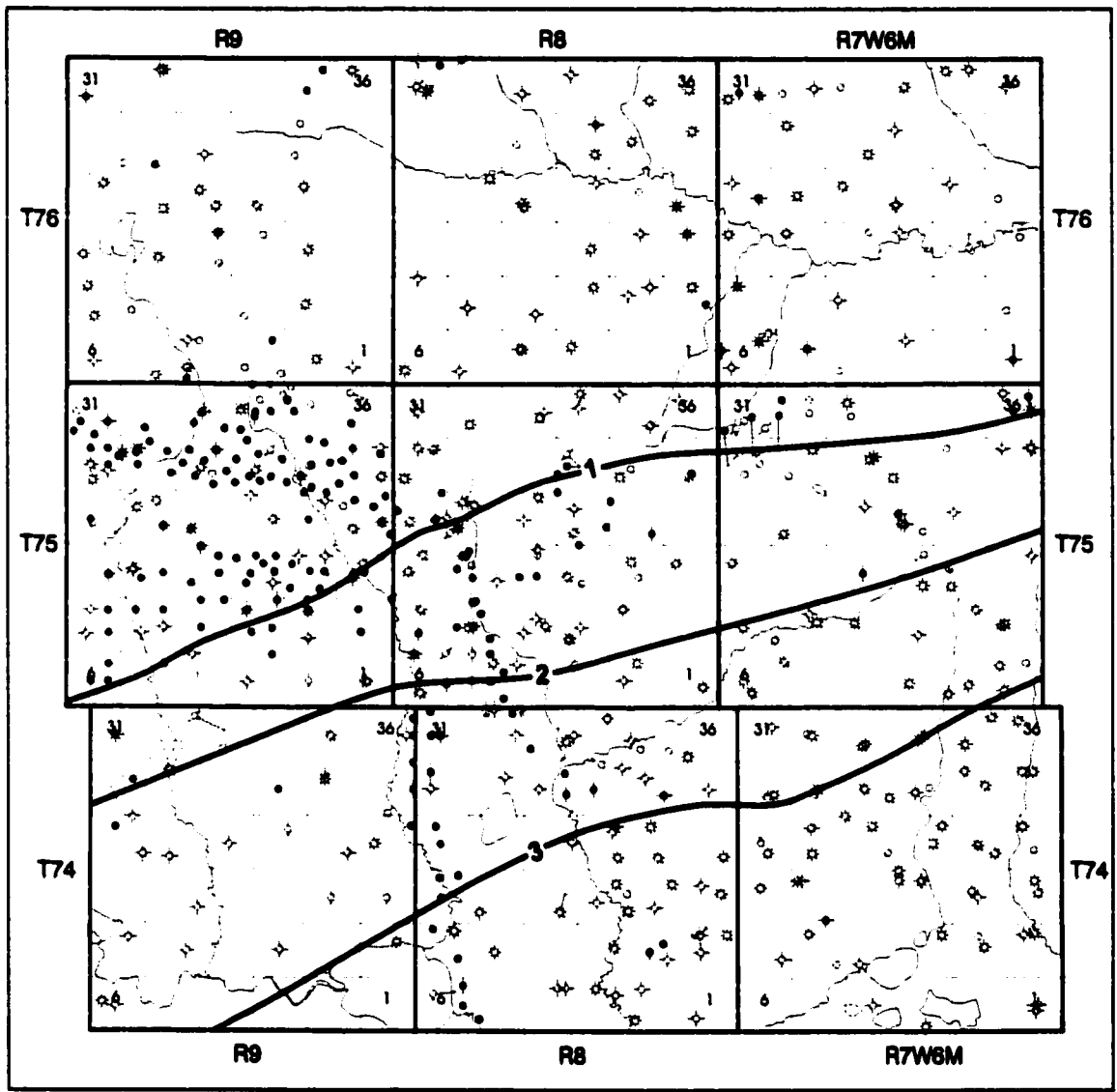
This facies is characterized by rare to no silt or sand grains and a massive to fissile texture. Because of the paucity of a contrasting grain size, bioturbation is difficult to detect in core, but upon detailed inspection is in fact moderate to intense and consists of *Helminthopsis* and small (<1-2 mm) *Planolites* and *Chondrites* burrows. Pyrite is common and occurs as small, dispersed millimeter-size blebs and infills of *Chondrites* and *Planolites* burrows (Figure 2.2). A single bivalve macrofossil was collected and identified to be *Tellina* Sp. (Chris Collum, personal communication 1997). In addition, samples from the Shale Break indicate a micropaleontological assemblage composed of abundant foraminifera tests, primarily from benthic agglutinated forms but also rare calcareous forms (Charles Henderson, personal communication 1997).

In the basal part of the Wilrich Formation, shale of Subfacies 2a contains thin (2-5 cm) beds of waxy bentonite and siderite-cemented layers up to 20 cm thick.

Subfacies 2b: Intensely Bioturbated Shale

This subfacies is present throughout the Bluesky Formation, particularly in the northwestern part of the study area. Generally it sharply overlies strata of Subfacies 2a, and is differentiated from the underlying shale by higher sand content and a more diverse trace fossil assemblage. In addition, it has been observed to overlie deposits of Lithofacies 1. It is commonly interstratified with and overlain by Lithofacies 3 (see below). Stratal thickness is highly variable and ranges from decimetres to a few metres thick. Dispersed fine to very fine sand grains and thin (10-50 cm) sandstone beds are common. Bioturbation ranges from moderate to intense and includes *Chondrites*, *Skolithos*,

Figure 2.4 Distribution of the Shale Break (Lithofacies 2a) within the study area, isopach contour interval is 1 m. The Shale Break is nearly 4 m thick in the southern part of the study area and thins to the north where it has been completely removed by subsequent submarine erosion.



Well Legend

○ Location	● Oil	☆ Gas
◊ Suspended	◆ Abandoned Oil	✱ Abandoned Gas
◇ Abandoned	◐ Suspended Oil	✱ Suspended Gas
		✱ Oil Prev Gas

Planolites, *Helminthopsis*, *Thalassinoides*, *Palaeophycus*, *Rosselia*, *Cylindrichnus* and *Zoophycos* burrows (Figure 2.5 and 2.6). Micropaleontological analyses yielded only a small number of foraminifera tests that were identified to be from a low diversity agglutinated faunal assemblage (Charles Henderson, personal communication 1997).

Convolute stratification of silty shale and very fine sandstone and silty fining upward beds 5-25 cm are present locally. In addition to a high silt content, strata typically also contain abundant fine carbonaceous material and rare coaly debris. Associated bioturbation is less intense ranging from rare to moderate, but contains a less diverse but similar assemblage to that described above.

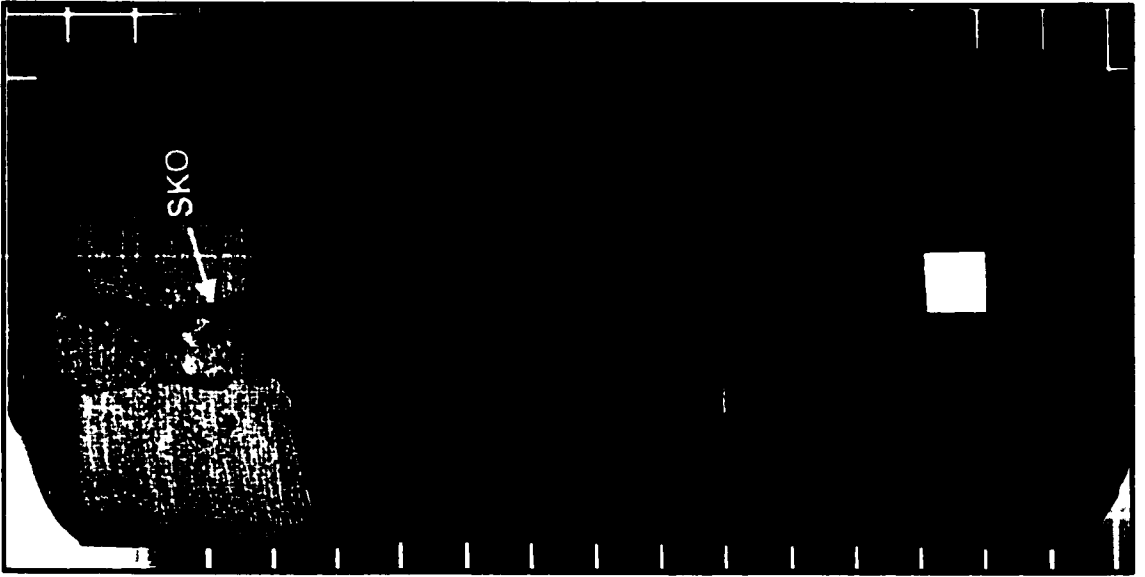
Subfacies 2c: Organic Rich Massive Shale

This subfacies is present only locally, and ranges from decimetres to 2 metres thick. It overlies strata of Lithofacies 5 or Lithofacies 3, and in turn is overlain by glauconitic sandstone of Lithofacies 1 or sandstone of Lithofacies 6 (Figure 2.7). Grain size and stratification is much more variable than Sub-facies 2a and 2b, with shale being massive to finely interstratified with silt, sandstone and occasionally coal laminae. Strata range from irregular laminae to massive or zones up to 10 cm thick of brecciated mudstone. Pyrite is present as small millimetre sized blebs.

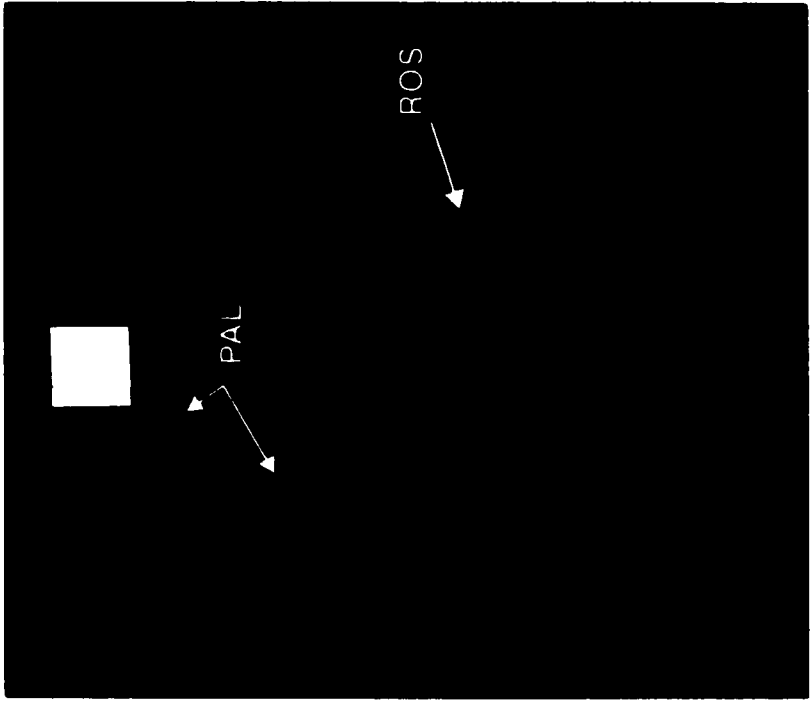
Bioturbation is rare with only very small *Planolites* and *Skolithos* burrows. Micropaleontological samples were mostly barren of foram tests, although rare agglutinated tests and one planispiral foram test were recovered (Charles Henderson, personal communication 1997).

Figure 2.5 Shoaling upward successions separated by fluvial sandstone and transgressive lag from 02/14-7-75-8W6 between 1584.2 – 1573.0 m. In the lower succession (Sequence 1) lower shoreface hummocky cross-stratified sandstone (Lithofacies 3) grades into upper shoreface medium scale cross-stratified and bioturbated (*Macaronichnus*) sandstone (Lithofacies 4) which is capped by a thin coal and rooted horizon (arrow). A sequence boundary is present at the base of fluvial sandstone (Lithofacies 5) overlying the coal horizon. A wave ravinement surface and transgressive lag of glauconitic sandstone (Lithofacies 1) separates underlying fluvial sandstone from distal marine shale (Lithofacies 2a) of the Shale Break. Sharply overlying the Shale Break is a coarsening upward succession of interstratified Lithofacies 2b and Lithofacies 3. This succession was deposited in the lower shoreface following a fall of relative sea level, the contact is therefore a forced regression (see also Figure 2.3).

Figure 2.6 Core photos of bioturbation in interstratified lower shoreface sandstone and shale of lithofacies 2b and 3. A) Stacked *Rosselia* (ROS) with small *Chondrites* around base, *Paleophycus* (PAL) B) Large lined Skolithos (SKO) and numerous small burrows including *Planolites*, *Cylindrichnus* and *Helminthopsis*. Scale bars are in centimetres.



B



A

Figure 2.7 Transgressive barrier succession overlying lower shoreface sandstone from 6-27-74-7W6 between 1587.3 – 1594.5 m. Lower shoreface hummocky cross-stratified sandstone (Lithofacies 3) is overlain by lagoonal shale (Lithofacies 2c) and tidal inlet sandstone (Lithofacies 6). The contact is a flooding surface-sequence boundary (F.S.-S.B.). Lagoonal shale was deposited behind an older barrier complex, the contact with overlying tidal inlet sandstone is a tidal ravinement surface. Tidal inlet sandstone is dominated by medium-scale cross-stratification, which upwards becomes intensely bioturbated by *Macaronichnus*.

FS - SB

LF 3

LF 6

LF 6

MAC

LF 6

Section 2.5 Interpretation

Massive to faintly-laminated shale of Lithofacies 2 is interpreted to have been deposited from suspension in a low-energy environment. The expansive distribution of subfacies 2a and 2b, and also their common association with Lithofacies 1, suggests that these strata accumulated beneath storm-weather wave base on a wide shelf. Based on biological data, in particular trace fossils associated with the *Zoophycos* Ichnofacies (cf. Ekdale et al. 1984) and a diverse foraminiferal assemblage, strata of Subfacies 2a were most probably deposited in a distal shelf setting (Pemberton et al., 1992a). The common occurrence of pyrite in these strata suggests the early diagenetic alteration of organic material under reducing conditions, which in turn may indicate dysaerobic to anaerobic conditions in the water near the seabed. Furthermore, abundant bentonite layers in shale of the Wilrich Formation suggests contemporaneous volcanism and suspension fallout of volcanic ash. In contrast to Subfacies 2a, Subfacies 2b strata are burrowed by forms of the *Cruziana* Ichnofacies (e.g. Ekdale et al. 1984), contain abundant dispersed sand and silt grains, and locally are interstratified with sandstone of Lithofacies 3. These features suggest deposition in a proximal shelf to distal lower shoreface setting. During fairweather mud accumulated from suspension, whereas silt and sand were deposited in layers during storms. Subsequently, however, extensive bioturbation by infaunal tracemakers caused the layers to be destroyed and the sand and silt sediment to become dispersed throughout the mud.

In Subfacies 2b local convoluted silty shale was likely the result of post depositional dewatering of strata, whereas associated thin upward-fining beds suggest deposition from small turbidity currents. Both features are common in prodelta settings

where high sedimentation rates, related to a proximal fluvial sediment source typically results in unstable, rapidly aggrading strata (Bhattacharya and Walker, 1992). The decreased abundance and diversity of burrows, suggests an ecological stress. This may be related to increased water turbidity and varying salinity (Moslow and Pemberton, 1988; Bhattacharya and Walker, 1992), which may be indicative of a local fluvial system.

Like subfacies 2a and 2b, Subfacies 2c was also deposited under low energy conditions, but in this case in a low-energy back-barrier lagoon. The paucity of trace fossils and foraminifera indicates stressed ecological conditions, which is consistent with a back-barrier lagoon. Moreover, these strata are overlain by transgressive lag deposits of Lithofacies 1 or tidal channel-fill deposits of Lithofacies 6 (see below), which indicate the landward migration of a barrier-bar complex and shoreface over older lagoonal deposits (Swift, 1968; Sanders and Kumar, 1975a). Interbeds of sandstone and siltstone sediment most probably represent deposition of coarse-grained sediment washed over the barrier and deposited in the lagoon during storms. Carbonaceous-rich sediment, on the other hand, was sourced locally from marshes that fringed the lagoon (Caldwell, 1971; Sanders and Kumar, 1975a).

Section 2.6 Lithofacies 3: Upper Very Fine Grained, Low-Angle Cross-Stratified

Sandstone

Strata of Lithofacies 3 are common in the study area and consist of light grey, upper very fine to upper fine sandstone. Stratigraphically-upward units typically coarsen. Concomitantly, interbeds of Subfacies 2b (15-100 cm thick), which are common in the lower part of a unit, become thinner and less abundant upward. Physical sedimentary

structures are dominated by low-angle cross-stratification with numerous low-angle truncation surfaces (Figure 2.3, 2.4). Trace fossils, although not abundant consist of *Skolithos* burrows and escape traces. Locally, however, intensely bioturbated, 5-20 cm thick zones that are dominated by *Paleophycus* burrows are present (Figure 2.8). Rare single bivalve shells have been observed and are identified as *Tellina* (Chris Collum, personal communication 1997). In addition, in township 74-7W6, thin layers of bivalve shells occur within a few meters of the lower contact (Figure 2.9). Shells include *Lima*, *Yoldia* and *Cardiid* bivalves (Chris Collum, personal communication 1997). Calcite cement is typically pervasive.

Lithofacies 3 strata overlie and in turn are overlain by several different lithofacies. In places these strata gradationally overlie and/or are interstratified with strata of Subfacies 2b (e.g. 14-7-75-8W6) (Figure 2.5), or abruptly overlie Subfacies 2a (e.g. 6-10-75-8W6, 6-6-75-7W6, 11-23-75-7W6) (Figure 2.3) or sharply overlie carbonaceous mudstone and coal of Lithofacies 7 (see below; 6-10-75-8W6). Similarly, the upper contact of Lithofacies 3 is highly variable. In places it is conformably overlain by Lithofacies 4 (see next), or is erosionally overlain by deposits of Lithofacies 1, 5 or 7 (see below).

Section 2.7 Interpretation

Upward-coarsening strata of Lithofacies 3 are interpreted to have been deposited on the lower shoreface of a prograding storm-dominated marine shoreline. In this part of the shoreface wave-orbital motion has been little altered from that in deep water and as a

Figure 2.8 Core photo of intense bioturbation by *Paleophycus* in lower shoreface sandstone of Lithofacies 3. Scale bar is in centimetres.

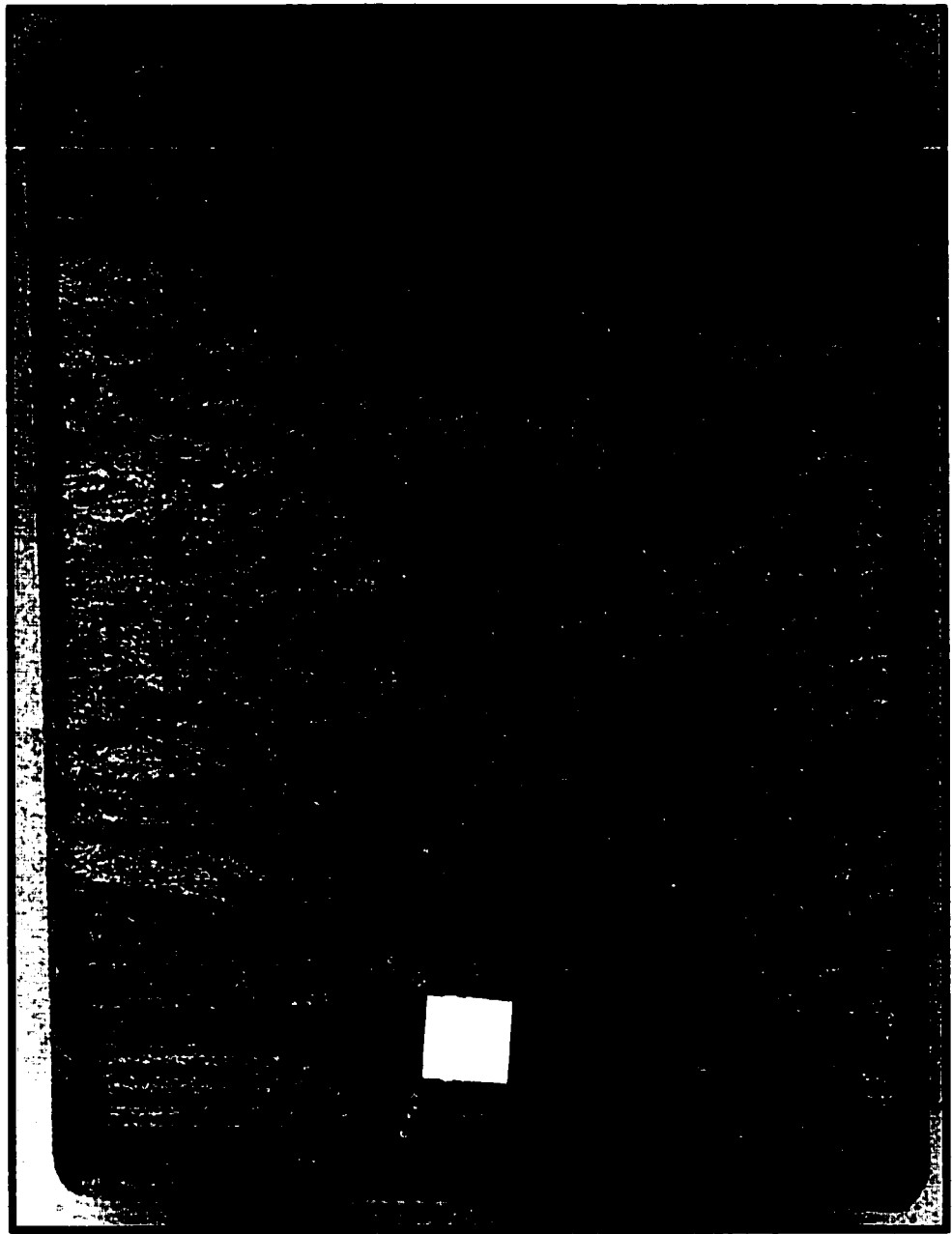
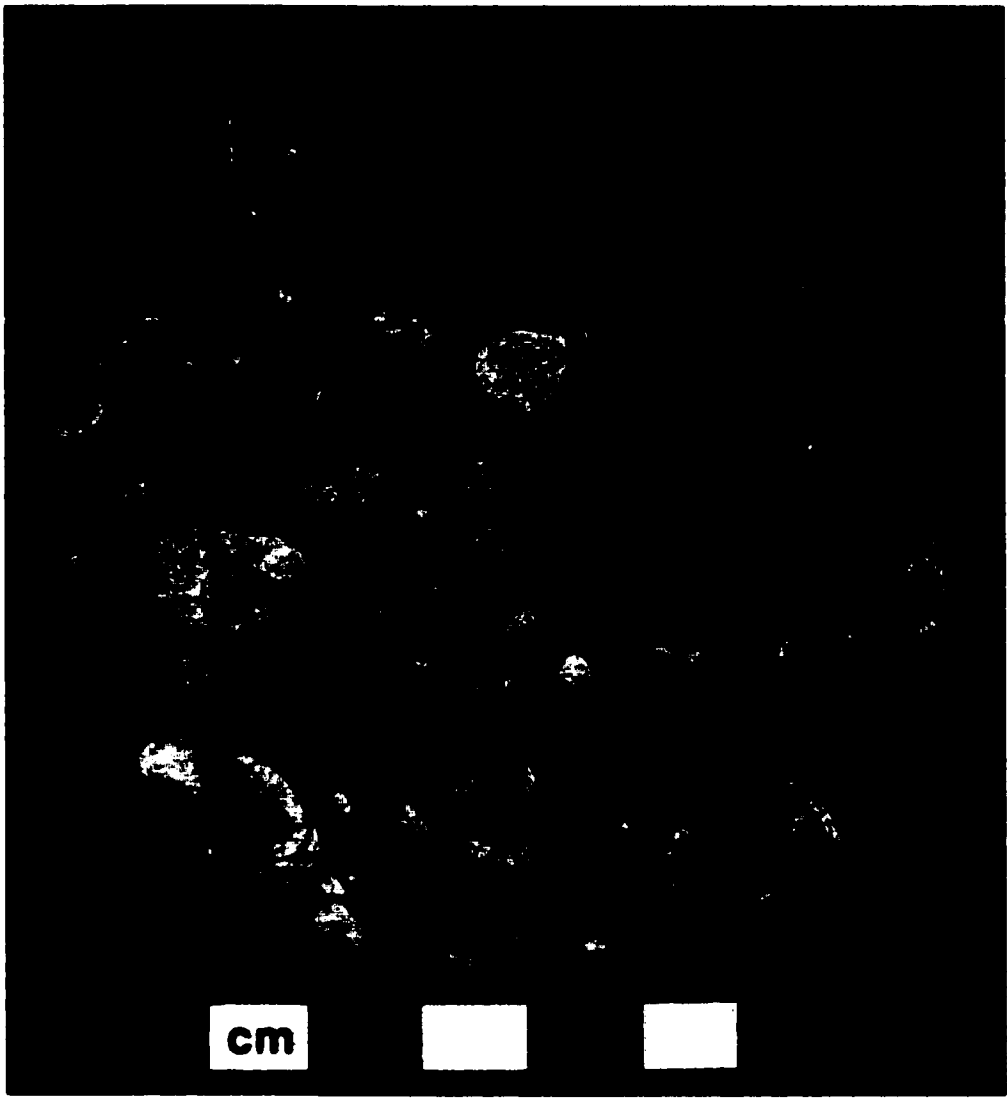


Figure 2.9 Plane view of bivalve shell layer in lower shoreface sandstone (Lithofacies 3) from 6-34-74-7W6 at 1625.0 m. Shells identified include *Lima*, *Yoldia* and *Cadiid* bivalves (Chris Collum, personal communication 1997). Coarse divisions on the scale are centimetres.



result bed-load sediment transport shows little asymmetry. During storms, therefore, high-energy, long-period storm waves generated large oscillatory bed forms that built preferentially upward and with little lateral migration (cf. Southard et al. 1990; Arnott and Southard 1990). These bed forms are interpreted to have formed the low-angle cross-stratification, interpreted to be hummocky cross-stratification, which is characteristic of Lithofacies 3. Biogenic structures are also consistent with a lower shoreface interpretation. The abundance of escape traces indicates episodes of high sedimentation and the rapid up-building of the sea bed, again most probably related to storm deposition on the lower shoreface (Pemberton et al., 1992a). *Skolithos* burrows, on the other hand, probably indicate the colonization of the sea bed by opportunistic tracemakers following storm-sand deposition (Frey and Pemberton 1985). Furthermore, the common occurrence of intensely bioturbated zones dominated by *Palaeophycus* burrows has been observed in other shoreface successions, particularly in the lower shoreface near the upper-shoreface transition (Brekke 1995; Arnott, 1993; MacEachern and Pemberton, 1982).

Section 2.8 Lithofacies 4: Upward-Coarsening, Fine to Medium Cross-Stratified to Intensely Bioturbated Sandstone

Strata of Lithofacies 4 gradationally overlie Lithofacies 3 strata and in turn are overlain by lithofacies 1 or 5 strata. Because of erosion by younger units (see below) the thickness of these strata varies, ranging from 1- 5 metres thick. Generally, Lithofacies 4 consists of well-sorted, upper fine to lower medium sandstone. The principal physical sedimentary structure is medium-scale cross-stratification. Small *Planolites*, *Skolithos*, and escape traces are common. Stratigraphically-upwards these strata are commonly

overlain by massive, intensely bioturbated sandstone dominated by *Macaronichnus* burrows or small meiofauna burrows (Figure 2.5). A rooted horizon and a thin coal (10-15 cm), and/or carbonaceous mudstone commonly caps the succession (Figure 2.5).

Section 2.9 Interpretation

Strata of Lithofacies 4 are interpreted to be upper shoreface overlain gradationally by foreshore deposits that were deposited on a prograding storm-dominated shoreline. Medium-scale cross-stratified sandstone was most probably deposited by subaqueous dunes that migrated in the upper shoreface (cf. Clifton et al., 1971). Bioturbation by *Macaronichnus* is associated with infaunal burrowing in intertidal to shallow subtidal sand (Clifton and Thompson, 1978). Therefore the intensely bioturbated (*Macaronichnus*) unit most likely represents deposition in the high-energy foreshore. The thin cap of carbonaceous mudstone and/or coal most probably represent vegetated backbeach deposits, and, therefore, form a conformable cap over the prograding nearshore succession.

Section 2.10 Lithofacies 5: Upward Fining Carbonaceous Coarse to Fine Sandstone

Lithofacies 5 occurs in both the Gething and Bluesky formations. It forms linear units that are 5–15 meter thick, up to 3 km wide and can be traced longitudinally for 10–30 km. In the Gething Formation these strata have been interpreted from geophysical logs and occur near the contact with the overlying Bluesky Formation (lithofacies 2b or 3). In the Bluesky Formation, strata of Lithofacies 5 sharply overlie lithofacies 3 or 7, and most commonly are sharply overlain by lithofacies 2b, 3 or 4. Strata are lithologically variable,

with beds ranging from decimeters to metres in thickness, and grain size ranging from coarse to upper-fine grained sandstone. Beds stack and form units 5-15 m thick that show an overall upward-fining trend. Thin centimetre-thick coal, and carbonaceous mudstone flasers occur locally but become thicker and more abundant in the upper part of an upward-fining succession. Fine organic debris is typically dispersed throughout the sandstone, but also is concentrated along laminae and bed boundaries. In addition, small chert pebbles and rounded to angular mud and coal rip-up clasts are dispersed within the sandstone beds or occur as thin 1–5 cm layers at the base of the bed. Physical sedimentary structures include medium and small-scale cross-stratification (Figure 2.5). Bioturbation is rare but locally is moderate within mudstone flasers and consists of small *Palaeophycus* and *Skolithos* burrows.

Section 2.11 Interpretation

Strata of Lithofacies 5 represent deposition in a braided fluvial system. Medium-scale cross stratification was formed by downstream-migrating subaqueous dunes (Cant and Walker, 1978). The upward fining of individual beds indicates the filling of discrete shallow, braided-fluvial channels (Miall, 1992). The paucity of overbank deposits suggests a fluvial system dominated by lateral accretion and limited aggradation. Recently it has been shown that braided-fluvial systems form preferentially under conditions of low accommodation (cf. Olsen et al, 1995). Here, because of the low rate of sedimentation (i.e. slow aggradation) rates of channel avulsion are similarly low (Heller and Paola, 1996). Consequently, fluvial channels show extensive lateral migration and as a result overbank deposits are eroded and therefore are only poorly preserved. Eroded

overbank deposits are most probably the source for angular mud and coal ripup clasts, thin coal flasers and dispersed carbonaceous debris that are common in Lithofacies 5 strata. Bioturbation within thin mudstone flasers suggests low flow conditions that allowed deposition from suspension and an upstream incursion of marine influence (Reinson, 1992).

Section 2.12 Lithofacies 6: Blocky Fine or Medium Sandstone

Lithofacies 6 has been observed in core in township 74-7W6 and 76-8W6. Here it occurs as a number of east-northeast-trending units that are 1-10 m thick and approximately 4–5 km wide. These strata abruptly overlie deposits of Subfacies 2c or Lithofacies 3 or 7, and in turn are gradationally overlain by strata of Lithofacies 3, or less commonly, abruptly by Lithofacies 1 (Figure 2.7, 2.10). The basal contact is commonly marked by abundant small angular mudstone or coal ripup clasts. Strata of Lithofacies 6 consists primarily of lower fine to medium sandstone. Pebbles and coarse sandstone, however, are present locally, and occur dispersed in finer-grained sandstone, concentrated along bed boundaries or rarely as beds of clast-supported conglomerate up to 15 cm thick. Interbeds of mudstone (Lithofacies 2c) up to 10 cm thick are uncommon. Physical sedimentary structures are dominated by medium-scale cross stratification, although small-scale asymmetrical cross-stratification and horizontal to gently dipping ($<20^\circ$) planar laminations are present locally. Bioturbation is generally rare. In the upper part, however, 50-200 cm-thick units that are moderately to intensely bioturbated by *Macaronichmus* burrows occur (Figure 2.7, 2.11). Locally, a rooted horizon and thin coal caps Lithofacies 6.

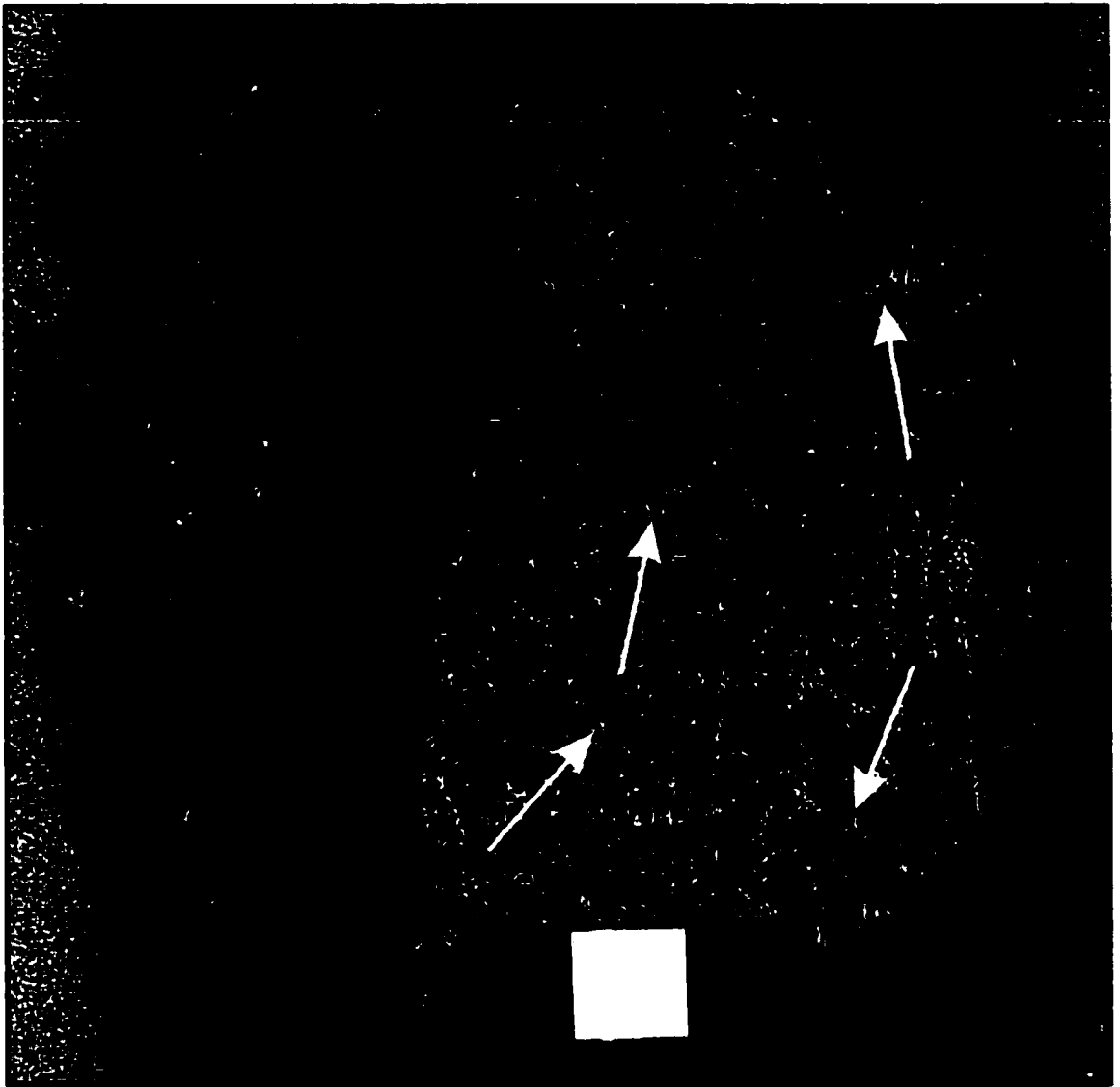
Figure 2.10 Coastal plain deposits of the Gething Formation overlain by marine deposits of the Bluesky Formation from 9-22-76-8W6 between 1467.5 – 1458.0 m. Coal and coaly very-fine grained sandstone (Lithofacies 7) is sharply overlain by tidal inlet sandstone (Lithofacies 6). The contact is a tidal ravinement surface and amalgamated flooding surface-sequence boundary (F.S.-S.B.). A wave ravinement surface separates tidal inlet sandstone from overlying lower shoreface shale and sandstone (Lithofacies 2b and 3).

Section 2.13 Interpretation

Strata of Lithofacies 6 represent barrier island complexes. A barrier complex separates marine shoreface from the backbarrier lagoon and may or may not be attached to the main shoreline (Reinson, 1992). Laterally migrating tidal-inlet channels erode previously deposited barrier deposits, forming a basal erosion surface that commonly is marked by a lag of pebbles and mud and coal clasts. Subaqueous dunes migrating under the influence of reversing tidal currents formed medium scale cross-stratification (Kumar and Sanders, 1974; Reinson, 1992). Sediment supplied by longshore drift causes the channel to fill and at the same time migrate laterally along the island (Reinson, 1992). Intense bioturbation in the upper portion of this lithofacies by *Macaronichnus* suggest the shallow high energy zone at the top of an inlet fill. Locally, the cap of coal or a rooted horizon indicates the stabilized and vegetated top of the barrier (Reinson, 1992).

Conglomerate beds represent deposition on the flood-tidal delta on the landward side of the barrier complex. Pebbles are transported through the tidal inlet and deposited on the flood-tidal delta. Ebb tidal currents, however, are too weak to erode and transport the pebbles back into the tidal inlet (Reinson, 1992). Horizontal to gently dipping planar laminated sandstone is interpreted to be upper-flow-regime plane bed formed likely as storm-generated shallow sheet flows that overtopped the barrier complex (Reinson, 1992).

Figure 2.11 Birds eye view of *Macaronichnus* burrows in Lithofacies 6 sandstone. Burrows are commonly faint and identified by a differentiation of light and dark coloured grains. Scale bar is in centimetres.



Section 2.14 Lithofacies 7: Carbonaceous Very-Fine Sandstone, Mudstone, and Coal

Fine-grained carbonaceous deposits of Lithofacies 7 are the principal lithofacies of the Gething Formation and are sharply overlain throughout the study area by lithofacies of the Bluesky Formation. Lithofacies 7 strata can be subdivided into two sub-facies: upward-fining sandstone, and carbonaceous mudstone to coal.

Subfacies 7a Carbonaceous Very-Fine Sandstone

Sandstone beds are sharp-based, 50-200 cm thick, and grade commonly upward to carbonaceous mudstone or coal. Beds stack and form units 1-5 m thick. Sand-sized sediment is poorly sorted (high silt content) and ranges from very fine to fine sandstone. Fine organic debris is commonly dispersed in the sandstone or is concentrated into laminae. Coal and mud rip-up clasts are common. Physical sedimentary structures are dominated by small-scale asymmetrical cross-stratification, which commonly has been plastically deformed (Figure 2.10).

Subfacies 7b Mudstone, and Coal

Carbonaceous mudstone and coal are typically interstratified and form beds 1-150 cm thick. These units gradationally overlie beds of upward-fining sandstone or abruptly overlie strata of Lithofacies 4. Small rootlets are common and extend downward into the underlying strata. Physical sedimentary structures are rare except for soft-sediment deformation structures and small syneresis cracks. Bioturbation by small *Planolites*, and *Gyrolithes* burrows is present locally. In addition, siderite and pyrite nodules occur locally.

Section 2.15 Interpretation

The fine grain size, high silt content and predominance of small-scale asymmetrical cross stratification of this lithofacies are consistent with deposition in a low energy environment characterized by unidirectional flow (Miall, 1992). Decimetre- to metre-thick fining-upward sandstone beds are characteristic deposits of meandering channels, and represents the lateral accretion of a meandering-fluvial point bar (Miall, 1992).

Carbonaceous mudstone and coal form in low energy terrestrial environments termed mires by the accumulation of organic matter and clay deposition (Diessel, 1992; Bohacs and Suter, 1997). Organic matter or peat production is controlled directly by climate and will accumulate up to the paleoground water table, which in these environments is the depositional base level (Bohacs and Suter, 1997). The accumulation and preservation of coal and carbonaceous mudstone is controlled by the ratio of the rate of peat production to the rate of accommodation space. Peat accumulation, and therefore the formation of coal, are highest when the rate of peat production roughly equals the accommodation rate (Bohacs and Suter, 1997). Carbonaceous mudstone are most likely preserved when the accommodation rate is greater than the peat production rate and the mire is drowned or the peat becomes diluted with mineral matter (Bohacs and Suter, 1997).

Synaeresis cracks are a form of shrinkage crack in mudstone beds that form subaqueously (Plummer and Gostin, 1981). Synaeresis form as a result of volumetric reduction because water is removed from the clay mineral, typically the result of fluctuation in the salinity of the depositing medium (Plummer and Gostin, 1981). Salinity

fluctuations such as these are common in tidally-influenced coastal plain environments. Moreover, small *Planolites* and *Gyrothites* burrows are common in tidally-influenced coastal plain where salinity variations present an ecological stress on the endemic biota (Pemberton et al., 1992a):

Section 3.0 Stratigraphy and Depositional Model

Section 3.1 Introduction

The Bluesky Formation records the change from coastal plain deposits of the Gething Formation through nearshore and shoreface environments to distal marine environment of the Wilrich Formation. Within the study area, the Bluesky Formation has been subdivided into three depositional sequences, they have been informally named Sequence 1 - Sequence 3. Each sequence consists of fluvial, and/or nearshore strata deposited during a rise of relative sea level (transgression) overlain by shoaling-upward marine successions (parasequences) deposited during local stillstands or the highstand of relative sea level (regression). These changes are the result of high order fluctuations of relative sea level that were superimposed on a longer-term episode of rising relative sea level. Changes in relative sea level in the study area are likely controlled by basin wide changes in sea level, local sediment supply and tectonic subsidence.

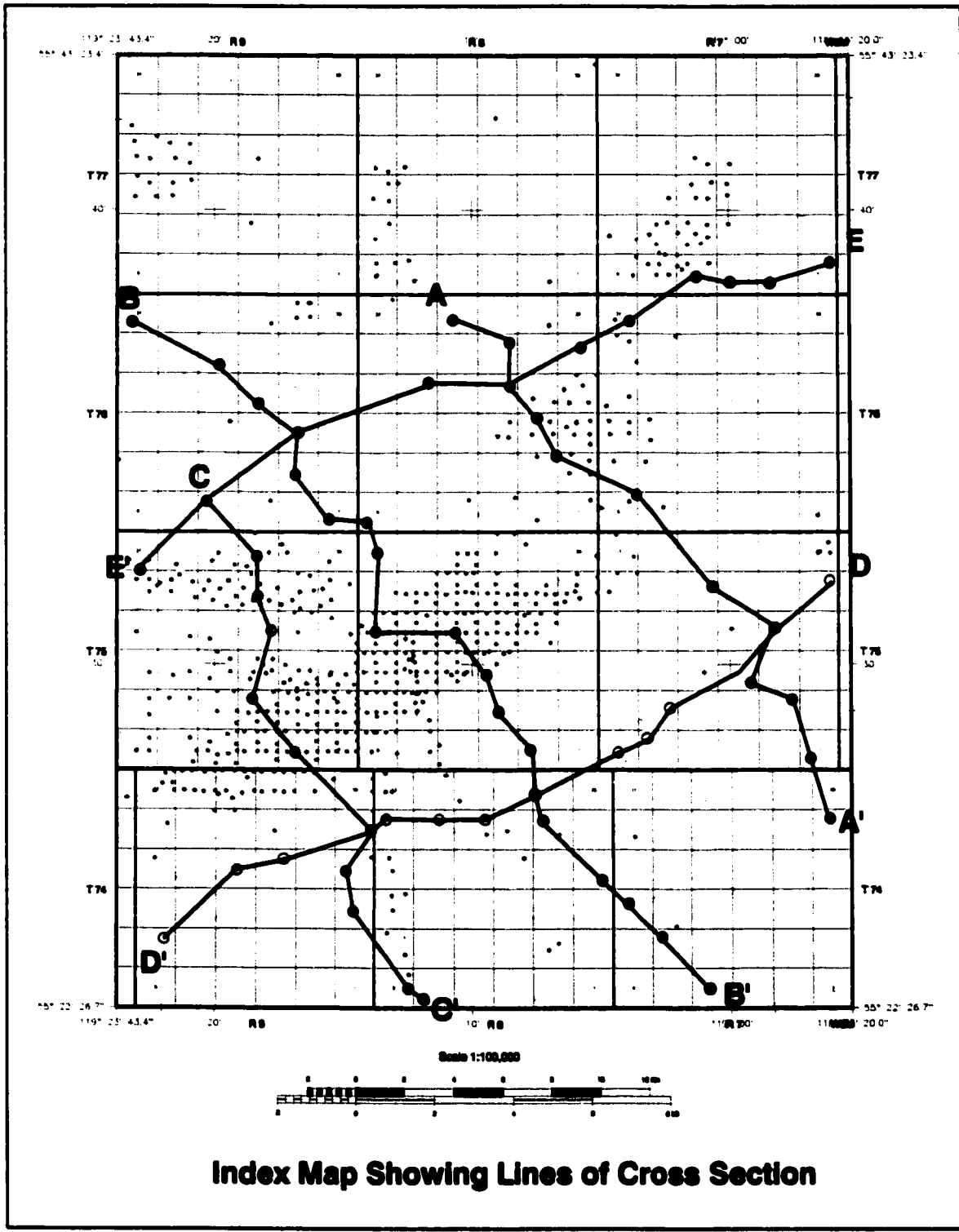
Section 3.2 Regionally Correlatable Surfaces

Four transgressive wave ravinement surfaces each associated with a rise of relative sea level, have been identified (WRS1 - WRS4; Figures 3.1 and 3.2).

Wave ravinement surfaces 1 and 2 are marked by a sharp contact between marginal marine strata and shoreface deposits. These surfaces are typically marked by only a thin lag of coarse sand dispersed in shale or coal and mudstone rip-up clasts in shoreface sandstone. Wave ravinement surface 3, however, is marked by a transgressive lag of glauconitic sandstone (Lithofacies 1). This surface is present throughout the study area and has been correlated to the transgressive surface identified by Brekke (1995)

Figure 3.1 Location of cross sections used in this study.

Figure 3.2 . back pocket Gamma ray curve cross sections (three foldouts). All cross sections use WRS3, a regional wave ravinement surface correlated throughout the study area, as a datum. A-A' to C-C' are northwest-southeast trending dip sections, D-D' and E-E' are northeast-southwest trending strike sections, see Figure 3.1 for location of cross sections. SB – Sequence Boundary; WRS – Wave Ravinement Surface; fs – Flooding Surface. Black vertical bars indicate cored intervals.



Index Map Showing Lines of Cross Section

to mark the base of the Bluesky Formation. This suggests that this transgressive surface represents a major transgression, and therefore, should be a useful surface for regional correlations. A transgressive lag of glauconitic sandstone at the top of the Bluesky Formation marks wave ravinement surface 4. This surface, like WRS3, is regionally correlatable and also is likely a useful marker.

In this study, wave ravinement surface 3 has been used as the datum on all stratigraphic cross sections (Figure 3.2). It is important to note that the most obvious stratigraphic datum is the surface that separates the Bluesky and overlying Wilrich formations. However, although this surface also represents a major flooding surface, the variable thickness of transgressive deposits (Sequence 3) at the top the Bluesky Formation (see below), and the topographical relief created, renders this surface ineffective in the study area. In addition, wave ravinement surface 3 may be used to divide the Bluesky Formation into two informal units: lower and upper. However, due to the overall landward stepping nature of the Bluesky Formation stratigraphy such designations cross depositional sequence boundaries, and therefore, are impractical for regional correlations. For example using WRS 3 to divide the Bluesky Formation into lower and upper units results in a lower unit that consists of Sequence 1 and lowstand, transgressive and stillstand strata of Sequence 2, while the upper unit consists of highstand strata of Sequence 2 and transgressive strata of Sequence 3 (see below).

Section 3.3 Sequence 1 - Upper Gething Channels and Parasequence 1

The Gething Formation underlying the Bluesky Formation consists of coaly sandstone and mudstone (Lithofacies 7) that were deposited on a marginal-marine coastal

plain. In addition, based on geophysical log interpretation a number of elongated, northwest-trending porous sandstone bodies ranging from 5-11 m thick have been identified (Figure 3.2-upper Gething channels). Correlation of coals in the upper Gething Formation suggest that they most probably have been truncated by these elongated sandstone bodies. Although these sandstones have not been observed in core, based on their blocky to upward increasing gamma ray response and association within coastal-plain deposits suggests they represent fluvial channel-fill sandstone (Lithofacies 5).

Gething Formation coastal plain deposits likely accumulated during earlier high order highstand phases. Thick sandstone bodies within the upper Gething Formation are valleys incised into the coastal plain during episodes of lowered relative sea level. The sequence boundary represents the valley boundaries. In turn, the valley filled during the ensuing rise of relative sea level. Cant and Abrahamson (1996) interpreted three stratigraphic horizons within the Gething Formation that host blocky sandstone units up to 20 metres thick to be incised valleys that formed on the coastal plain during separate episodes of relative sea level fall. However, details of Gething stratigraphy are beyond the scope of this work and will not be discussed further.

Abruptly overlying Gething Formation coastal-plain and fluvial deposits are marine shale (Lithofacies 2b) and shoreface sandstone (Lithofacies 3 and 4) of the lower Bluesky Formation. The transgressive, or wave ravinement surface (WRS1), is sharp and overlain by a carbonaceous-rich sandstone or a thin lag of coarse sand beneath a thick succession of marine shale. Where marine shale and sandstone overlies coastal plain deposits the surface represents an amalgamated sequence boundary-flooding surface (SB-FS).

The transgressive limit occurs in the southernmost part of the study area where shoreface sandstone thins and grades laterally into coeval coastal-plain deposits of the Gething Formation. Upward-coarsening shoreface deposits (Parasequence 1) of Sequence 1 indicate a northeast-southwest trending shoreline that prograded toward the northwest during the highstand phase (Figures 3.2 and 3.3a). Parasequence 1 is up to 12 m thick, but because of incision by younger units is commonly thinner or absent.

Section 3.4 Sequence 2

A fall of relative sea level following the deposition of Sequence 1 shifted the marine part of the Bluesky basin to the northwest of the study area. Within the study area a through-going fluvial system incised a northwest-trending paleovalley. This paleovalley is up to 5 km wide and is filled with fluvial sandstone (Lithofacies 5) up to 12 m thick (Figure 3.4). In places where Sequence 1 has been completely eroded, the sequence boundary overlies coaly shale and sandstone of the Gething Formation. Deposits within the paleovalley fine upward with thin rarely bioturbated mudstone and coal couplets becoming more abundant near the top of the paleovalley fill. Coarse grained sandstone at the base of the valley-fill most likely represent deposition in a lowstand to early transgressive fluvial system. Finer grained sandstone and mudstone and coal couplets in the upper part of the fill indicate more variable energy conditions possibly related to tidal influence. A tidal influence is further supported the presence of rare bioturbation. These strata, therefore, are most probably deposited during rising relative sea level and related to transgression. As relative sea level continued rising a northeast-southwest-trending barrier complex formed. The basal erosional contact with marine deposits of Sequence 1

Figure 3.3 Depositional environments of Sequence 1 and lower part of Sequence 2 of the Bluesky Formation. a) Highstand Sequence 1; Muddy and coaly coastal plain deposits (Gething Formation) present in the south part of the study area grade into shoreface deposits (Parasequence 1) which fine to the northwest. b) Lowstand Sequence 2; A northwest flowing fluvial system incised into underlying deposits forming a valley. c) Transgression Sequence 2; Tidally influenced fluvial system deposited within the northwest trending valley. Outside of the valley a transgressive barrier complex trending northeast incised into underlying deposits. d) Stillstand Sequence 2; Northwest prograding shoreface deposits (Parasequence 2) were influenced by the still active fluvial system. Parasequence 2 is overlain by a regional wave ravinement surface representing renewed transgression.

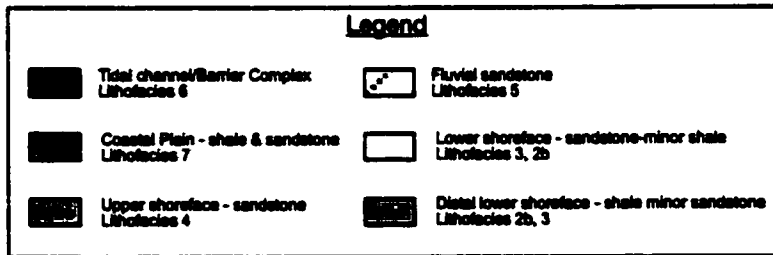
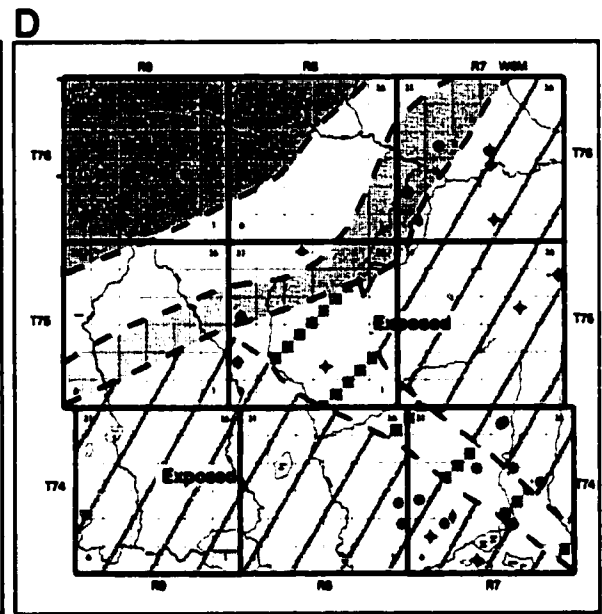
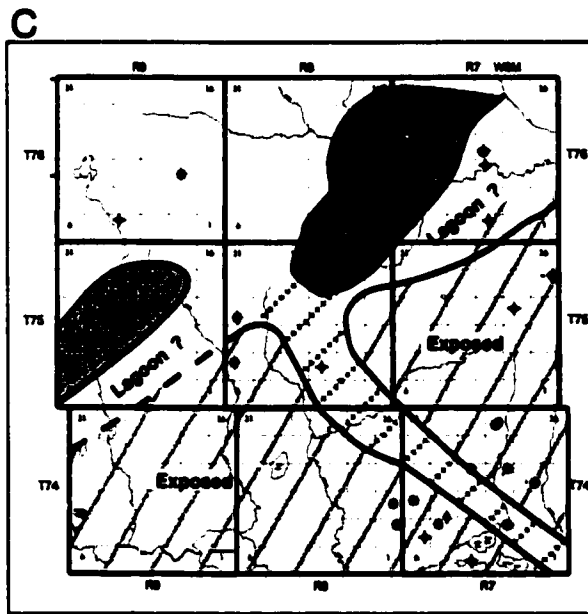
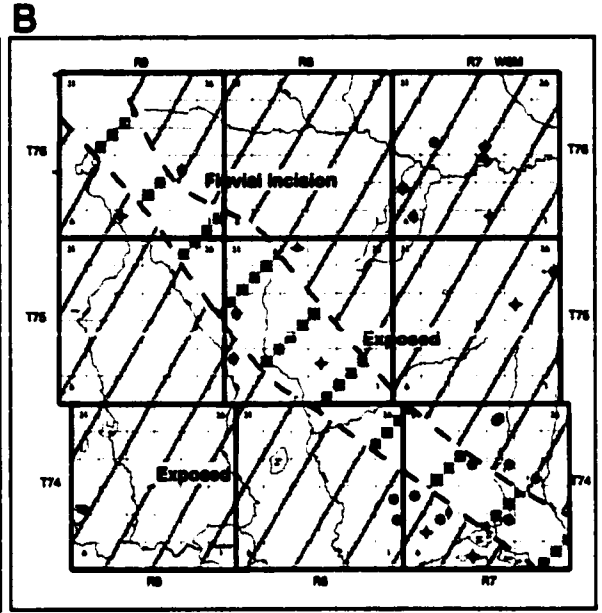
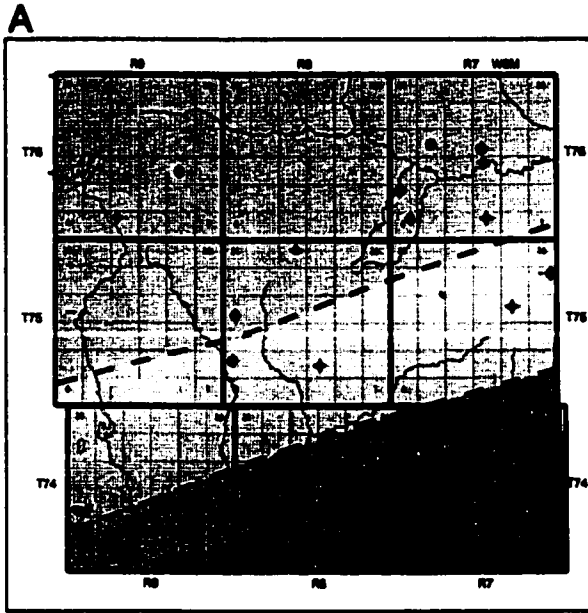
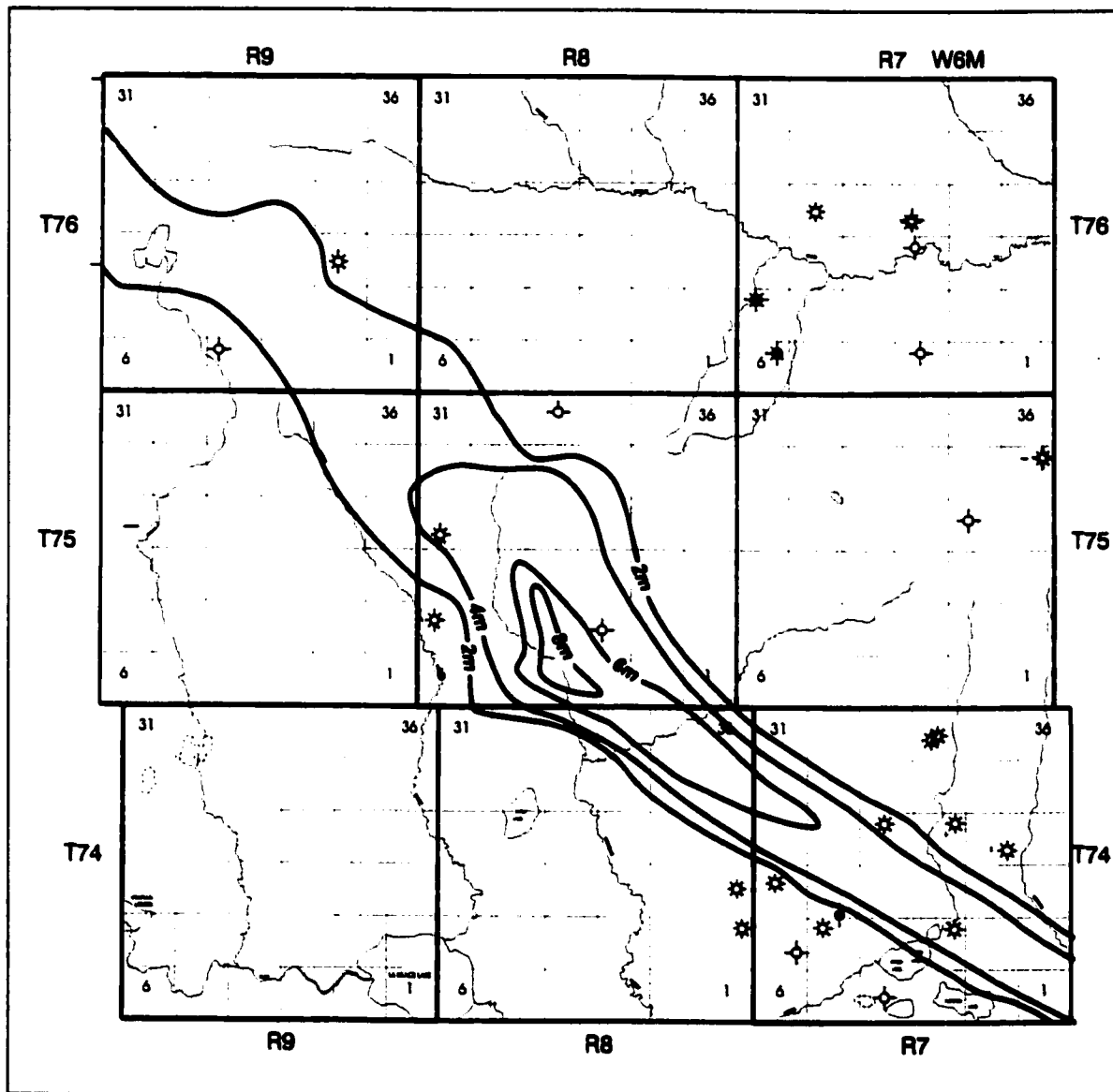


Figure 3.4 Distribution of fluvial sandstone (Lithofacies 5) at base of Sequence 2. Isopach contours are in 2 m intervals.



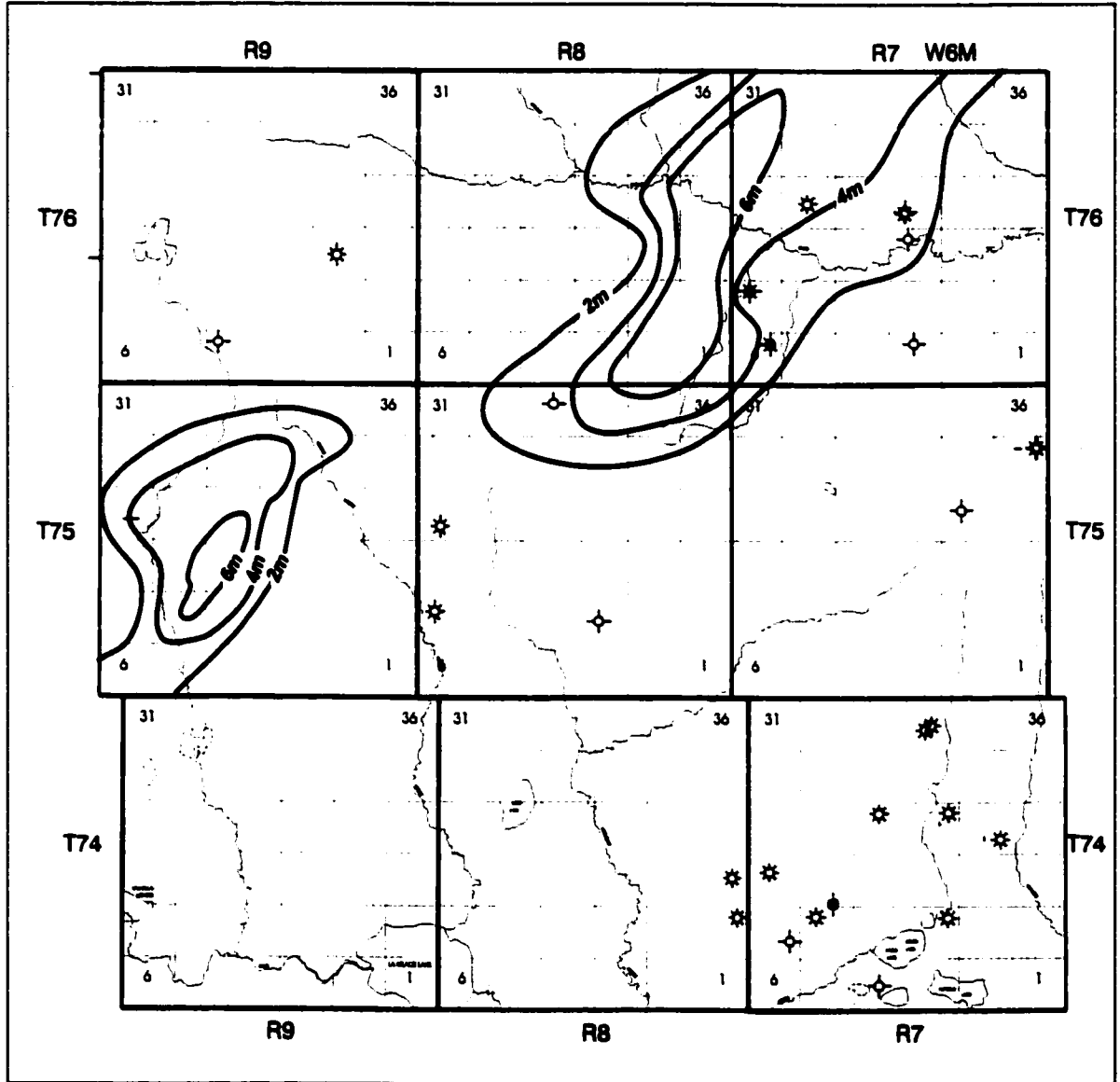
Well Legend

○ Location	● Oil	☆ Gas
◐ Suspended	◆ Abandoned Oil	☆● Abandoned Gas
◑ Abandoned	◐● Suspended Oil	☆◐ Suspended Gas
		☆●◐ Oil Prev Gas

represents a tidal ravinement surface, which in turn is overlain by tidal-inlet-fill sandstone (Lithofacies 6). This sandstone has been observed in core in townships 76-7, -8, -9W6 and forms a 2-8 m sandstone unit 3 to 4 km wide (Figure 3.5). Overlying fluvial and tidal inlet deposits in the northern part of the study area is wave ravinement surface 2 overlain by sandstone and shale (Lithofacies 4, 3 and 2b). Unlike other shoreface deposits within the study area, the lower shoreface sandstone and shale contains significant silt and carbonaceous material, soft-sediment deformation structures and thin turbidites interpreted to indicate deposition in a prodelta setting. Here, because of the presence of a point source of sediment (fluvial source), sedimentation rates are high and as a result the substrate is commonly unstable and therefore prone to soft-sediment deformation. In addition, common thin turbidites most probable represent deposition during episodes of high sediment flux to the delta front, which in turn probably associated with periods of high river discharge. These observations suggest that the shoreface, or more accurately delta-front, in the northern part of the study area was supplied by sediment from the northwest-trending fluvial system and formed a northwest prograding parasequence (Parasequence 2) up to approximately 10 m thick.

Parasequence 2 and fluvial deposits are overlain by wave ravinement surface 3. This suggests that Parasequence 2 is a wave-dominated delta deposited during a stillstand of relative sea level. This stillstand occurred during an overall rise of relative sea level and may be a local feature formed as the result of increased local sediment supply from the active fluvial system. Lateral to this fluvial source of sediment stillstand deposits may be absent, and the sedimentary succession may indicate continuous transgression.

Figure 3.5 Distribution of tidal inlet sandstone (Lithofacies 6) at the base of Sequence 2. Isopach contours are in 2 m intervals.



Well Legend

○ Local ion	● Oil	⊛ Gas
◊ Suspended	◆ Abandoned Oil	⊛ Abandoned Gas
◇ Abandoned	◊ Suspended Oil	⊛ Suspended Gas
		⊛ Oil Prev Gas

Wave ravinement surface 3 is a regional surface and traceable across the study area. It overlies prodelta deposits of Parasequence 2 and fluvial sandstone. This surface is marked by a thin (<1 m) transgressive lag of glauconitic sandstone (Lithofacies 1) and represents a continued rise of relative sea level. Locally, lagoonal shale (Lithofacies 2c) forms thin (<1 m) units that underlie the wave ravinement surface. The Shale Break (Lithofacies 2a) overlies the transgressive lag in the southern half of the study area, and thins from approximately 3m thick in township 74-7W6 toward the northwest (Figure 2.4). The Shale Break represents the most distal deposits of Sequence 3 and likely contains the maximum flooding surface just above the contact with the underlying transgressive lag.

Sharply overlying the Shale Break in the southern part of the study area is lower shoreface sandstones (Lithofacies 3) that grade northward to lower shoreface interstratified sandstone and shale. In the northern part of the study area where the Shale Break is absent lower shoreface sandstone and shale overlie the transgressive lag. The sharp contact between the Shale Break and overlying lower shoreface sandstone and shale represents a fall of relative sea level and a basinward shift of lower shoreface onto the distal shelf strata. Because the shale was deposited in a distal marine setting it is likely that it would have formed a unit with little variation in thickness. Thinning of the Shale Break toward the northwest, therefore, is interpreted to be the result of erosion associated with a forced regression (cf. Posamentier et al., 1992; Walker and Plint, 1992). However, the thickening of the Shale Break to the southeast is interpreted to be a result of locally increased subsidence and preservation (see Section 4.1).

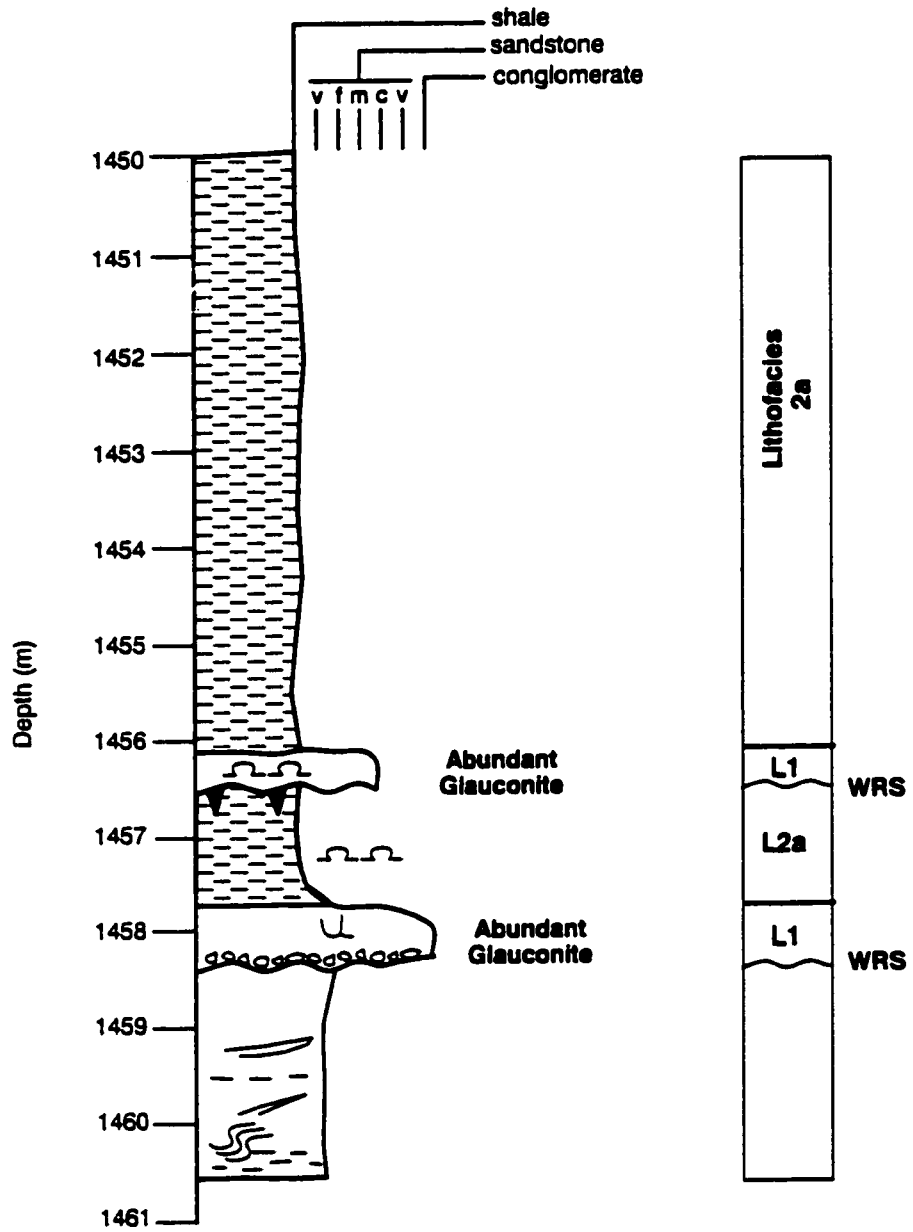
Lower shoreface sandstone and shale overlying the Shale Break form two northwest-prograding parasequences (parasequences 3 and 4) separated by a flooding surface. In the northern part of the study area the surface is marked by dark green glauconitic sandstone, and in the south by a ~30 cm thick interstratified succession of sandstone with minor shale partings and bivalve shell layers (Figure 2.9). Total thickness of the two parasequences ranges from 5 metres in the northern part of the study area to approximately 12 metres in the south. In addition, these strata and also strata of Sequence 3 (see below), thin toward the northeast. For example, in township 76-7W6 the succession is only 1.5 metres thick (Figure 3.6) and consists of a wave ravinement surface overlain by glauconitic sandstone (Lithofacies 1) and shale (Lithofacies 2a), in turn overlain by a sequence boundary-wave ravinement surface marked by glauconitic sandstone (Lithofacies 1) of Sequence 3 (see below). Erosion occurred during transgression associated with the overlying Sequence 3. In township 76-7W6 Sequence 3 has been completely reworked except for the basal transgressive surface and part of the Shale Break (Figure 3.6). The reduced preservation in this area is linked to decreased accommodation space likely influenced by local structural reactivation (see Section 4.2).

Section 3.5 Sequence 3

Sequence 2 deposition was terminated by a fall of relative sea level, the rationale for this sequence boundary will be discussed below. Sequence 3 consists of tidal inlet channel (Lithofacies 6) sandstone and locally lagoonal shale (Lithofacies 2c) overlain by a transgressive lag of glauconitic sandstone (Lithofacies 1) and distal marine shale of the Wilrich Formation (Lithofacies 2a). Sequence 3 is present across the study area but is

Figure 3.6 Core description of 14-3-76-7W6. See Appendix 1 for legend of symbols used.

14-3-76-7W6



thickest in three east-northeast trending units (Figure 3.7), interpreted to be remnant barrier bar complexes. The preserved barrier complexes are informally referred to in this study as the northwestern sand-body, the Valhalla Shoal and the La Glace Barrier.

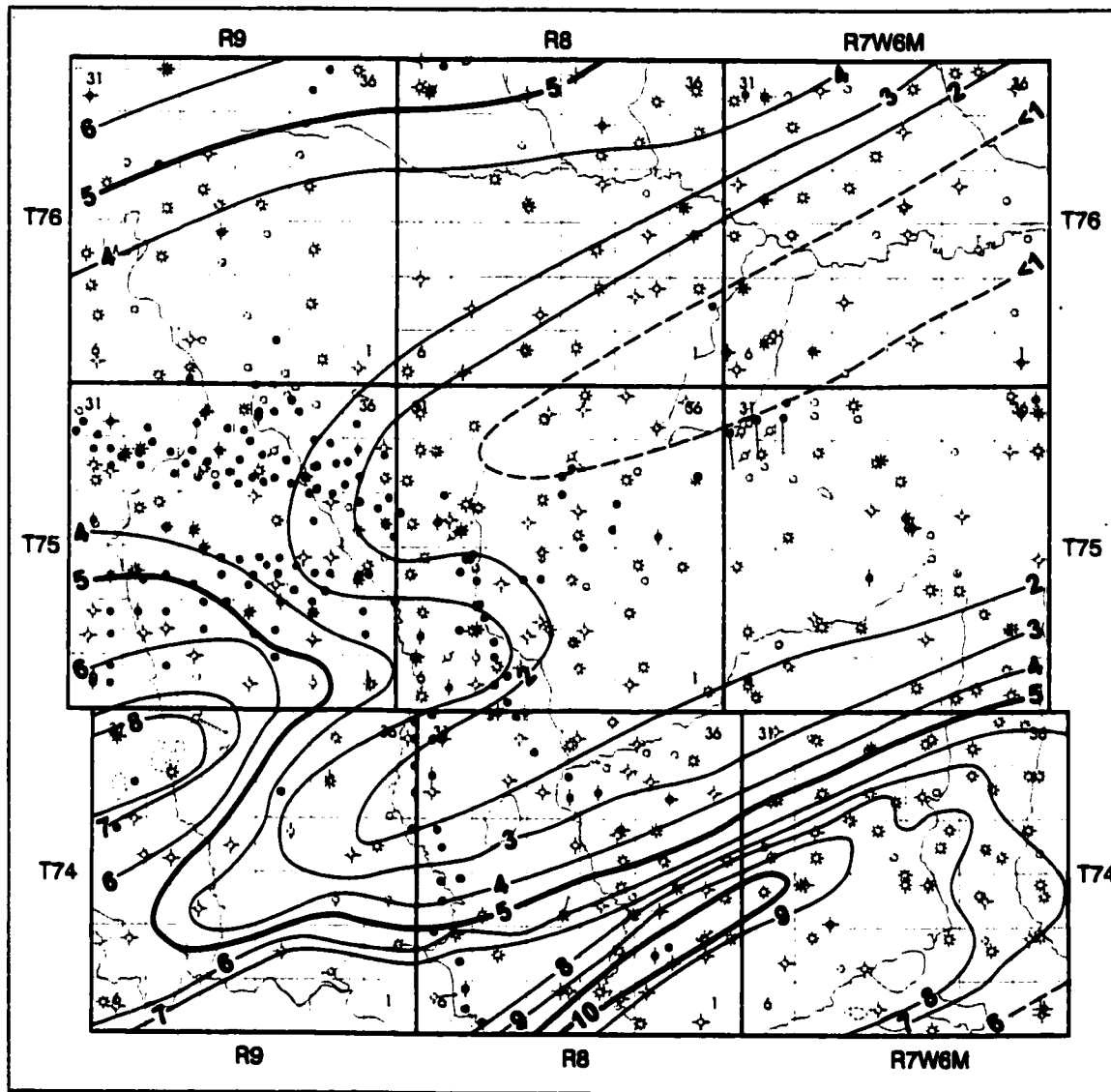
Northwestern Sand-body

The northwestern sand-body runs east-northeast in the northwest corner of Township 76-9W6 and is generally outside of the study area. In the northwestern corner of the study area the sandstone unit is 8 m thick and overlies lower shoreface shale and sandstone of Sequence 2. Although, the unit has not been observed in core, geophysical response and the units stratigraphic position suggests that the sandstone is a barrier complex of Lithofacies 6.

Valhalla Shoal

Trending east-northeast through the northern part of township 74-9W6 a thick unit of washover sandstone (Lithofacies 6) and glauconitic sandstone (Lithofacies 1) has been identified (Figures 2.1 and 3.8). This unit ranges in thickness from 2.5-8.5 m and is up to 6 km wide. In core the unit has been observed in the 6-10-75-8W6 well and consists of 1.5 m of gently dipping planar laminated washover sandstone beds, sharply overlying finer grained lower shoreface sandstone (Parasequence 4 of Sequence 2). An unlined *Skolithos* burrow of the *Glossifungites* ichnofacies extends down from the surface separating these two unit (Figure 3.9). The succession is then overlain by a 2 m thick transgressive lag consisting of glauconitic sandstone; the basal contact is sharp, scoured and burrowed (Figure 2.2 and 3.8). The lag of glauconitic sandstone is thickest along an east-northeast trend where it is up to 3 metres thick and approximately 2 km wide

Figure 3.7 Distribution of Sequence 3 transgressive deposits through the study area. Isopach contour interval is in metres. Three east-northeast trending units are discernible in the study area based on thickness. These units are labeled on the map and are informally referred to in this study as the northwestern sand-body, the Valhalla Shoal and the La Glace Barrier complex.



Well Legend

○ Location	● Oil	☆ Gas
◊ Suspended	◆ Abandoned Oil	✱ Abandoned Gas
◇ Abandoned	◈ Suspended Oil	✱ Suspended Gas
		✱ Oil Prev Gas

Figure 3.8 Core description of 6-10-75-8W6 core 1. See Appendix 1 for legend of symbols used.

6-10-75-8W6

Core 1

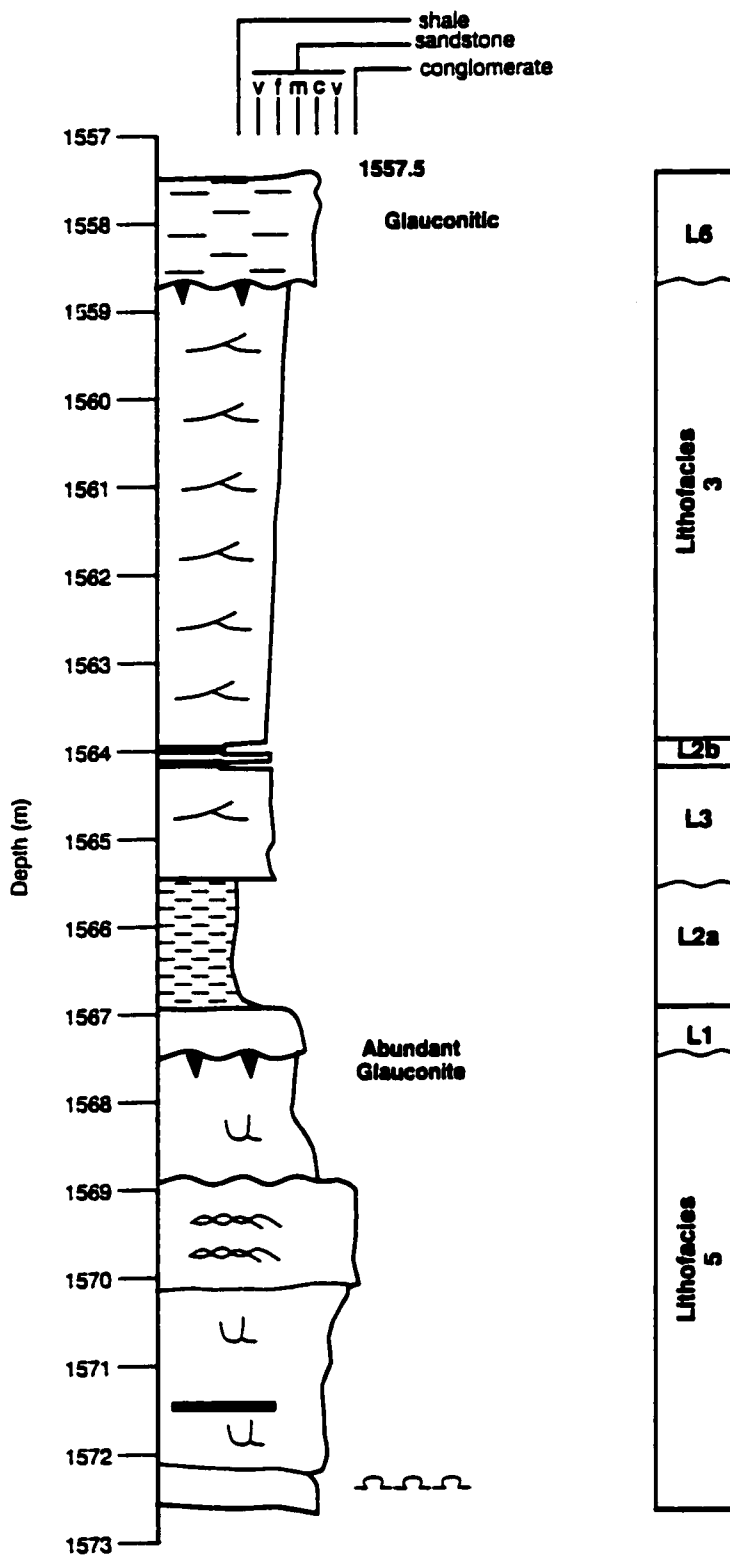
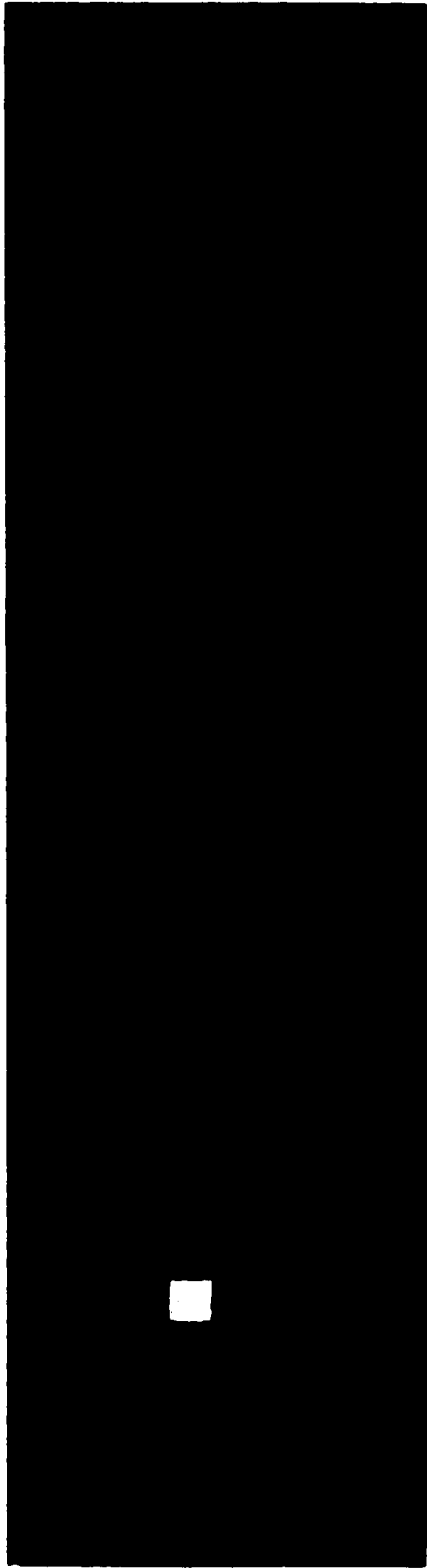


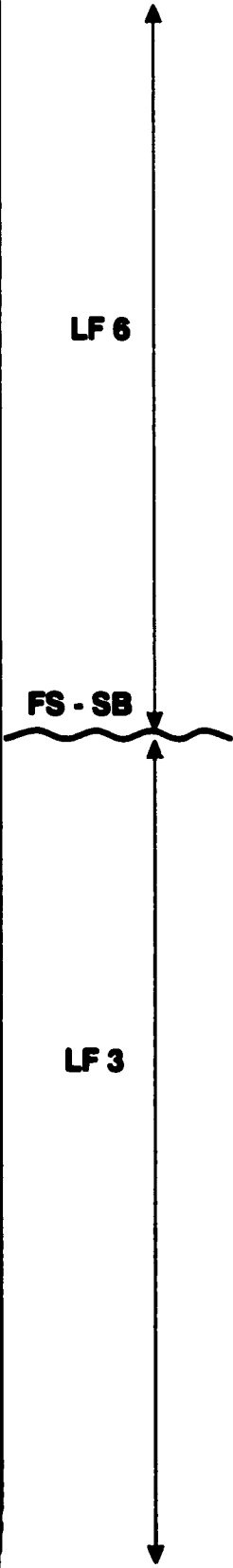
Figure 3.9 Core photo of the contact between lower shoreface sandstone and overlying washover sandstone from 6-10-75-8W6 at 1559.8 m. The contact is a sand on sand contact which is marked by a change from hummocky cross-stratified very fine grained sandstone to planar laminated fine grained sandstone. In addition, an unlined *Skolithos* burrow hangs from the contact and is interpreted to be of the Glossifungites ichnofacies representing burrowing into a firm substrate. Scale at the bottom is in centimetres.



LF 6

FS - SB

LF 3

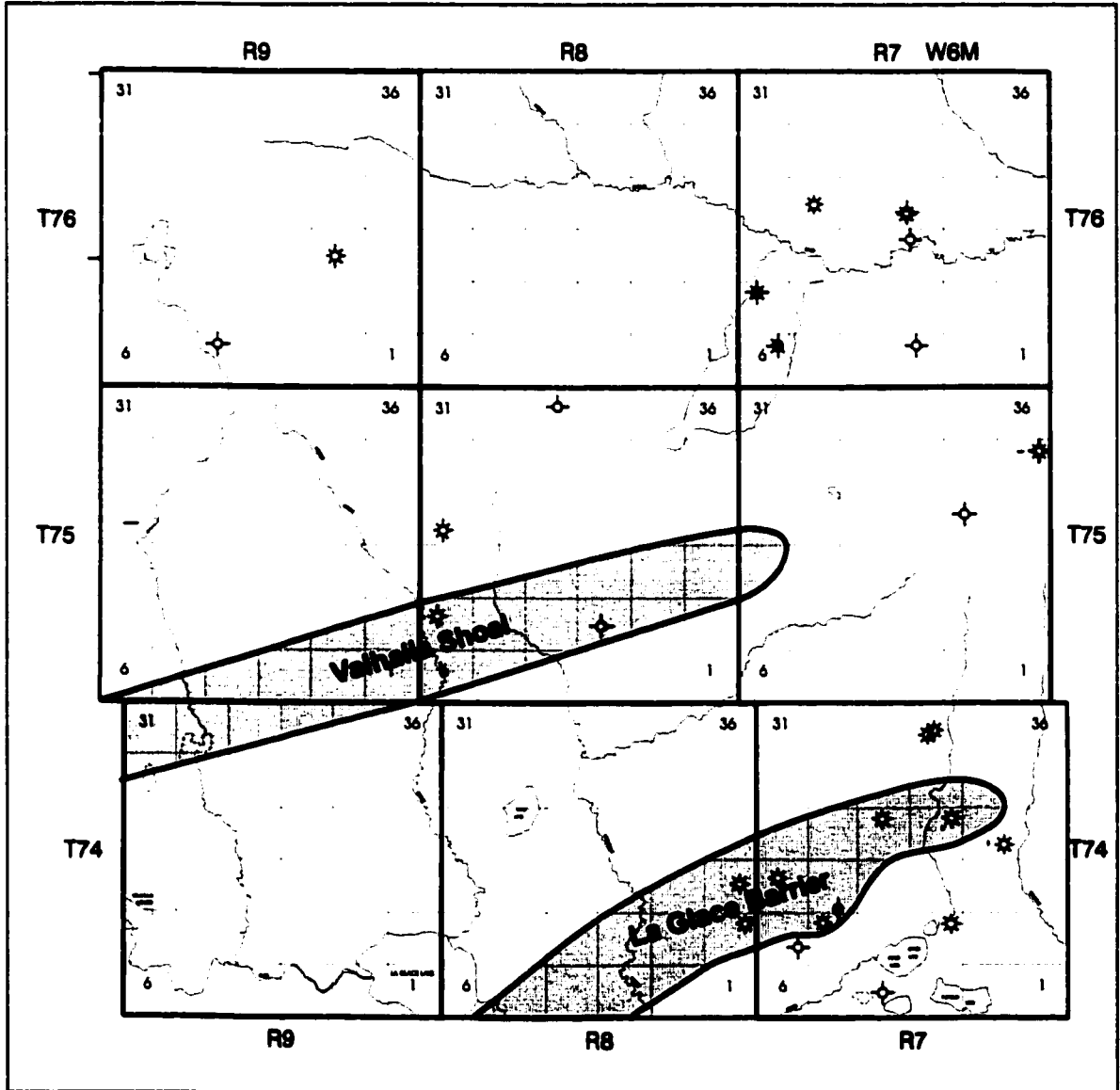


forming elongated porous unit that produces gas in the Valhalla Field (See Section 5.3; Figure 3.10).

La Glace Barrier

In the southeastern part of the study area (La Glace field), townships 74-7W6 and 74-8W6 (Figure 3.10), tidal inlet sandstone (Lithofacies 6) and locally, a thin 10-100 cm thick unit of lagoonal shale (Lithofacies 2c) sharply overlies lower shoreface sandstone (Parasequence 4). Within the study area this succession is up to 11 m thick and forms an east-northeast trending unit, which extends beyond the study area toward the west through township 73-9W6 and east through township 74-6W6 (Figure 3.10). The barrier complex thins along strike to the northeast, and also rapidly toward the northwest. This unit is possibly as wide as 10 km, and is thickest along a ridge that is less than 2 km wide. Cores penetrating the top of the ridge commonly have a thin coal and rooted horizon capping tidal inlet sandstone. To the southeast of the ridge in township 74-7W6 strata contain a higher concentration of gravel and coarse sandstone near the base of Lithofacies 6. A transgressive lag of glauconitic sandstone approximately 50 cm thick overlies the succession. East-northeast trending sandstone units at the top of Bluesky Formation formed as barrier complexes that were preserved during transgression of the Boreal Sea. The overlying distal marine shale of the Wilrich Formation was deposited during the subsequent highstand. The deposition and preservation of transgressive deposits during the Holocene has been extensively described along the south coast of Long Island, New York (Swift, 1968; Kumar and Sanders, 1974; Sanders and Kumar, 1975a; Sanders and Kumar, 1975b; Swift 1975; Rampino and Sanders, 1980) and on the Mississippi Delta (Penland et al., 1988). As a result of this body of work three models have been developed

Figure 3.10 Location of the Valhalla Shoal and La Glace barrier complex. The Valhalla Shoal consists of glauconitic sandstone (Lithofacies 1) and formed as a subtidal shoal from the reworking of a barrier complex. The La Glace barrier complex is an in-place drowned barrier which underwent little reworking after being drowned. The island consists of shallowing upward tidal inlet sandstone capped by a thin coal and rooted horizon. See Figure 3.12 for the depositional model.



Well Legend

○ Location	● Oil	☆ Gas
◊ Suspended	◆ Abandoned Oil	✱ Abandoned Gas
◊ Abandoned	◊ Suspended Oil	✱ Suspended Gas
		✱ Oil Prev Gas

to describe modern barrier bar complexes during transgression: 1) shoreface retreat (Swift, 1968); 2) in-place drowning (Sanders and Kumar, 1975a); 3) transgressive submergence (Penland et al., 1988).

Shoreface retreat describes the progressive landward movement of shoreface erosion during transgression. During shoreface retreat barrier complexes progressively override back-barrier lagoonal deposits. However, as retreat continues much of the barrier and lagoonal deposits are eroded by shoreface erosion. The end result, therefore, is a thin potentially extensive deposit of thin lagoonal deposits erosionally overlain by a thin transgressional lag deposit.

In-place drowning describes the landward stepping of barrier bar complexes (Saunders and Kumar, 1975). Rather than continual landward transgression the barrier complex aggrades in response to sea level rise. The barrier is separated from the mainland by the expanding back-barrier lagoon and is eventually drowned. A new barrier complex forms landward. Depending on the amount of reworking, part or all of the barrier complex is preserved. Transgressive submergence is somewhat similar to in-place drowning. The model was developed to explain Holocene delta lobe abandonment on the Mississippi River delta. When abandoned the delta lobe is reworked into a barrier complex, which when drowned continues to be reworked eventually forming a sub-tidal shoal (Penland et al. 1988). The shoal is effectively a thick lag deposit (Arnott, 1995).

Transgressive deposits in Sequence 3 of the Bluesky Formation form distinct linear east-northeast trending units. When an underlying datum, such as the base of the Shale Break or the base of Sequence 3, is used to correlate the transgressive deposits,

thickness variations form ridges blanketed by shale of the basal Wilrich Formation. Unlike shoreface retreat in which a thin continuous transgressive deposit is preserved, these distinct ridges likely formed by the in-place drowning of individual barrier complexes.

The initial transgressive barrier complex in the study area formed during transgression after a fall of relative sea level at the end of deposition of Sequence 2. The northwestern sand-body formed as a barrier complex disconformably overlying lower shoreface sandstone and shale of Sequence 2. An alternate interpretation is that the sandstone is upper shoreface sandstone (Lithofacies 4), regardless of the interpretation the sandstone indicates a proximal marine environment to the north of the study area and a fall of relative sea level. And therefore, a sequence boundary lies at the base of this unit separating it from Sequence 2.

When this northwestern sand-body barrier complex was drowned a new barrier complex became established approximately 20 km to the southeast (paleolandward). This barrier complex, which extends through Townships 74-9W6 to 75-8W6, was the precursor to the Valhalla Shoal. The position of the barrier complex was determined based on backbarrier washover deposits in the 6-10-75-8W6 well and the increased thickness of the transgressive lag of glauconitic sandstone along this trend. The Valhalla barrier complex was drowned in-place and reworked by waves in the upper shoreface. This winnowed much of the fine grained sediment and formed a good reservoir quality subtidal shoal deposit (Figure 3.11).

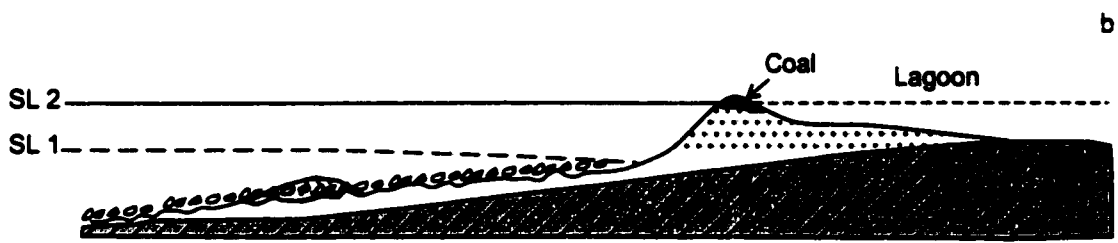
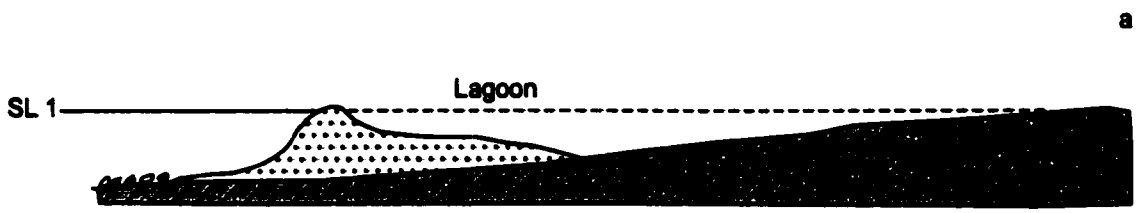
A new barrier bar complex (the La Glace Barrier) formed approximately 12 km to the southeast in township 74-7W6. The La Glace barrier complex has a thin coal and rooted

horizon at the top of the complex suggesting that the barrier was a vegetated island. The barrier complex is cored by sandstone that was deposited in laterally migrating tidal inlets. A concentration of pebbly sandstone and thin beds on the southeast side (lagoonal) of the barrier represent abandoned flood tidal deltas. The coarser grained material is moved through the base of the active tidal channel into the backbarrier environment where it is deposited on the flood tidal delta. Coarse material transported seaward through the tidal channel would be deposited on an ebb tidal delta, however, because of intense wave erosion ebb tidal deltas are rarely preserved (Reinson, 1992). The basal lag of pebbles commonly observed in the transgressive lag of glauconitic sandstone are most likely from the reworking of the ebb tidal delta. Within the tidal channel only a thin lag of coarse material is deposited at the base (Reinson, 1992). As tidal channels migrate laterally flood-tidal deltas are formed along the length of the barrier complex. Thinning of the La Glace barrier complex to the northeast in township 74-7w6 is likely in response to structural reactivation along an older fault reducing subsidence and accommodation space. However, in this area no coal or rooted horizon has been observed capping the barrier complex and so may indicate the position of the active tidal channel when the barrier complex was drowned.

The La Glace complex was drowned and the shoreline moved to the south out of the study area. A thin lag deposit overlies the La Glace barrier complex, however, the excellent preservation of the barrier complex features indicates that only minimal reworking occurred. The Bluesky Formation within the study area was then overlain by shale of the lower Wilrich Formation. Shale was deposited on the distal shelf of programming shoreface successions during the subsequent highstand. The maximum

Figure 3.11 Depositional model of Valhalla Shoal and La Glace barrier complex.

a) Initially an east-northeast barrier complex formed in approximately the position of the Valhalla Shoal. The barrier complex aggraded with rising relative sea level until it was overcome and drowned in-place. b) A new barrier complex formed in the position of the La Glace barrier complex approximately 12 km landward. Wave energy in the shoreface reworked the older barrier complex forming a subtidal shoal consisting of winnowed barrier deposits. Further rising relative sea level drowned the La Glace barrier complex in-place and likely formed a new barrier complex to the south of the study area (not shown). Unlike the Valhalla barrier the La Glace barrier complex was not substantially reworked. See Figure 3.10 for map location of the barrier complexes. Modified from Sanders and Kumar (1975).



flooding surface of Sequence 3 is likely present in the basal few meters of the Wilrich Formation shale and corresponds to the third order maximum flooding surface of the Mannville Group (Cant and Abrahamson, 1996). It is interesting to note that additional high order Bluesky Formation sequences may be present to the south of the study area. If so, Bluesky Formation highstand deposits to the south may be time equivalent to the basal Wilrich Formation within the Peace River Arch area.

Section 3.6 Summary

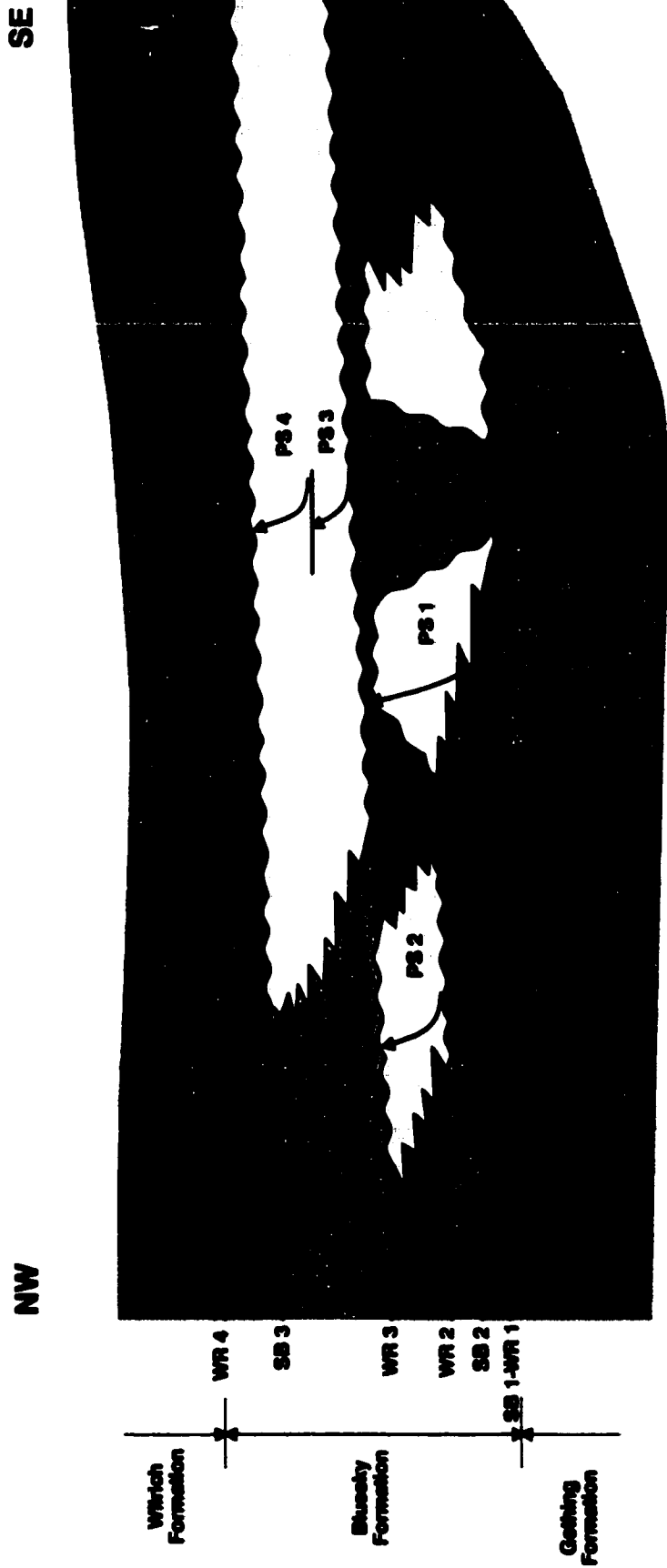
Lithofacies associated with rising relative sea level or transgression include: Lithofacies 1 glauconitic sandstone, Lithofacies 5 fluvial sandstone, Lithofacies 6 barrier sandstone and Lithofacies 2c lagoonal shale. Transgressive successions within the Bluesky Formation overlie a basal sequence boundary formed as an exposure surface or locally by downward cutting of fluvial systems during falling relative sea level or lowstand. The basal sequence boundary is overlain by fluvial sandstone (Lithofacies 5) and/or tidal inlet sandstone (Lithofacies 6) and rarely by lagoonal shale (Lithofacies 2c). The succession is overlain by a wave ravinement surface, which forms by wave erosion in the upper shoreface. Reworking commonly leaves only a transgressive lag of glauconitic sandstone (Lithofacies 1), which is then overlain by sandstone or shale deposited by an ensuing stillstand or highstand phase.

In the Bluesky Formation, stillstand or highstand phase deposits are typified by thin (less than 12 m) northwest prograding shoreface succession. Stratigraphically-upward distal marine shale (Lithofacies 2a), overlain by shale (Lithofacies 2b), lower shoreface sandstone (Lithofacies 3) and finally upper shoreface sandstone (Lithofacies 4)

correspond to deposition under shoaling conditions.

Sequence 1 comprises lowstand/transgressive fluvial sandstone of the Gething Formation that filled a number of northwest-trending paleovalleys incised into older coastal plain deposits of the Gething Formation. During the ensuing highstand a single marine Bluesky Formation parasequence was deposited, overlying a wave ravinement surface, throughout most of the study area (Figure 3.12). A fall of relative sea level shifted marine environments to the northwest of the study area and caused a northwest flowing fluvial system to be incised into exposed strata of Sequence 1. During a subsequent rise of relative sea level fluvial deposits of Sequence 2 filled the valley system and a northeast trending barrier bar complex developed in the northern part of the study area. Locally, rising relative sea level was stalled and stillstand conditions created because of high sediment flux supplied from the still-active fluvial system. This area corresponds to a wave-dominated deltaic complex that prograded to the northwest (Figure 3.12). Renewed rising relative sea level produced a wave ravinement surface across the study area marked by a transgressive lag generally <1m thick. Highstand strata overlying the transgressive surface are distal marine shale (the Shale Break), the maximum flooding surface is located near the base of this shale. Northwest prograding lower shoreface deposits sharply overlie the shale and were deposited following a forced regression (Figure 3.12). The presence of a sequence boundary between sequences 2 and 3 was inferred by the presence of a sharp based sandstone in the northwestern most corner of the study area interpreted to be a preserved barrier complex. An alternative

Figure 3.12 Summary stratigraphy and lithofacies distribution of the Bluesky Formation in the study area. Sequence 1 consists of Upper Gething Formation incised valleys, cut during lowstand into Gething Formation coastal plain deposits, and marine deposits of Parasequence 1 (PS1). During a lowstand following deposition of Sequence 1 a northwest trending incised valley cut into deposits of Sequence 1. During the following transgression fluvial deposits filled the valley and a barrier complex formed in the northern part of the study area. Marine deposits of Parasequence 2 were deposited during a stillstand. Features consistent with prodelta deposition within lower shoreface deposits of Parasequence 2 suggest that the fluvial system was active. Continued transgression resulted in a regional wave ravinement surface (WRS3) overlain by distal marine shale of the highstand. Lower shoreface deposits of parasequences 3 and 4 were deposited following a relative fall of sea level. A further fall of relative sea level shifted marine environments to the north of the study area during the following rise of relative sea level transgressive barrier complexes of Sequence 3 formed and were partially to wholly preserved by in-place drowning. Highstand deposits of Sequence 3 within the study area are distal marine shales of the Wilrich Formation. Vertical thickness of units not to scale.



interpretation is that this sandstone is upper shoreface sandstone following a forced regression. With either interpretation this unit represents a fall of relative sea level following deposition of Sequence 2 and therefore a sequence boundary lies at its base. Capping the Bluesky Formation are transgressive barrier complexes of Sequence 3 were deposited during the final transgression of the Boreal Sea. The barrier complexes were partially to nearly completely preserved by in-place drowning during a continuous rise of relative sea level. Highstand deposits are represented by distal marine shale of the Wilrich Formation which overlie the Bluesky Formation throughout the study area (Figure 3.12).

Section 4.0 Regional Tectonic Influence

The study area is situated on the southeast flank of the Peace River Arch (Figure 1.2). Structures associated with the arch have been interpreted by various authors to have influenced deposition from the Paleozoic through to the Late Cretaceous (Cant, 1988; O'Connell, 1988; O'Connell et al., 1990; Barclay et al., 1990; Reinson et al, 1993; Moslow and Davies, 1997). For example, basement rooted faults along the flank of the Peace River Arch influenced Devonian fringing reefs pre-, syn- and post-depositionally (Reinson, 1993). During the Early Carboniferous grabens and half grabens of the Dawson Creek Graben Complex formed over the crest of the Peace River Arch, possibly in response to extension related to west coast orogenesis (Figure 4.1) (Barclay et al., 1990; O'Connell et al., 1990). The margins of the grabens are sub-parallel to the basement rooted faults identified by Reinson (1993) (Figure 4.2). A thickening of the Carboniferous strata is attributed to increased accommodation space over the graben structures (Barclay et al., 1990). Later, O'Connell (1988) reported that the Bluesky Formation thickened over the crest of the Peace River Arch likely in response to reactivation of the axial graben. In context with this study some of the reverse faults previously identified by Reinson (1993) pass through the study area (Figure 4.2).

Section 4.1 Depositional and Structural Trends

Within the study area, the Bluesky Formation forms two principal depositional trends; east-northeast-west-southwest and the other northwest-southeast. These are manifested by thickness changes of transgressive and regressive deposits, particularly in

Figure 4.1 Early Carboniferous graben and half grabens of the Dawson Creek Graben System modified from Barclay et al. (1990).

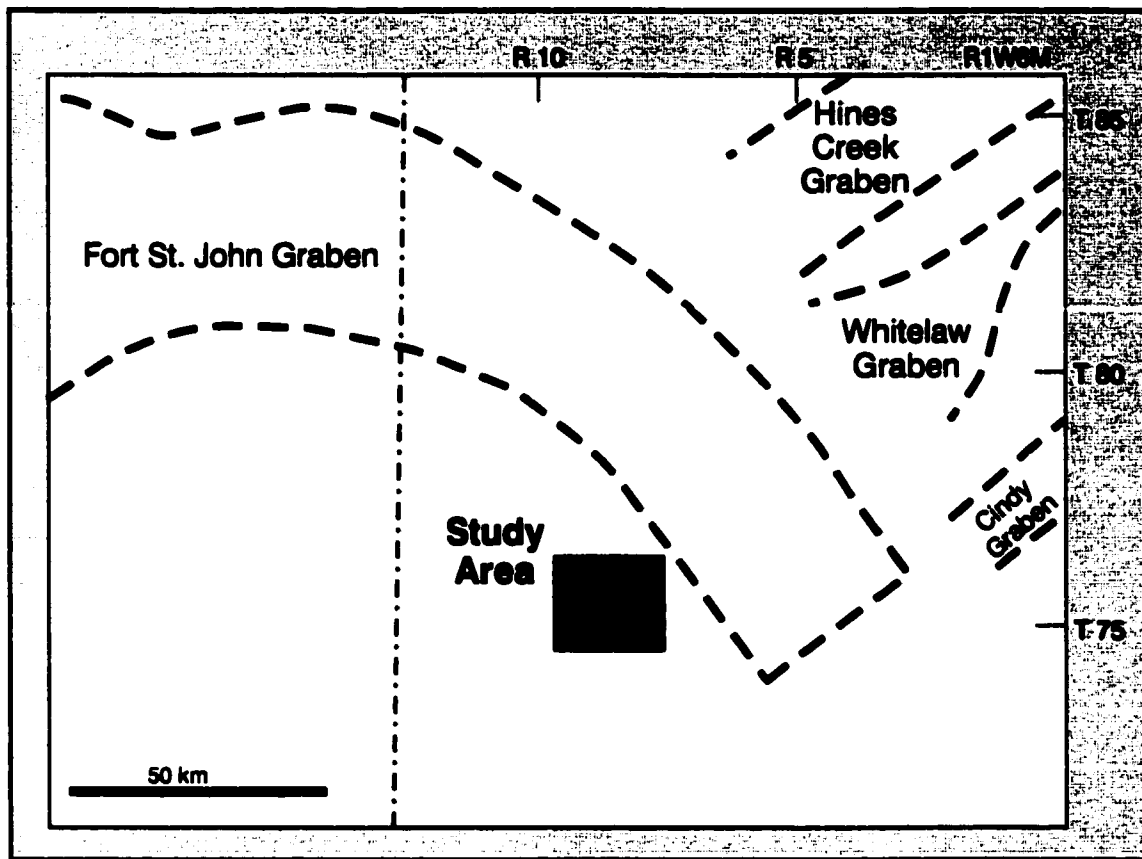
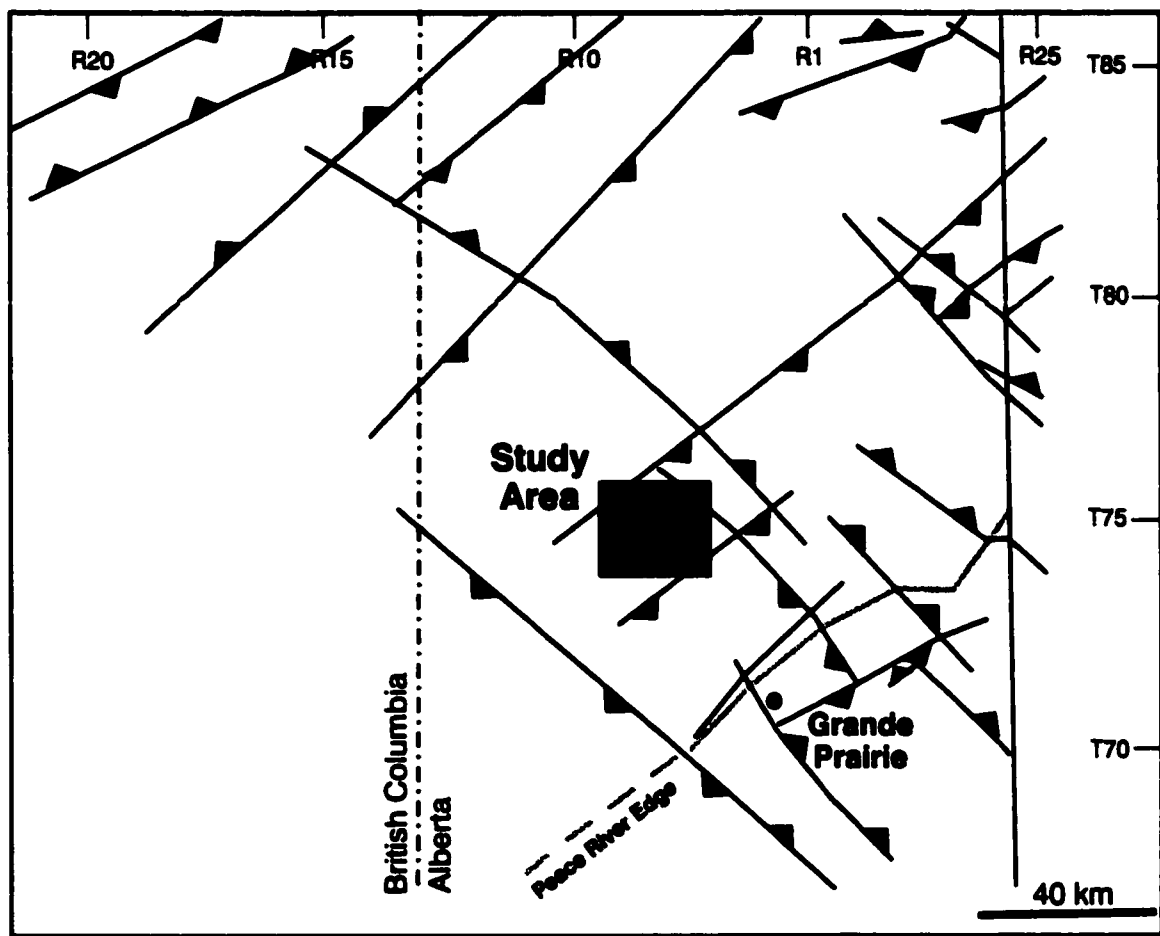


Figure 4.2 Basement rooted reverse faults in the vicinity of the study area modified from Reinson et al. (1993).



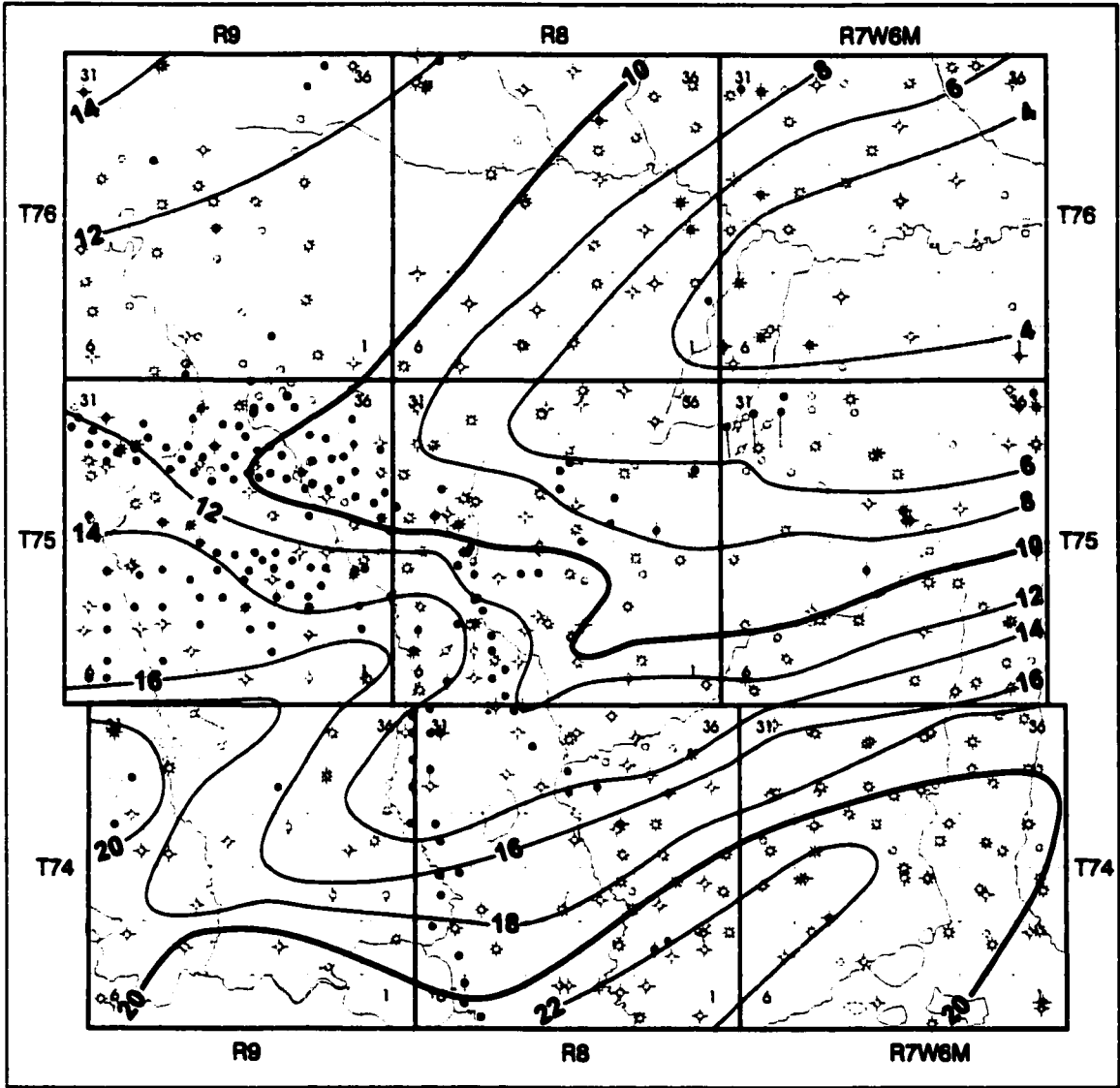
sequences 2 and 3 of the Bluesky Formation (Figure 4.3), and by modern-day structural relief along the top of the Bluesky Formation (Figure 4.4).

The east-northeast-west-southwest trend is most evident in the distribution of Sequence 3 transgressive deposits that cap the Bluesky Formation. These strata thicken significantly in three east-northeast-trending units (see Section 3.5) that are up to 8-10m thick and approximately 10 km wide. Elsewhere these strata are generally of the order of 1-3.5 m thick (Figure 3.7). Thickened transgressive deposits of Sequence 3 have been interpreted to represent the position of barrier bar complexes drowned during transgression. In addition, highstand distal marine shale of Sequence 2 (Shale Break) generally thickens to the southeast, (Figure 2.4). Which is coincident with the thickening of transgressive deposits of Sequence 3.

The second trend, orientated northwest-southeast, is made evident by a progressive thickening of the Sequence 2 highstand deposits from the northeast toward the southwest. In township 76-7W6, Sequence 2 is approximately 2 m thick and comprises transgressive lag overlain by distal marine shale (Figure 3.6). Toward the southwest in township 75-9W6, however, Sequence 2 is approximately 12 metres thick and consists of a transgressive lag overlain by distal marine shale overlain by lower shoreface sandstone.

Modern-day structure along the top of the Bluesky Formation dips toward the southwest, however local anomalies are present. The most pronounced anomaly is orientated northwest-southeast and runs through the southeast corner of township 76-7W6 (Figure 4.4). Such local variations are most probably the result of post-depositional faulting.

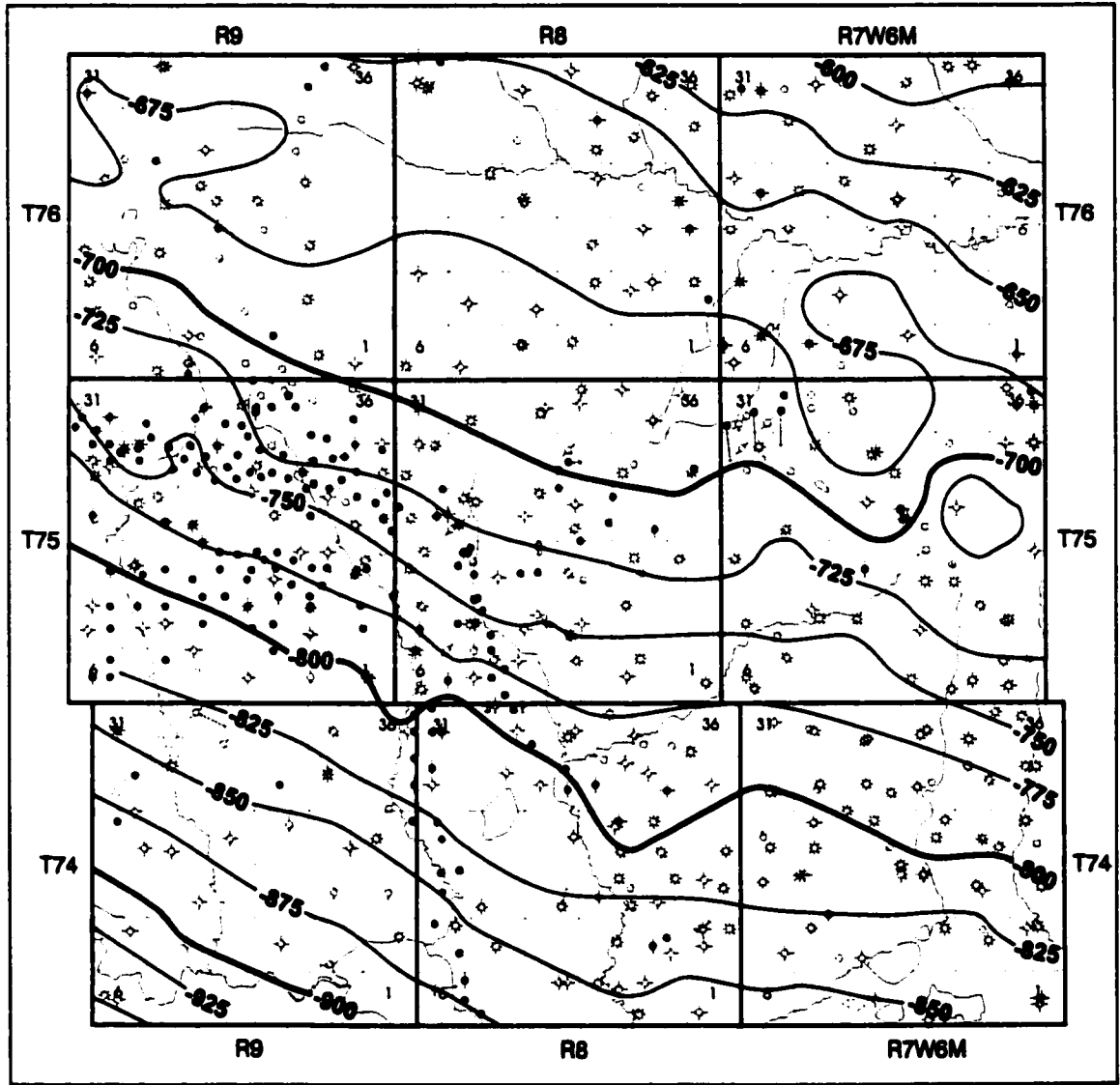
Figure 4.3 Isopach map of the highstand deposits of Sequence 2 and transgressive deposits of Sequence 3 (WRS3 to the top of the Bluesky Formation). Note the east-northeast trending units, which thin to the northeast. Contour interval is 2 m.



Well Legend

○ Location	● Oil	☆ Gas
◊ Suspended	◆ Abandoned Oil	✱ Abandoned Gas
◇ Abandoned	◈ Suspended Oil	✱ Suspended Gas
		✱ Oil Prev Gas

Figure 4.4 Modern-day structural relief of the top of the Bluesky Formation. The general slope is to the southeast; structural anomalies appear as variation of the slope. A major northwest trending anomaly and east-northeast trending anomaly have been shaded. See Figure 4.1 for the location of Devonian faults in the region, which may be responsible for modern-day structural anomalies. Contour interval is 5 m.



Well Legend

○ Location	● Oil	☆ Gas
◊ Suspended	◆ Abandoned Oil	⊠ Abandoned Gas
◇ Abandoned	◈ Suspended Oil	⊡ Suspended Gas
		⊣ Oil Prev Gas

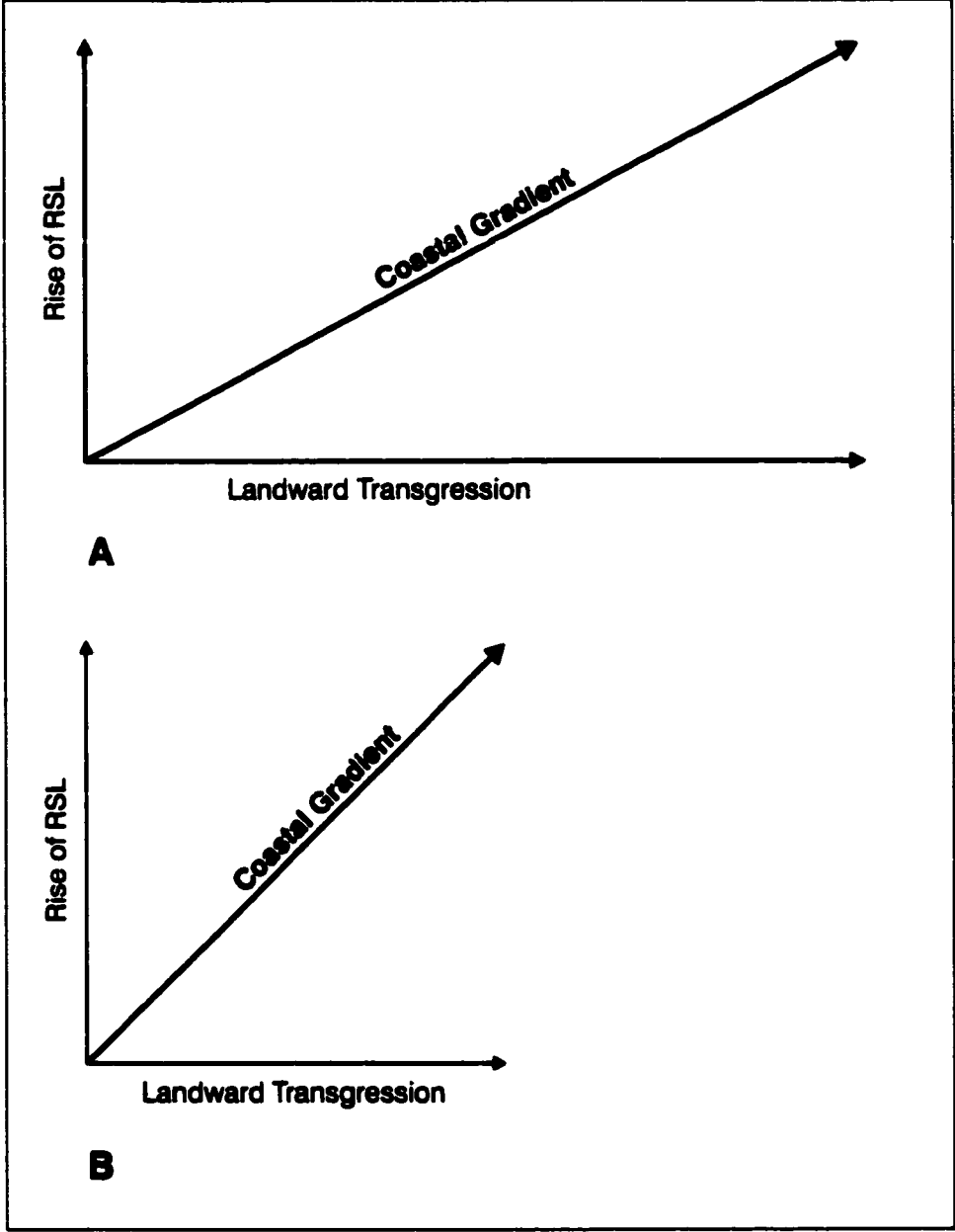
Section 4.2 Interpretation

A northwest trending basement-rooted reverse fault (the Webster Fault), which was active in the Devonian and reactivated during the Triassic, passes through the study area and underlies the observed structural anomalies in the top of the Bluesky Formation (Figure 4.2) (Reinson et al., 1993; Moslow and Davies 1997). This suggests that the Webster Fault and other sub-parallel faults were active after deposition of the Bluesky Formation, resulting in the observed modern-day structural anomalies (Figure 4.4).

Basement rooted reverse faults trending east-northeast pass through the northwest and southeast corners of the study area (Figure 4.2). Thick accumulations of Sequence 3 transgressive deposits are present on the northwest side (foot-wall) of these faults suggesting that pre- or syn-depositional reactivation of these faults influenced deposition.

During transgression if the rate of relative sea level rise is constant, the rate of transgression is a function of the gradient of the marginal-marine coastal plain. As the gradient of the coastal plain increases, the ratio vertical aggradation to landward migration will also increase (Figure 4.5). So that even with rising relative sea level the shoreline will be stable allowing the vertical aggradation of sediments. Where the gradient of the coastal plain is lower, the ratio of vertical aggradation to landward migration will also be lower. With rising relative sea level the landward migration of the shoreline will be more important than the vertical aggradation of sediments. Therefore, it is expected that the potential for preservation of nearshore sediments during rising relative sea level will be greatest on high gradient coastal plains, since the vertical aggradation of sediments is greater. In the Bluesky Formation transgressive deposits are preserved preferentially

Figure 4.5 Relationship between the landward transgression and gradient of the coastal plain. a) Where the gradient of the coastal plain is low landward transgression is great and aggradation of sediments is low. b) If the gradient of the coastal plain is high aggradation of sediments is much more likely.



adjacent to the fault because of increase aggradation by locally increasing the gradient of the coastal area, thereby influencing the position of barrier development.

Thinning of the Shale Break toward the northwest may have been controlled by differences in accommodation space related to local faulting. However, because the Shale Break was deposited on a distal shelf thickness variation is likely caused by post-depositional submarine erosion related to a fall of relative sea level. The Shale Break is preferentially preserved on the down-thrown side of the fault. In addition, preservation of the Shale Break is greatest nearest the fault (Figure 4.6).

The axis of the Cretaceous foreland basin is to the west of the study area (Figure 4.7) (Jackson, 1984; Stott, 1993). Thickening of the Bluesky Formation to the west is related to increased accommodation space towards the axis of the basin. However, thinning of the upper unit of the Bluesky Formation across the Webster Fault suggests that reactivation of faults played a role in local accommodation space.

Section 4.3 Summary

The data suggest that older Paleozoic structures were reactivated and influenced deposition and preservation of the Bluesky Formation along two depositional and structural trends. The first trend is most evident in transgressive deposits, which are preferentially preserved in east-northeast trending units. Preservation of transgressive facies is linked to increased accommodation space associated with the footwall of reactivated reverse faults. The second trend is evident in an increase in thickness of the upper unit of the Bluesky Formation from the northeast to the southwest and is related to

Figure 4.6 Preservation of the Shale Break due to increase subsidence nearing a reactivated fault. a & b) Shale is deposited evenly from suspension regardless of sea floor topography. b) Submarine erosion in the lower shoreface erodes the Shale Break. Sea floor topography resulting from the reactivation of local faults results in increased accommodation space and the preferential preservation of the Shale Break.

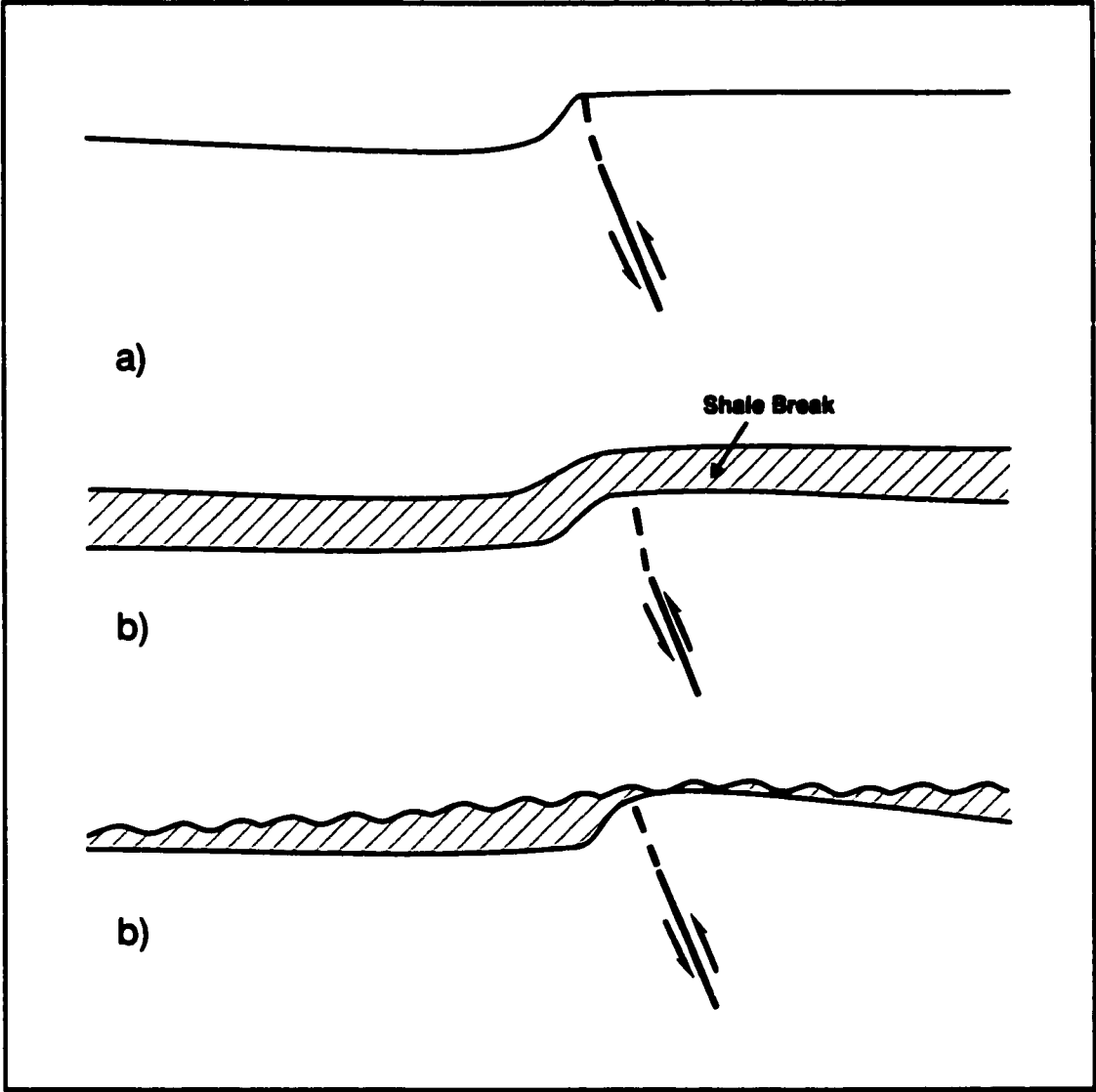


Figure 4.7 Axis of the Albian foreland basin in relation to the study area. Note that the study area lies on the edge of the basin and in this position is expected to have less accommodation space created than to the west. Modified from Stott (1993).



increased accommodation space approaching the axis of the foreland basin. Within the study area, however, northwest trending reverse(?) faults influenced local accommodation space and have created modern-day anomalies on the top structure of the Bluesky Formation.

Section 5.0 Petroleum Geology

The study area falls includes Valhalla and La Glace fields as defined by the Alberta Energy and Utilities Board (Figure 5.1). The Bluesky Formation produces from 19 gas pools within the Valhalla field with total initial estimated reserves of 3212×10^6 m³, the La Glace field hosts 4 gas pools with a total initial estimated reserves of 1502×10^6 m³ (EUB, 1997). In this area Lower Cretaceous and Jurassic coal and coaly shale contain abundant organic material (Masters, 1984). The organic material is derived from terrestrial plants and therefore is dominantly a Type III kerogen (which produces mainly gas) and are the most likely source of gas in the Bluesky Formation

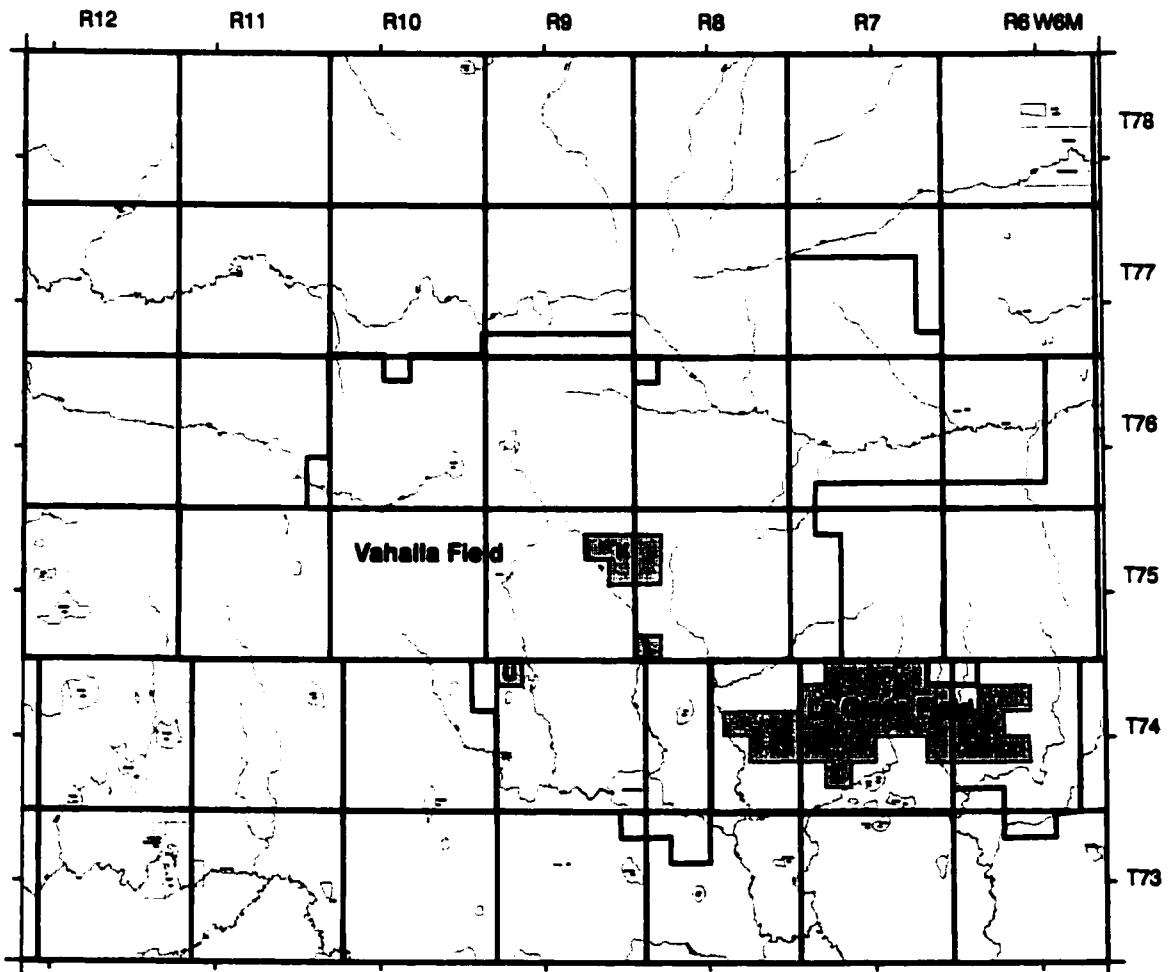
Four pools consisting of three different reservoir lithofacies were selected for study (Figure 5.1). These include the Bluesky K, L and U pools of the Valhalla Field and the Bluesky A pool of the La Glace Field. In the southern part of the Peace River Arch,.

Section 5.1 Valhalla Bluesky K Pool

The Valhalla Bluesky K pool was discovered in 1992 at 02/8-24-75-9W6. The pool comprises four producing wells with total initial reserves of 277×10^6 m³ (Figure 5.1) (EUB, 1997).

The reservoir zone has been cored at 6-19-75-8W6. In this well gas is produced from fluvial sandstone (Lithofacies 5) in the interval between 1603.0 – 1611.0 m (Figure 5.2). Tight lower shoreface sandstone and shale provide the lateral and top seals for the reservoir. A permeability-porosity cross plot displays a linear relationship between porosity and permeability for this lithofacies (Figure 5.3).

Figure 5.1 Gas fields and pools referred to in this study producing from the Bluesky Formation in the vicinity of the study area (EUB, 1997)



—— La Glace Bluesky A
—— Vahalla Bluesky

Figure 5.2 Core log of 02/6-19-75-8W6. Lithofacies 5 can be differentiated into a lower coarser unit and finer grained upper unit containing mud and organic rich laminae. A significant porosity and permeability change is also noted see Figure 5.5. See Appendix 1 for legend of symbols used.

02/6-19-75-8W6

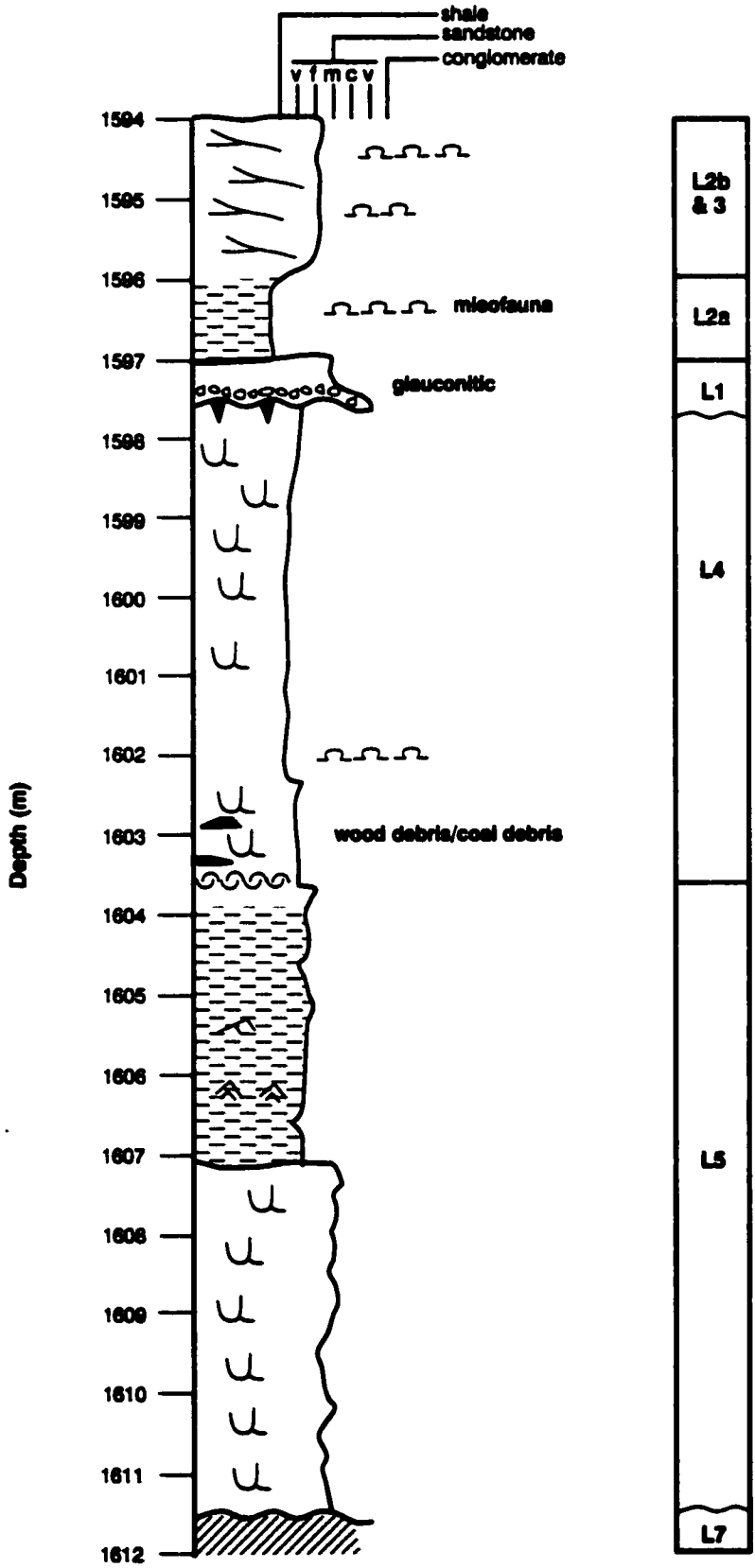
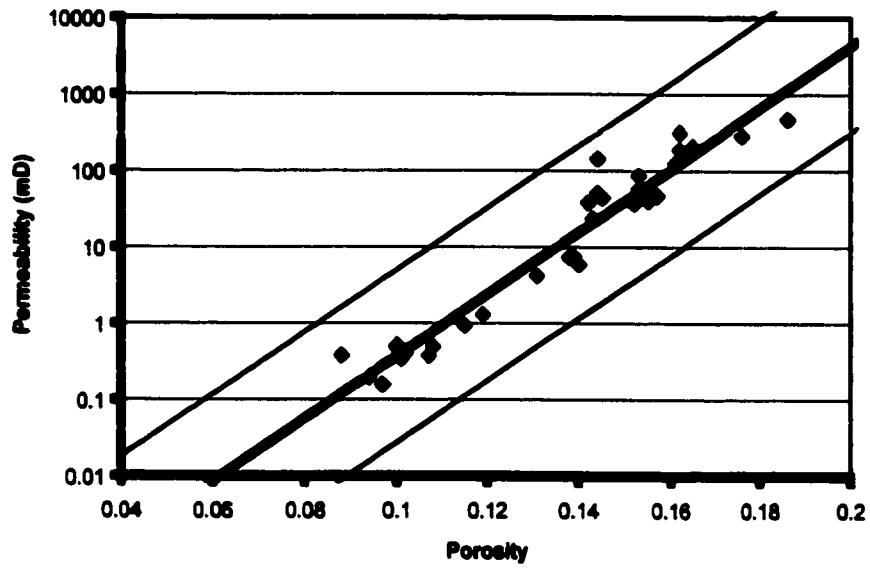


Figure 5.3 Permeability – porosity cross plot of Lithofacies 5 from the reservoir zone at 02/6-19-75-8W6. The heavy black line is the line of best fit, light black lines are plus and minus 1 standard deviation.



A change in grain size was observed in core within the producing zone. Above 1607.10 m the sandstone fines and contains an increased number of carbonaceous shale laminae. When core analysis data are separated into upper and lower units and replotted it becomes evident that two groupings are present (Figure 5.4). The lower coarser grained unit has an average porosity of 15% and permeability of 104.5 mD, the upper unit has an average porosity of 10% and permeability of 0.4 mD. The spatial distribution of the two units may affect reservoir continuity. In addition, and productivity may be affected where the finer grained portion of Lithofacies 5 is present.

Section 5.2 La Glace Bluesky A Pool

The La Glace Bluesky A pool produces from tidal inlet sandstone (Lithofacies 6) of a transgressive barrier bar. The pool, discovered in 1979 at 7-30-74-7W6, has had a net cumulative production of $566 \times 10^6 \text{ m}^3$ from an initial established reserves of $1298 \times 10^6 \text{ m}^3$ gas (EUB, 1997). A total of 13 wells within this pool produce along the trend of the La Glace barrier complex within the study area (Figure 5.1).

The porosity-permeability relationship was determined from the extensive core control in township 74-7W6 (Figure 5.5). To determine the effect of bioturbation the data was grouped based on core description of the presence of *Macaronichnus* burrows. Porosity and permeability is best developed near the top of the lithofacies where it is intensively bioturbated by *Macaronichnus* (Figure 5.5).

During transgression this barrier island complex was drowned and preserved as a ridge on the shelf and subsequently buried by shale of the Wilrich Formation. The

Figure 5.4 Permeability – porosity cross plot of Lithofacies 5 from the reservoir zone at 02/6-19-75-8W6 divided into two units based on grain size differences observed in core. Red triangles are fine grained unit, black squares are coarser basal part of the lithofacies. The heavy black line is the line of best fit, light black lines are plus and minus 1 standard deviation.

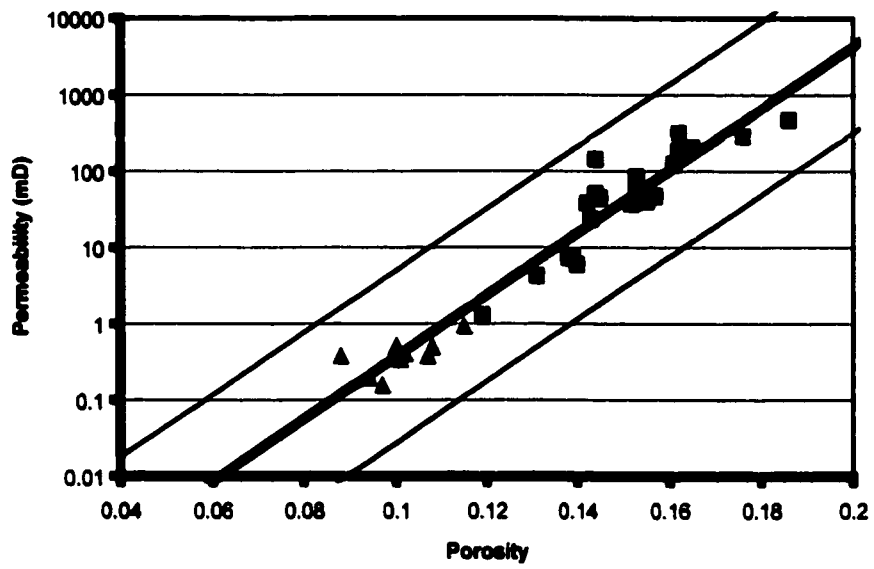
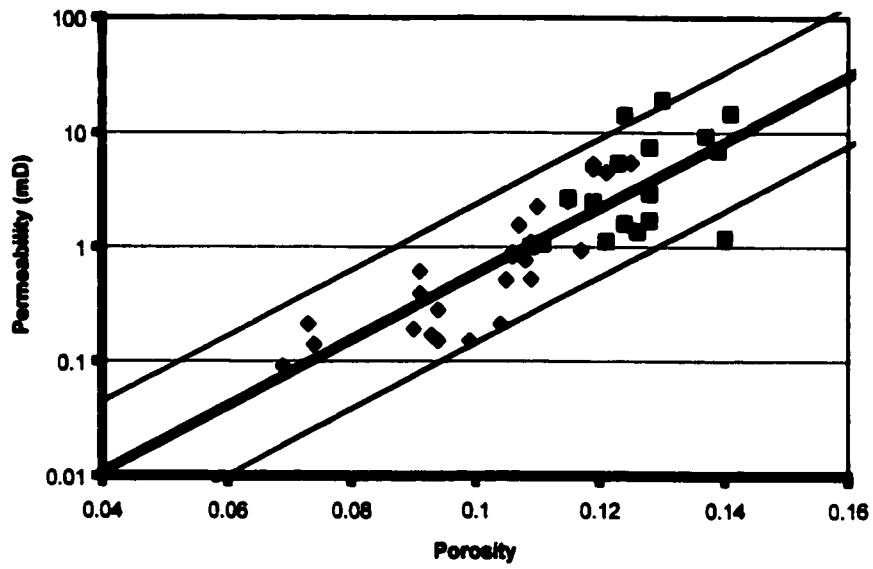


Figure 5.5 Permeability – porosity cross plot of Lithofacies 6 from producing wells in the La Glace Bluesky A pool divided into two units based on the presence intense bioturbation by *Macaronichnus*. Black squares are samples from where the lithofacies is bioturbated by *Macaronichnus*. The heavy black line is the line of best fit, light black lines are plus and minus 1 standard deviation.



overlying shale provides an effective lateral and top seal to the barrier complex. In addition, up-dip to the northeast the barrier complex thins forming a stratigraphic pinch-out and trap (Figures 3.7 and 3.10).

Section 5.3 Valhalla Bluesky L and U Pools

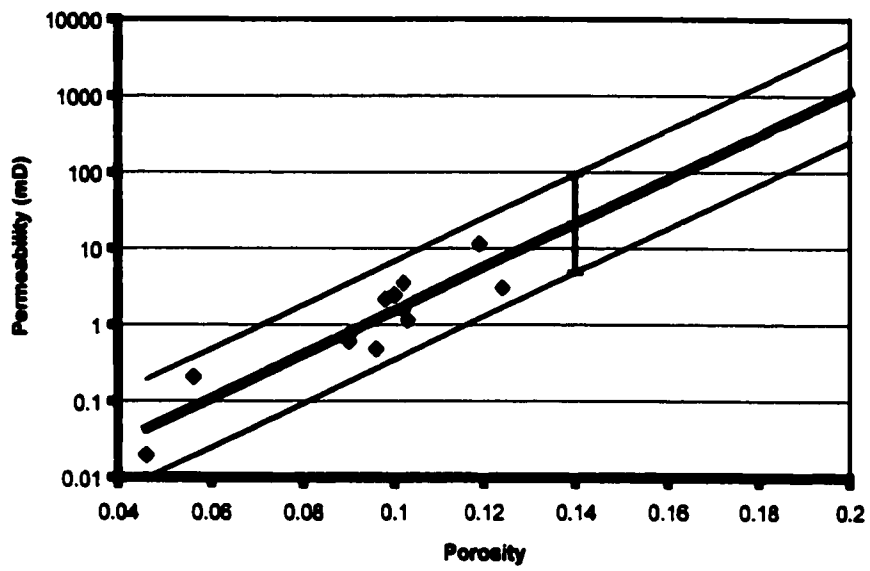
Production in the Valhalla Bluesky L and U pools is from the upper few metres of the Bluesky Formation. These strata are interpreted to be a transgressive lag consisting of glauconitic sandstone (Lithofacies 1) that was formed by the reworking of a barrier bar complex and the formation of a subtidal shoal. The two pools are situated on the Valhalla shoal and contain a single well each: 6-31-74-9W6 and 02/14-6-75-8W6 (Figure 5.1). The Bluesky L pool was discovered in 1989 with total initial established reserves of $219 \times 10^6 \text{ m}^3$, the Bluesky U pool, discovered in 1983, had a total initial established reserves of $31 \times 10^6 \text{ m}^3$ (EUB, 1997).

A porosity-permeability cross plot was created using core analysis from nearby wells that contain Lithofacies 1. The reservoir lithofacies is cored along strike at 6-10-75-8W6 and to the south of the reservoir trend at 11-18-74-7W6 (Figure 5.6).

The porosity of the reservoir interval from neutron porosity logs of the producing wells is approximately 14 %, the corresponding permeability is interpreted to be between 4 and 95 mD (Figure 5.6). This is higher than that observed in core from the non-producing wells possibly due to differences in the amount of reworking and shale content within the lithofacies.

Like the La Glace Bluesky A pool this pool was preserved as a ridge of sediment

Figure 5.6 Permeability – porosity cross plot of Lithofacies 1 from non-producing wells with core, see text for locations. The heavy black line is the line of best fit, light black lines are plus and minus 1 standard deviation. Estimated porosity from wells producing from this facies is 14%.



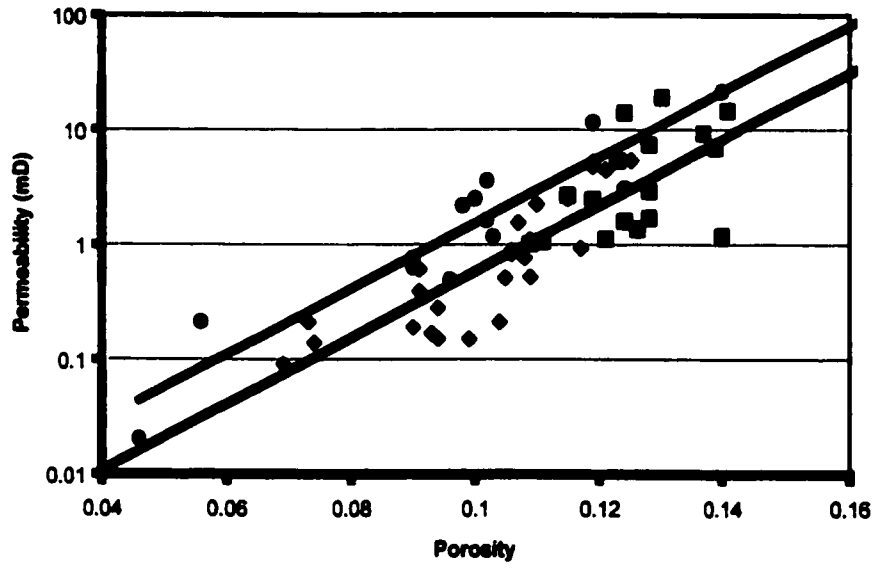
during transgression and overlain by Wilrich Formation shale which acts as a lateral and top seal. This reservoir facies is not as extensive as the La Glace Bluesky A pool and pinches up-dip to the northeast (Figures 3.7 and 3.10). It is interesting to note that this shoal of Lithofacies 1 is interpreted to have formed by the reworking of a submerged barrier bar complex of Lithofacies 6 tidal inlet sandstone. A porosity-permeability cross plot of Lithofacies 1 and Lithofacies 6 displays two parallel trends (Figure 5.7). The reworking and winnowing of the barrier complex has resulted in an increase of permeability in Lithofacies 1 as compared to Lithofacies 6.

Section 5.4. Summary

Of the three different reservoir types discussed, the reservoir within fluvial sandstone (Lithofacies 5) has the greatest porosity and permeability observed. Grain size variations have a great impact on the porosity of this lithofacies and likely represents sub-facies deposited with the fluvial environment. The association of a lower porosity, smaller grained sub-facies with the higher porosity, coarser grained sub-facies may act to compartmentalize and reduce production from this lithofacies.

Barrier bar complexes and subtidal shoals form linear sandstone bodies (Lithofacies 6 and 1) that can host gas reservoirs. Reservoirs hosted within deposits of a barrier complex have been observed at the top of the Bluesky Formation and are preserved transgressive deposits. The La Glace Bluesky A pool and the Valhalla Bluesky L and U pools are both hosted within near-shore transgressive deposits. The La Glace Bluesky A pool is an example of a barrier island complex and the Valhalla Bluesky L and U pools are

Figure 5.7 Permeability – porosity cross plot of Lithofacies 1 from Figure 5.6 and Lithofacies 6 from Figure 5.5. Black squares are samples from where the Lithofacies 6 is bioturbated by *Macaronichnus*, blue diamonds are the remainder of Lithofacies 6, red circles are measurements from Lithofacies 1. The heavy black line is the line of best fit of Lithofacies 6, red is Lithofacies 1. Note the increased permeability of Lithofacies 1 is interpreted to have formed from the reworking of Lithofacies 6 in the upper shoreface.



hosted within a shoal formed by subsequently reworking of the barrier complex. Reworking of the barrier complex presumably results in a decrease of the thickness and size of the barrier complex and the formation of a lag deposit, which has a higher permeability than the original barrier deposits (Figure 5.7).

Section 6.0. Discussion

This study does not dispute recent work from the Peace River Arch Region (Clark, 1978; Jackson, 1984; Smith et al. 1984; O'Connell, 1988; Oppelt, 1989; LeDrew, 1992; Male 1992; Brekke 1995), that observed the Bluesky Formation as fluvial/near-shore transgressive deposits and regressive shoreface deposits.

Brekke (1995) indicates that shoreface deposits in the upper Gething Formation are difficult to distinguish from the overlying Bluesky Formation due to their deposition in similar environments. Brekke (1995) picked the Bluesky-Gething formational contact at a regional transgressive lag overlying supposed Gething Formation shoreface deposits (WRS 3). Using this surface as the formational contact Sequence 1 and the lower part of Sequence 2 of this study would be grouped within the Gething Formation. However, the Gething Formation is dominantly coastal plain deposits, with the associated shoreline of the Boreal Sea during the late Aptian in northeastern British Columbia (Stott, 1973). As pointed out by O'Connell (1988), a transgression of the Boreal Sea into Alberta prior to Bluesky time was noted by Jackson (1984) but is speculative and difficult to distinguish. In this study therefore, the base of the Bluesky Formation was consistently picked where shoreface deposits overlie coastal plain deposits of the Gething Formation.

The contact between the Bluesky and Gething formations throughout most of the study area is a transgressive wave ravinement surface within Sequence 1 where marine shale and sandstone overlie coaly coastal plain deposits. Within the study area it can be shown that marine shoreface deposits of Sequence 1 pass laterally into coastal plain deposits of Gething Formation. It is presumed that beyond the transgressive limit of Sequence 2 (to the south of the study area) highstand coastal plain deposits would be

present and termed Gething Formation.

Within the study area highstand regressive deposits of Sequence 2 comprise lower shoreface and offshore shale. The Shale Break within the study area is overlain disconformably by lower shoreface sandstone. The contact is the result of a fall of relative sea level and represents a forced regression. However, the study area was near the margin of the foreland basin at that time (Figure 4.6) (Jackson, 1984; Stott, 1993). Here accommodation space is less and local sedimentation patterns may have been significantly affected by local older structures that were reactivated during deposition of the Bluesky Formation. As discussed earlier, the Shale Break is present at least 40+ km toward the west. Tentative correlations with the work of Brekke (1995) places the Shale Break at the base of a coarsening upward succession (Figure 11 and 12 of Brekke, 1995). Given that to the west of the study area the contact between the Shale Break and overlying lower shoreface sandstone appears gradational, the sharp contact within the study area is most likely only a local feature. This suggests that the sharp-based sandstone observed in the study area is the result of reduced accommodation space nearing the margin of the foreland basin, controlled by local reactivated structures.

Transgressive deposits Sequence 3 include local ridges formed as barrier bar complexes overlain by a regional lag deposit. Recent work by O'Connell (1997) reinterpreted barrier complexes in the La Glace field as fluvial/estuarine deposits overlying a lowstand unconformity. He noted that the fluvial complex is traceable east-west for 200 km and is incised into an underlying tightly cemented shoreface succession. O'Connell (1997) is correct in his identification of a sequence boundary at the base of the reservoir unit at La Glace, however, this study interprets this succession as a preserved

barrier complex formed during transgression. The preserved transgressive deposits of Sequence 3 produce topographical relief on the upper surface of the Bluesky Formation and therefore, if the sharp sandstone to shale transition between the Bluesky and Wilrich formations is used as a datum it appears the coarser more proximal deposits have incised into lower shoreface deposits. By using a lower datum, such as the base of the Shale Break, the relief produced by the barrier complexes can be observed on cross sections.

The mechanisms for the preservation of transgressive deposits are largely a function of sediment supply, gradient of the coast and the rate of relative sea level rise. In the Bluesky Formation within the Valhalla region thick preserved transgressive barrier complexes coincide with the down-thrown footwall of older reverse faults. Structural reactivation of older structures was suggested by O'Connell (1988), who attributed thickening of Bluesky Formation shoreline sandstone to structural reactivation of the axial graben of the Peace River Arch. Within the study area evidence for structural reactivation includes modern-day structural anomalies of the top along the Bluesky Formation following the trend of known faults. Evidence supports the activity of the faults during and after deposition of the Bluesky Formation, and suggest that changes in the coastal gradient may have affected the position and preservation of transgressive deposits.

In summary, the Bluesky Formation comprises high order sequences deposited during the progressive transgression of the Boreal Sea. In the Valhalla region the deposition and preservation of transgressive and regressive marine deposits was controlled by reactivation of older basement rooted structures.

Section 7.0. Conclusions

1. The Bluesky Formation lies between coastal plain deposits of the Gething Formation and distal marine shale of the Wilrich Formation and records the progressive transgression of the Boreal Sea during the late Aptian to early Albian. The main conclusions of this thesis are summarized below.
2. Based on core observations 7 lithofacies were identified. Bluesky Formation deposition environments vary from marginal marine fluvial sandstone through nearshore and distal marine environments. Based on paleoenvironmental distribution of the lithofacies the Bluesky Formation in the Valhalla regional can be subdivided into 3 high order sequences.
3. Northwest trending valleys were incised into coastal plain deposits of the Gething Formation and filled by fluvial sandstone during subsequent transgression. Overlying, the fluvial sandstone is a wave ravinement surface; where valleys are not present the wave ravinement surface is amalgamated with the sequence boundary. Highstand deposits of Sequence 1 consist of a single northwest-prograding marine parasequence. The transgressive limit has been identified in the southern part of the study area where marine sandstone passes laterally into coastal plain coaly shale and sandstone of the Gething Formation.
4. A fall of relative sea level following the deposition of Sequence 1 resulting in lowstand incision. During the subsequent rise of relative sea level fluvial deposits of

Sequence 2 filled the valley system and a northeast trending barrier bar complex developed in the northern part of the study area. Locally, retrogradation was interrupted by a period of stillstand during which marine sandstone and shale were deposited in a northwest prograding delta, fed by sediment supplied from the still active fluvial system. Subsequently resumed retrogradation formed a wave ravinement surface across the study area. Overlying the transgressive surface is distal marine shale of the highstand, the maximum flooding surface is most likely located near the base of this shale. This unit is in turn overlain by a sharp-based sandstone deposited as a result of a forced regression.

5. Preserved transgressive barrier complexes of Sequence 3 cap the Bluesky Formation and were deposited and preserved during the final transgression of the Boreal Sea during Bluesky time. Highstand deposits of Sequence 3 are distal marine shales of the Wilrich Formation. The presence of a sequence boundary between sequences 2 and 3 was inferred by the presence of a sharp based sandstone in the northwestern most corner of the study area interpreted to be a preserved barrier complex. An alternative interpretation is that this sandstone is an upper shoreface sandstone following a forced regression. Nevertheless, irrespective of interpretation this unit represents deposition following a fall of relative sea level and therefore forms the sequence boundary that caps Sequence 2 and lies at the base of Sequence 3.
6. Reactivated Paleozoic structures influenced the deposition and preservation of the Bluesky Formation. Progressive thickening of the Bluesky Formation from the

northeast to southwest is attributed to increasing accommodation space nearing the axis of the foreland base, and reactivated Devonian northwest trending faults. Increased preservation of the Shale Break to the southeast is likely the result of increased accommodation space on the down-thrown side of a reactivated fault. Ridges of sediment at the top of the Bluesky Formation were deposited as barrier bar complexes that were drowned during the final transgression of the Boreal Sea through the study area. Reactivation of east-northeast trending Devonian faults may have influenced the position of drowned barrier complexes by changing the local gradient of the coast and may have increased preservation by increasing local accommodation space. Modern-day anomalies in the slope of the top of the Bluesky Formation represent faults related to reactivation of faults after deposition of the Bluesky Formation.

Section 7.0 References

- Alberta Energy and Utilities Board, 1997. Alberta's reserves of crude oil, gas, natural gas liquids, and sulphur at 31 December 1996. Alberta Energy and Utilities Board Statistical Series 97-18. Calgary, Alberta.
- Alberta Study Group, 1954. Lower Cretaceous of the Peace River Region. In: Western Canada Sedimentary Basin, Rutherford Memorial Volume, L.M. Clark (ed.). American Association of Petroleum Geologists, Tulsa, Oklahoma, p. 268-252.
- Alway, Robert 1995. Sedimentology and Stratigraphy of the Lower Cretaceous Bluesky Formation, Aitken Creek Field, British Columbia. University of Alberta, Master of Science.
- Amorosi, A., 1995. Glaucony and Sequence Stratigraphy: A conceptual Framework of Distribution in Siliciclastic Sequences. *Journal of Sedimentary Research*, v. B65, n. 4, pp. 419-425.
- Cederwall, D.A., 1989. The Lower Cretaceous. In: Geophysical atlas of Western Canadian hydrocarbon pools, N.L. Anderson, L.V. Hills and D.A. Cederwall (eds.). CSEG/CSPG, Canada, pp. 217-281.
- Arnott, R.W.C. and Southard, J.B., 1990. Exploratory flow-duct experiments on combined-flow bed configurations, and some implications for interpreting storm-event stratification: *Journal of Sedimentary Petrology*, v. 60, p. 211-219.
- Arnott, R.W.C., 1993. Sedimentological and sequence stratigraphic model of the Falher "D" Pool, Lower Cretaceous, northwestern Alberta. *Bulletin of Canadian Petroleum Geology*, v. 41. n. 4 p. 453-463.
- Arnott, R.W.C., 1995. The parasequence definition – are transgressive deposits inadequately addressed? *Journal of Sedimentary Research*, v. B65, n. 1, p. 1-6.
- Badgley, P.C., 1952. Notes on the subsurface stratigraphy and oil and gas geology of the Lower Cretaceous Series in Central Alberta. *Geological Survey of Canada Paper* 52-11, 12 p.
- Banerjee, Indranil and Davies, Edward H., 1988. An Intergrated Lithostratigraphic and Palynostratigraphic Study of the Ostracode Zone and Adjacent Strata in the Edmonton Embayment, Central Alberta. In: *Sequences, Stratigraphy, Sedimentology: Surface and Subsurface*, D.P. James and D.A. Leckie (eds.). Canadian Society of Petroleum Geologists, Memoir 15, p. 261-274.
- Barclay, J.E., Krause, F.F., Campbell, R.I., Utting, J., 1990, Dynamic casting and growth

- faulting: Dawson Creek Graben Complex, Carboniferous-Permian Peace Embayment, Western Canada. In: O'Connell, S.C. and Bell, J.S. (eds.), *Geology of the Peace River Arch: Bulletin of Canadian Petroleum Geology Special Volume 38A*, p. 115-145.
- Bhattacharya, J.P., and Walker, R.G., 1992. Deltas. In: *Facies Models, Response to Sea Level Change*. R.G. Walker and N.P. James (eds.), Geological Association of Canada. pp. 157-177.
- Bohacs, K., and Suter, J., 1997. Sequence stratigraphic distribution of coaly rocks: Fundamental controls and paralic examples. *Bulletin of the American Association of Petroleum Geologists*, v. 81, n. 10, p. 1612-1639.
- Brekke, H.G., 1995. Ichnology and sedimentology of the lower Cretaceous Bluesky Formation, Sinclair field area, west central Alberta. Unpublished M.Sc. thesis, University of Alberta, Edmonton, Alberta, 164 p.
- Cant, D.J. and Abrahamson, B., 1996. Regional distribution and internal stratigraphy of the Lower Mannville. *Bulletin of Canadian Petroleum Geology*, vol.44 no. 3, p. 508-529.
- Cant, D.J. and Walker, R.G., 1978. Fluvial processes and facies sequences in the sandy braided South Saskatchewan River, Canada. *Sedimentology*, v. 25, pp. 625-648.
- Clark, I.D., 1978. Depositional history of the Bluesky Formation (Lower Cretaceous) Fort St. John region, northeastern British Columbia. Unpublished B.Sc. thesis, University of Waterloo, Ontario, 74 p.
- Clifton, H.E., Hunter, R.E. and Phillips, R.L., 1971. Depositional structures and processes in the non-barred high-energy nearshore. *Journal of Sedimentary Petrology*, v. 41, n. 3, p. 651-670.
- Clifton, H.E., and Thompson, J.E., 1978. *Macaronichnus segregatis*- A Feeding Structure of Shallow Marine Polychaetes. *Journal of Sedimentary Petrology*, vol. 48, p. 1293-1302.
- Diessel, C.F.K., 1992. *Coal-bearing depositional systems*: Berlin, Springer-Verlag, 721 p.
- Droser, M.L. and Bottjer, D.J., 1986. A semiquantitative field classification of ichnofabric. *Journal of Sedimentary Petrology*, v. 56, p. 558-559.
- Eckdale, A.A., Bromley, R.G. and Pemberton, S.G., 1984. Ichnology: the use of trace fossils in sedimentology and stratigraphy. *Society of Economic Paleontologists and Mineralogists, Short course n. 15*, p. 317.

- Finger, K.I., 1983. Observations on the Lower Cretaceous Ostracode zone of Alberta. *Bulletin of Canadian Petroleum Geology*, vol.31 no. 4, p. 326-337.
- Folk, R., 1968. *Petrology of Sedimentary Rocks*. Hemphill's Book Store, Austin, Tex., 170p.
- Frey, R.W. and Pemberton, S.G., 1985. Biogenic structures in outcrops and core: I, Approaches to Ichnology, *Bulletin of Canadian Petroleum Geology*, v. 33, pp. 72-115.
- Glaister, R.P., 1959. Lower Cretaceous of southern Alberta and adjoining areas. *American Association of Petroleum Geologists Bulletin*, V. 43, p. 590-640.
- Glass, D.J., 1990. *Lexicon of Canadian Stratigraphy, Volume 4, Western Canada, Including Eastern British Columbia, Alberta, Saskatchewan and Southern Manitoba*. Canadian Society of Petroleum Geologists, Calgary, Alberta.
- Heller, P.L. and Paola, C., 1996. Downstream changes in alluvial architecture: An exploration of controls on channel-stacking patterns. *Journal of Sediment Research*, v. 66, n. 2, p. 297-306.
- Jackson, P.C., 1984. Paleogeography of the Lower Cretaceous Mannville Group of Western Canada. In Masters, J.A., *ed.*, Elmworth - case study of a deep basin gas field: *American Association of Petroleum Geologists Memoir* 38, p. 79-114.
- Leckie, D.A. and Smith, D.G., 1992, Regional setting, evolution, and depositional cycles of the Western Canada Foreland Basin, IN: R.W. Macqueen and D.A. Leckie, (eds.), *Foreland Basins and Fold Belts: Tulsa, Oklahoma, AAPG Memoir* 55, p. 9-46.
- LeDrew, N., 1992. Stratigraphy, sedimentology, and depositional model of the Lower Cretaceous Bluesky Formation, in west central Alberta from core and well logs. Unpublished B.Sc. thesis, Memorial University, St. John's, Newfoundland. 84 p.
- MacEachern, J.A. and Pemberton, S.G., 1982. Ichnological aspects of the Cretaceous shoreface successions and shoreface variability in the Western Interior Seaway of North America. In: S.G. Pemberton (ed.). *Applications of ichnology to petroleum exploration; a core workshop*, pp. 57-84.
- Male, W.H. 1992. The sedimentology and ichnology of the lower Cretaceous (Albian) Bluesky Formation in the Karr area west-central Alberta. In: *Applications of Ichnology to Petroleum Exploration: A Core Workshop*, S.G. Pemberton (ed.). *Society of Economic Paleontologists and Mineralogists Core Workshop* n. 17, p. 33-56

- Masters, J.A., 1984. Lower Cretaceous Oil and Gas in Western Canada. In Masters, J.A., *ed.*, Elmworth - case study of a deep basin gas field: American Association of Petroleum Geologists Memoir 38, p. 1-34.
- Miall, A.D., 1992. Alluvial Deposits. In: Facies Models, Response to Sea Level Change. R.G. Walker and N.P. James (eds.), Geological Association of Canada. pp. 119-142.
- Monger, J.W.H., 1989, Overview of cordilleran geology. In: B.D. Ricketts, ed., Western Canada Sedimentary Basin, a case history: Calgary, Alberta, CSPG, p. 9-32.
- Monger, J.W.H., and Hutchison, W.W., 1971. Metamorphic map of the Canadian Cordillera. Geological Survey of Canada, Paper 70-33, 61 pp.
- Moore, P.F., 1989. The Kaskaskia Sequence: Reefs, Platforms and Foredeeps The Lower Kaskaskia Sequence – Devonian. In: B.D. Ricketts, ed., Western Canada Sedimentary Basin, a case history: Calgary, Alberta, CSPG, p. 9-32.
- Moslow, Thomas, F. and Pemberton, S. George, 1988. An Integrated Approach to the Sedimentological Analysis of Some Lower Cretaceous Shoreface and Delta Front Sandstone Sequences. In: Sequences, Stratigraphy, Sedimentology: Surface and Subsurface, D.P. James and D.A. Leckie (eds.). Canadian Society of Petroleum Geologists, Memoir 15, p. 373-386.
- Moslow T.F. and Davies, G.R., 1997. Turbidite reservoir facies in the Lower Triassic Montney Formation, west-central Alberta. In: Moslow, T.F. and Wittenberg, J. (eds.), Triassic of the Western Canada Sedimentary Basin: Bulletin of Canadian Petroleum Geology Special Volume 45. n. 4, p. 507-536.
- O'Connell, S.C., 1988. The distribution of the Bluesky facies in the region overlying the Peace River Arch, northwestern Alberta. In: James, D.P. and Leckie, D.A. (eds.), Sequences, stratigraphy, sedimentology: surface and subsurface: Canadian Society of Petroleum Geologists Memoir 15, p. 401-416.
- O'Connell, S.C., Dix, G.R., Barclay, J.E., 1990, The origin, history, and regional structural development of the Peace River Arch, Western Canada. In: O'Connell, S.C. and Bell, J.S. (eds.), Geology of the Peace River Arch: Bulletin of Canadian Petroleum Geology Special Volume 38A, p. 4-24.
- O'Connell, S., 1997. The recognition of a regional lowstand unconformity within the Bluesky Formation and its influence on production in the Sexsmith field, west-central Alberta. CSPG – SEPM Joint Convention, Program with Abstracts, p. 210.
- Olson, T., Steel, R., Hogseth, K., Skar, T. and Roe, S., 1995. Sequential architecture in a fluvial succession: Sequence Stratigraphy in the Upper Cretaceous Mesaverde

- Group, Price Canyon, Utah. *Journal of Sedimentary Research*, vol. B65., no. 2, p. 265-280.
- Oppelt, H.P., 1989. Sedimentology, stratigraphy and ichnology of the Bluesky Formation in northeastern British Columbia. Unpublished M.Sc. thesis, University of Alberta, Edmonton, Alberta. 204 p.
- Pemberton, S.G. and Frey, R.W., 1985. The *Glossifungites* ichnofacies: modern examples from the Georgia Coast, U.S.A., in Curran, H.A., (ed) *Biogenic Structures: Their use in interpreting depositional environments*, Society of Economic Paleontologists and Mineralogists, Special Publication 35, pp. 234-259.
- Pemberton, S.G., MacEachern, J.A., and Frey, R.W., 1992a. Trace fossil facies models: Environmental and Allostratigraphic Significance. In: *Facies Models, Response to Sea Level Change*. R.G. Walker and N.P. James (eds.), Geological Association of Canada. pp. 47-72.
- Pemberton, S.G., Reinson, G.E., and MacEachern, J.A., 1992b. Comparative ichnological analysis of a Late Albian estuarine valley-fill and shelf-shoreface deposits, Crystal Viking Field, Alberta. In: *Applications of Ichnology to Petroleum Exploration: A Core Workshop*, S.G. Pemberton (ed.). Society of Economic Paleontologists and Mineralogists Core Workshop n. 17, p. 219-318.
- Penland, S., Boyd, R., and Suter, J.R., 1988. Transgressive depositional systems of the Mississippi River delta plain: a model for barrier shoreline and shelf development: *Journal of Sedimentary Petrology*, v. 58, p. 932-949.
- Posamentier, H.W., Allen, G.P., James, D.P. and Tesson, M., 1992. Forced regressions in a sequence stratigraphic framework: Concepts, examples and exploration significance. *American Association of Petroleum Geologists Bulletin*, v. 76, n. 11, p. 1687-1709.
- Plummer, P.S. and Gostin, V.A., 1981. Shrinkage cracks: desiccation or syneresis? *Journal of Sedimentary Petrology*, v. 51, p. 1147-1156.
- Pugh, D.C., 1960. The subsurface Gething and Bluesky formations of northeastern British Columbia. Geological Survey of Canada, Paper 60-1, 20 p.
- Kumar, N. and Sanders, J.E., 1974. Inlet sequence: a vertical succession of sedimentary structures and textures created by the lateral migration of tidal inlets. *Sedimentology*, vol. 58, p. 491-532.
- Rampino, M.R. and Sanders, J.E., 1980. Holocene transgression in south-center Long Island, New York. *Journal of Sedimentary Petrology*, v. 50, p. 1063-1080.












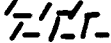



- Reinson, G.E., Lee, P.J., Warters, W., Osadetz, K.G., Bell, L.L., Price, P.R., Trollope, F., Campbell, R.I. and Barclay, J.E., 1993. Devonian gas resources of the Western Canada Sedimentary Basin. Geological Survey of Canada, Bulletin 452, 157 p.
- Reinson, G.E., 1992. Transgressive barrier island and estuary systems. In: Facies Models, Response to Sea Level Change. R.G. Walker and N.P. James (eds.), Geological Association of Canada. p. 179-194.
- Sanders, J.E., and Kumar, N., 1975a. Evidence of shoreface retreat and in-place "drowning" during Holocene submergence of barriers, shelf off Fire Island, New York: Geological Society of America Bulletin, v. 86, p. 65-76.
- Sanders, J.E., and Kumar, N., 1975b. Holocene shoestring sand on inner continental shelf off Long Island, New York. American Association of Petroleum Geologists Bulletin, v. 59, n. 6, p. 997-1009.
- Smith, D.G., Zorn, C.E., and Sneider, R.M., 1984. The Paleogeography of the Lower Cretaceous of Western Alberta and Northeastern British Columbia in and Adjacent to the Deep Basin of the Elsworth Area. in Masters, J.A., *ed.*, Elsworth - case study of a deep basin gas field: American Association of Petroleum Geologists Memoir 38, p. 49-77.
- Southard, J.B., Lambie, J.M., Federico, D.C., Pile, H.T. and Weidman, C.R., 1990. Experiments on bed configurations in fine sands under bidirectional purely oscillatory flow, and the origin of hummocky cross-stratification: Journal of Sedimentary Petrology, v. 60, p. 1-17.
- Stott, D.F., 1973. Lower Cretaceous Bullhead Group between Bullmoose Mountain and Tetsa River, Rocky Mountain Foothills, northeastern British Columbia. Geological Survey of Canada, Bulletin 219, p. 228.
- Stott, D.F., 1975. The Cretaceous system in Northeastern British Columbia. In: Caldwell, W.G.E., (*ed.*), The Cretaceous system in the western interior of North America, The Geological Association of Canada Special Paper Number 13, pp. 441-467.
- Stott, D.F., 1993. Evolution of Cretaceous Foredeeps: A comparative analysis along the length of the Canadian Rocky Mountains. In: Caldwell, W.G.E. and Kauffman, E.G., (*ed.*), Evolution of the Western Interior Basin, Geological Association of Canada Special Paper 39, pp. 131-150.
- Swift, D.J.P., 1968. Coastal erosion and transgressive stratigraphy: Journal of Geology, v. 76, p. 444-456.
- Swift, D.J.P., 1975. Barrier island genesis: evidence from the Middle Atlantic shelf of North America: Sedimentary Geology, v. 14, p. 1-43.

- Vossler, S.M. and Pemberton, S.G., 1988. Ichnology of the Cardium Formation (Pembina oilfield): implications for depositional and sequence stratigraphic interpretations. In: Sequences, Stratigraphy, Sedimentology: Surface and Subsurface, D.P. James and D.A. Leckie (eds.), Canadian Society of Petroleum Geologists, Memoir 15, pp. 237-253.
- Walker, R.G., 1995. Sedimentary and tectonic origin of a transgressive surface of erosion: Viking Formation, Alberta, Canada. *Journal of Sedimentary Research*, vol. B65, no. 2, p. 209-211.
- Walker, R.G. and Plint, A.G., 1992. Wave- and storm-dominated shallow marine systems. *in*: Walker, R.G. and James, N.P. (eds.), *Facies Models: Response to Sea Level Change*. Geological Association of Canada.

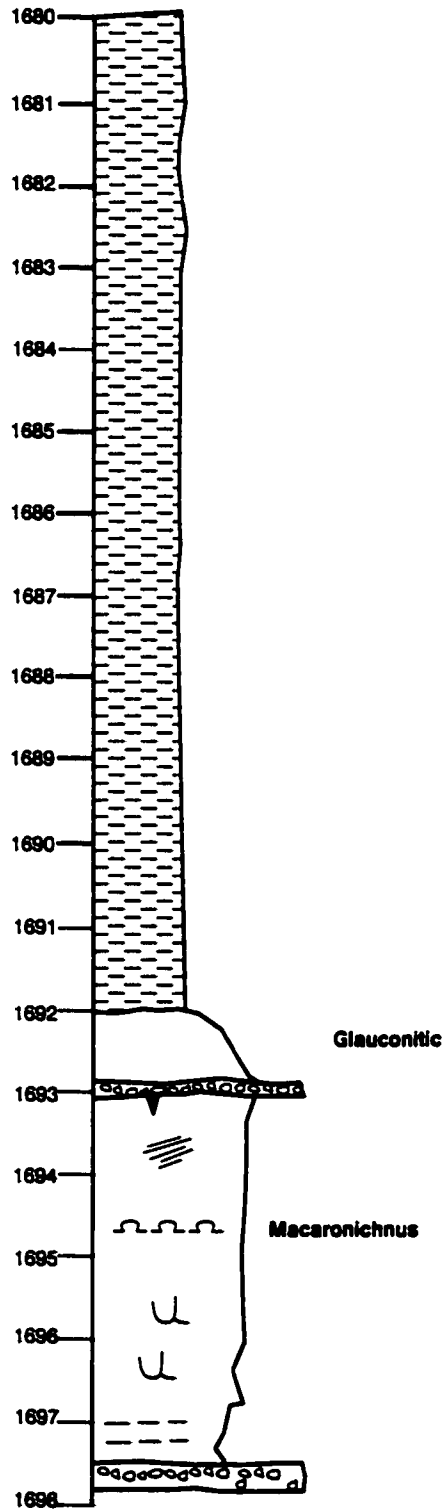
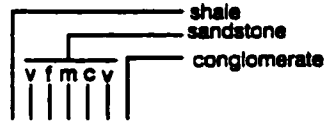
Appendix A: Core Logs

Core Log Legend

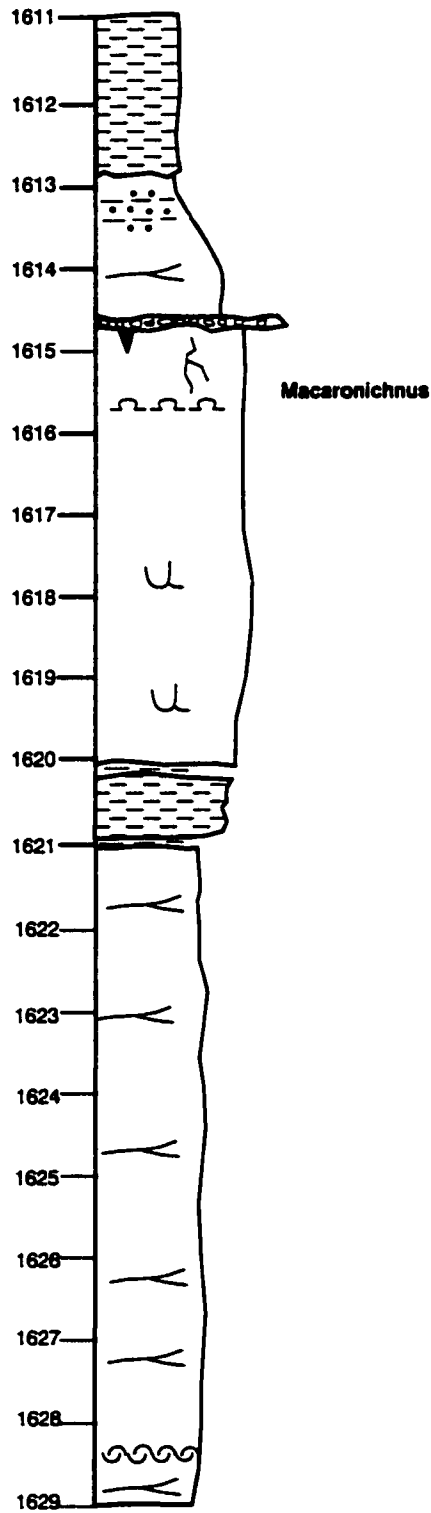
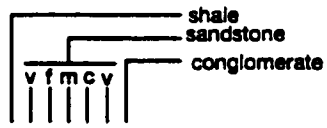
Sedimentological symbols

	bioturbation		low angle cross strat - HCS
	shell lag		low angle core cross laminate
	gravel lag		glassfungites/horizon
	shale partings		coaly laminae
	small scale unidirectional across strat		coal
	med scale		coaly mudstone
	wave cross strat		soft sed. deformation
	scour/erosional contact		
WRS	wave revinement surface	TRS	tidal revinement surface

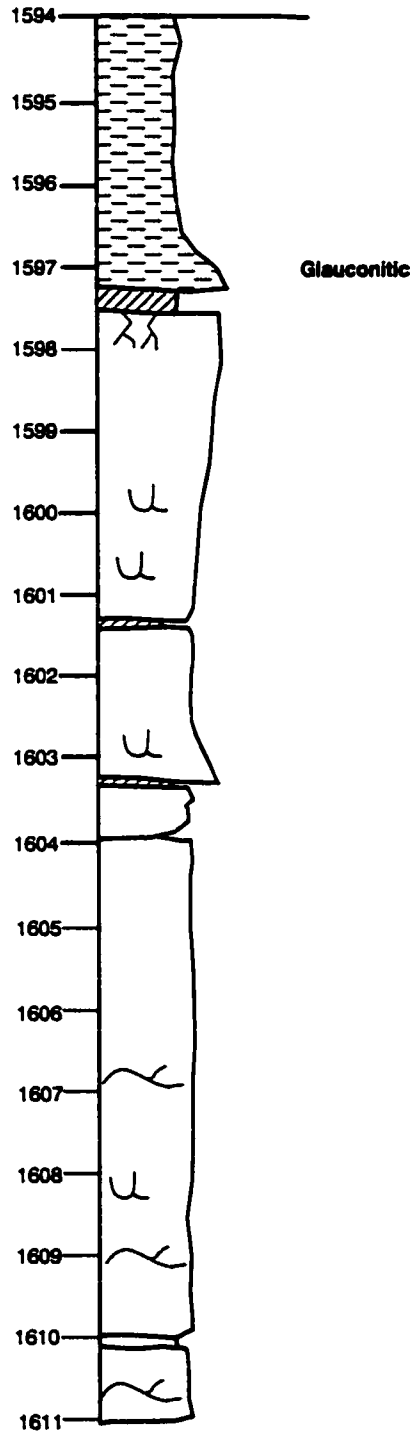
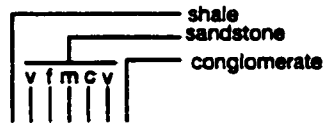
06-04-74-7W6



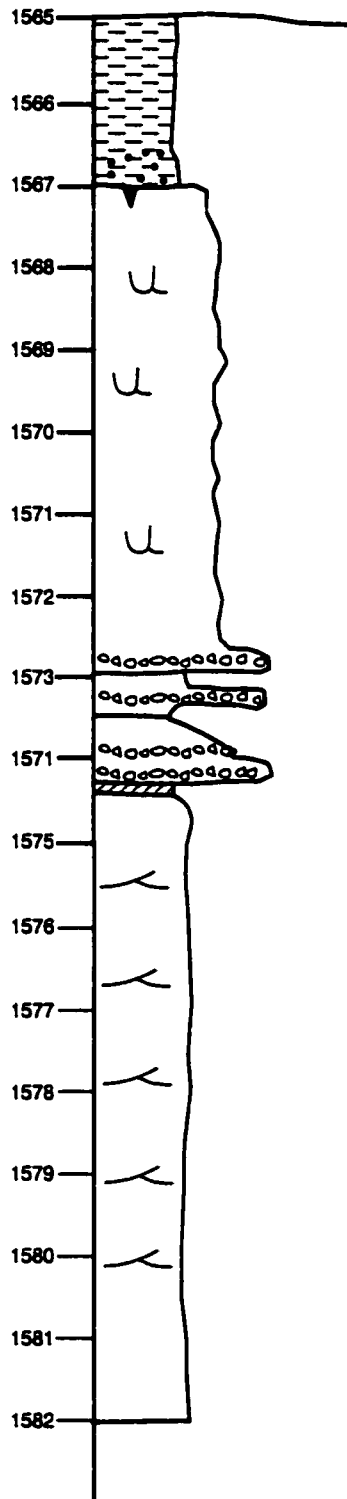
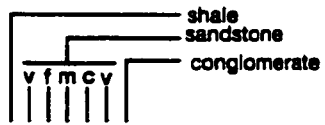
08-07-74-7W6



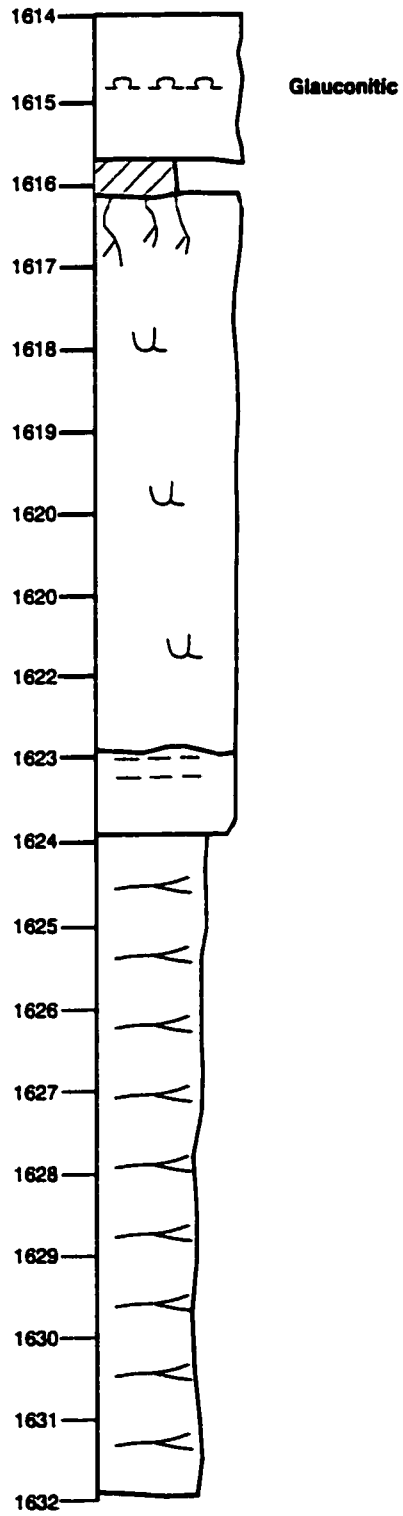
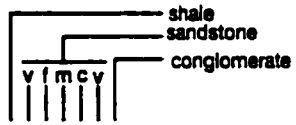
14-08-74-7W6



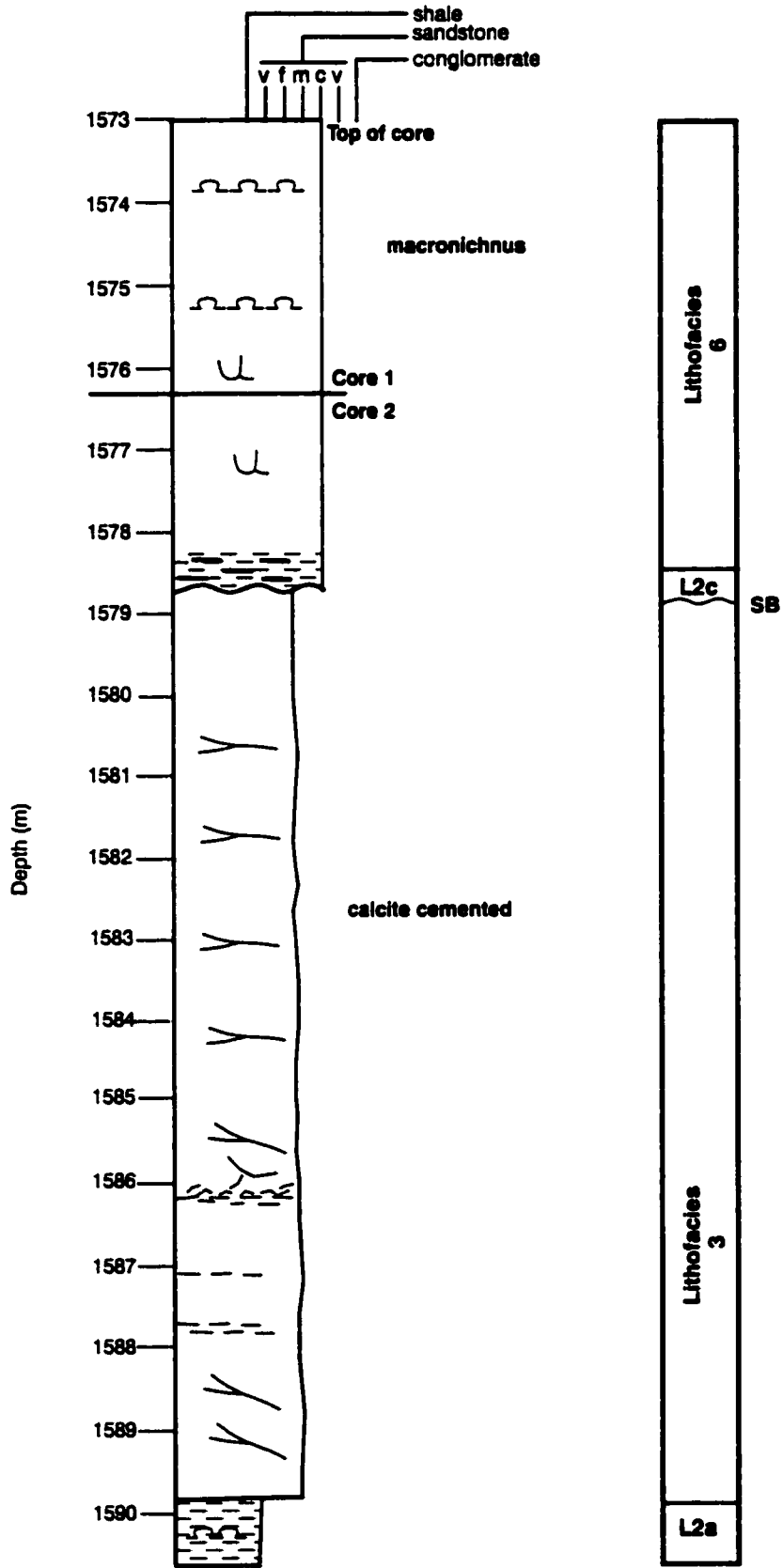
16-10-74-7W6



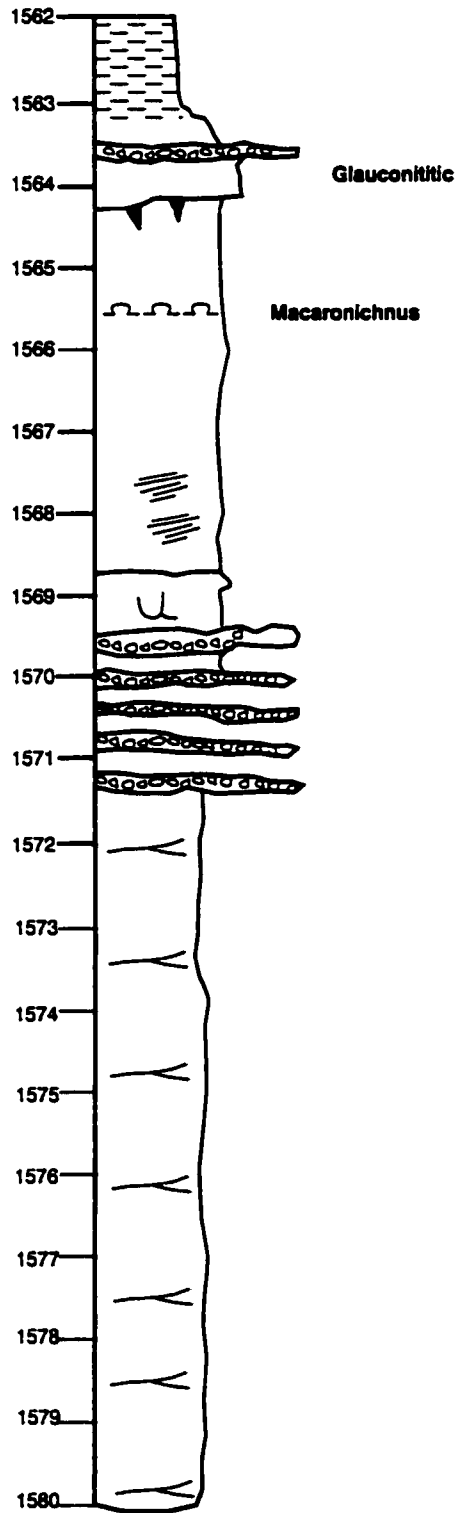
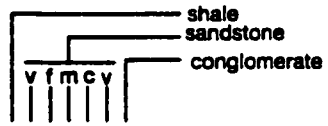
11-18-74-7W6



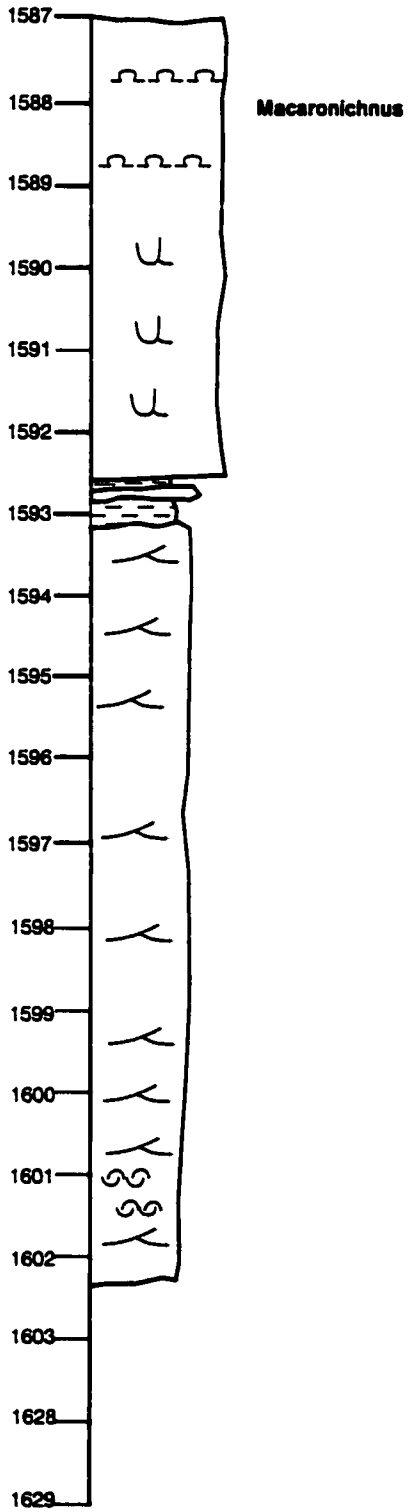
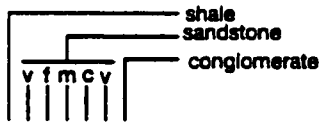
14-21-74-7W6



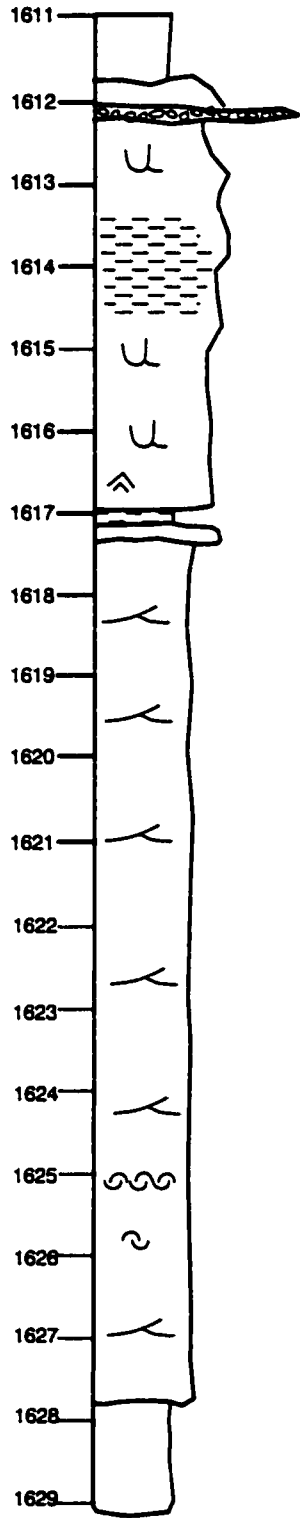
08-23-74-7W6



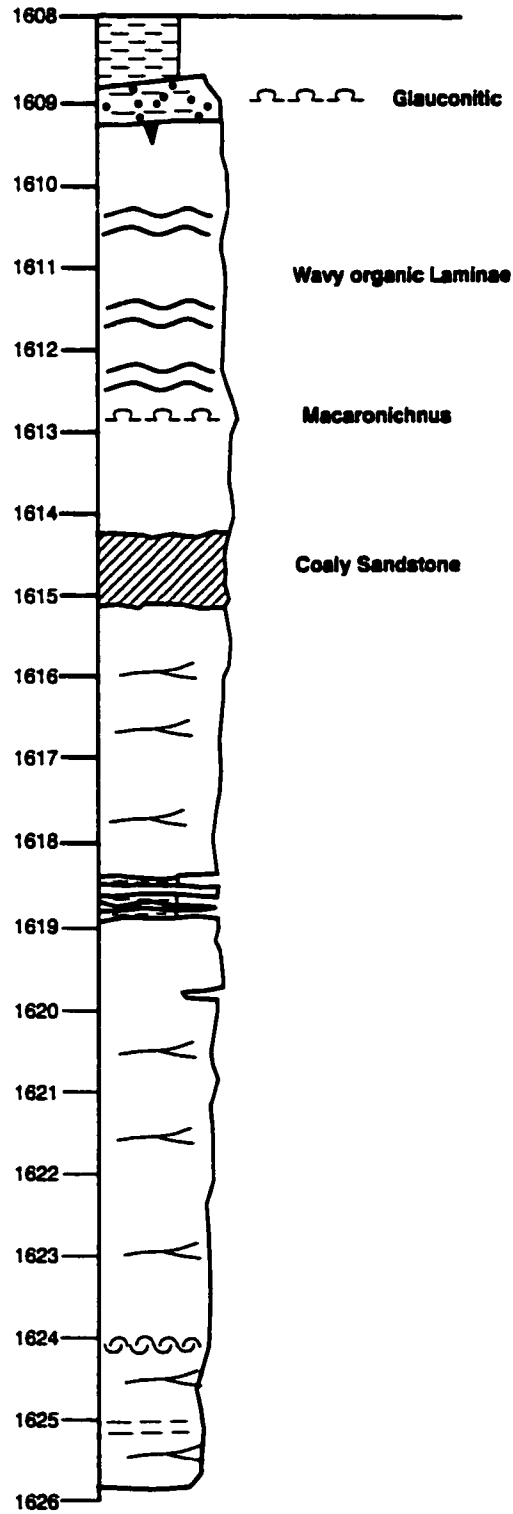
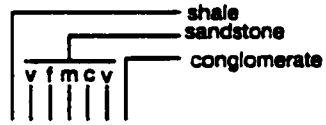
02/06-27-74-7W6



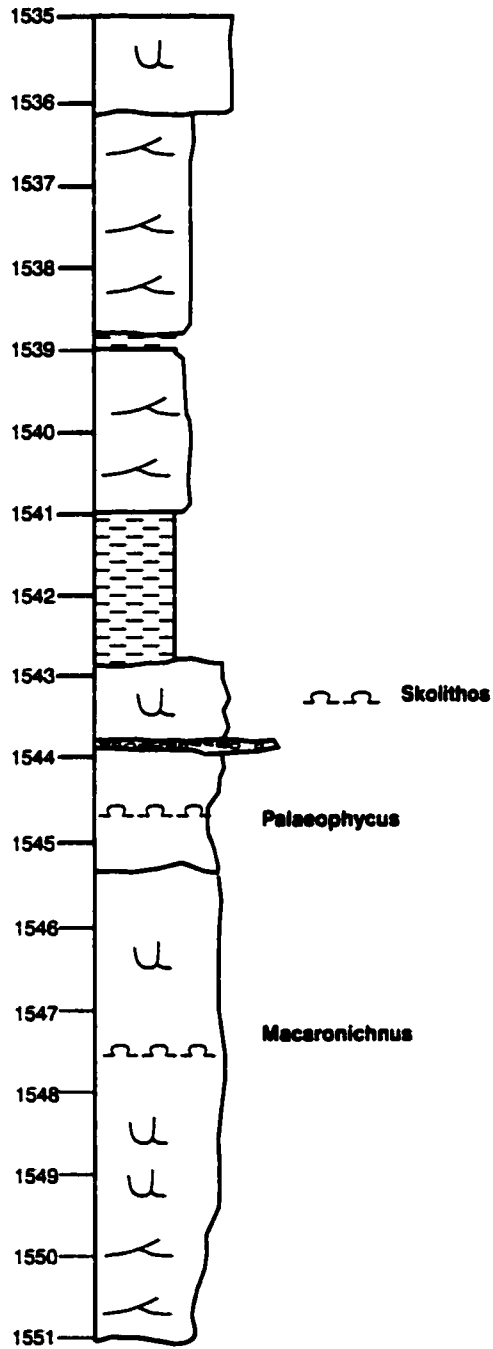
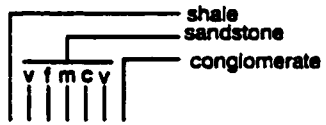
06-34-74-7W6



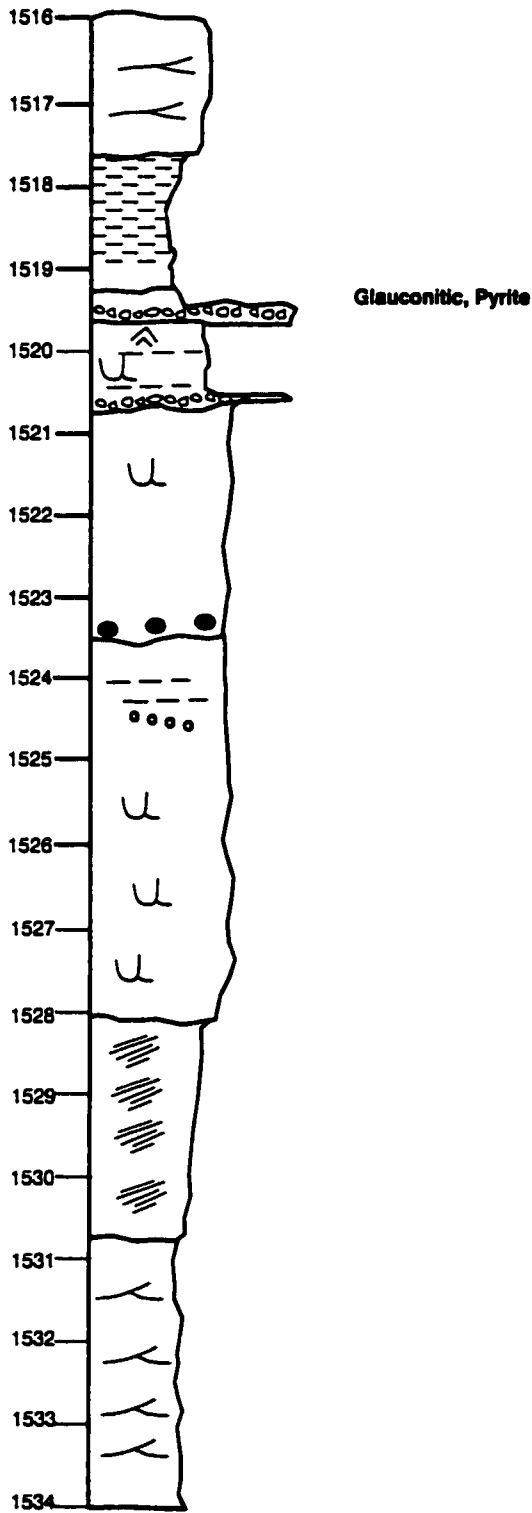
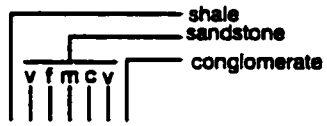
10-13-74-8W6



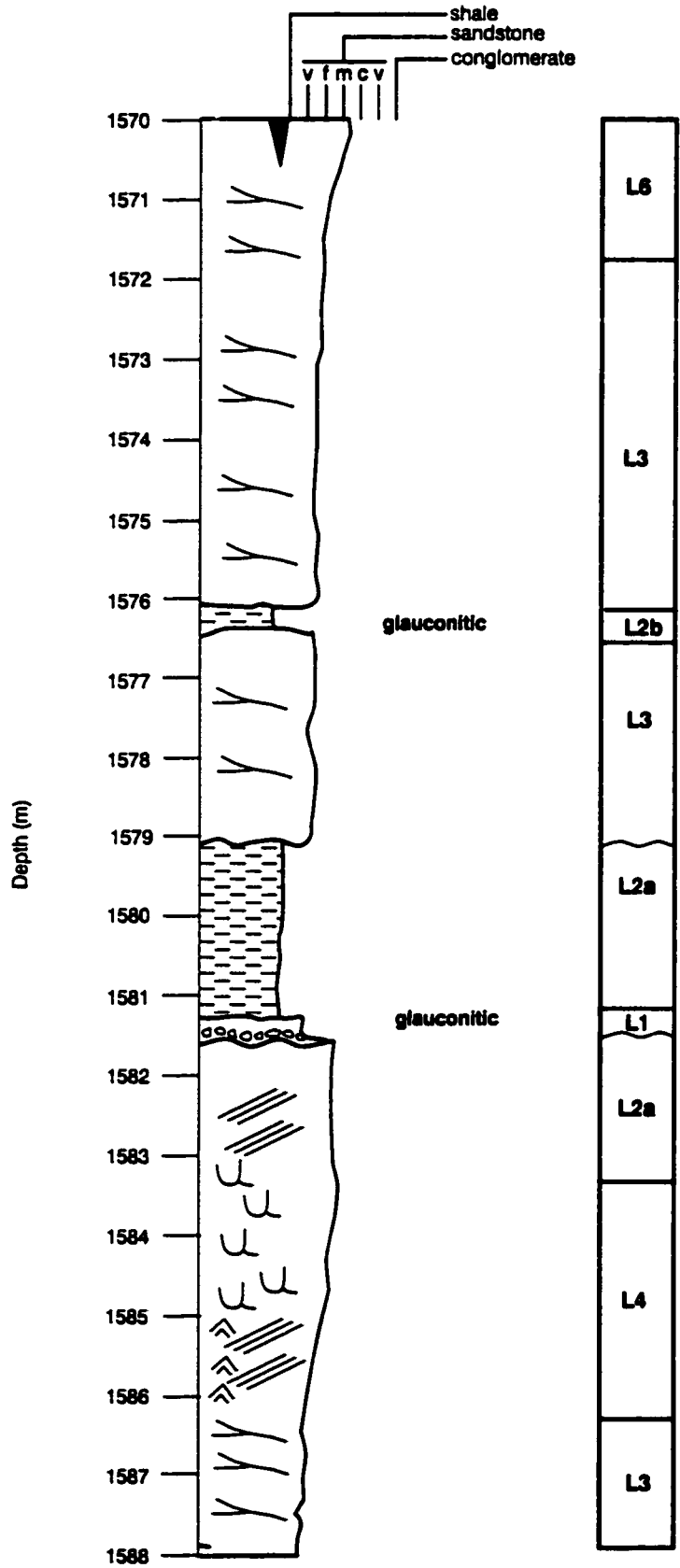
11-23-75-7W6



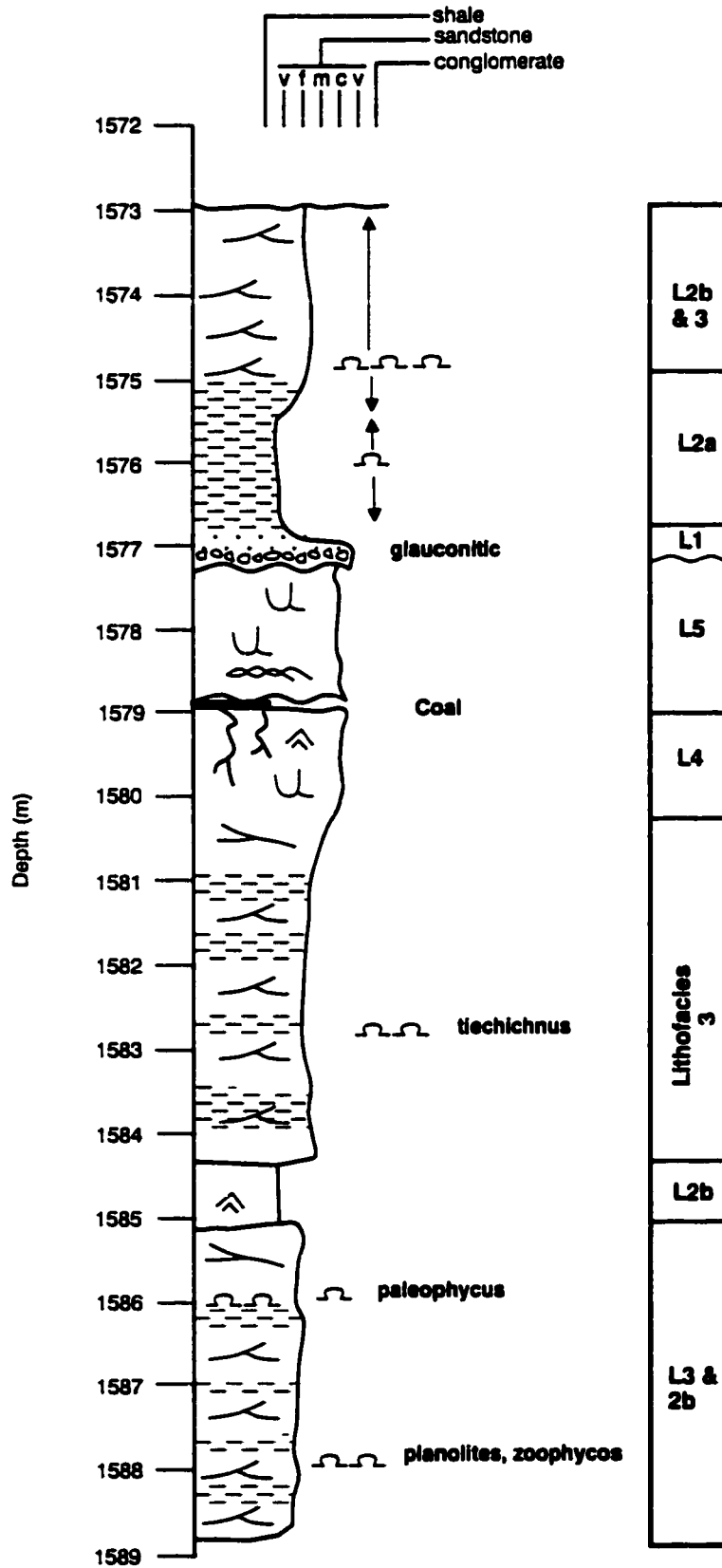
02/16-25-75-7W6



6-6-75-7W6

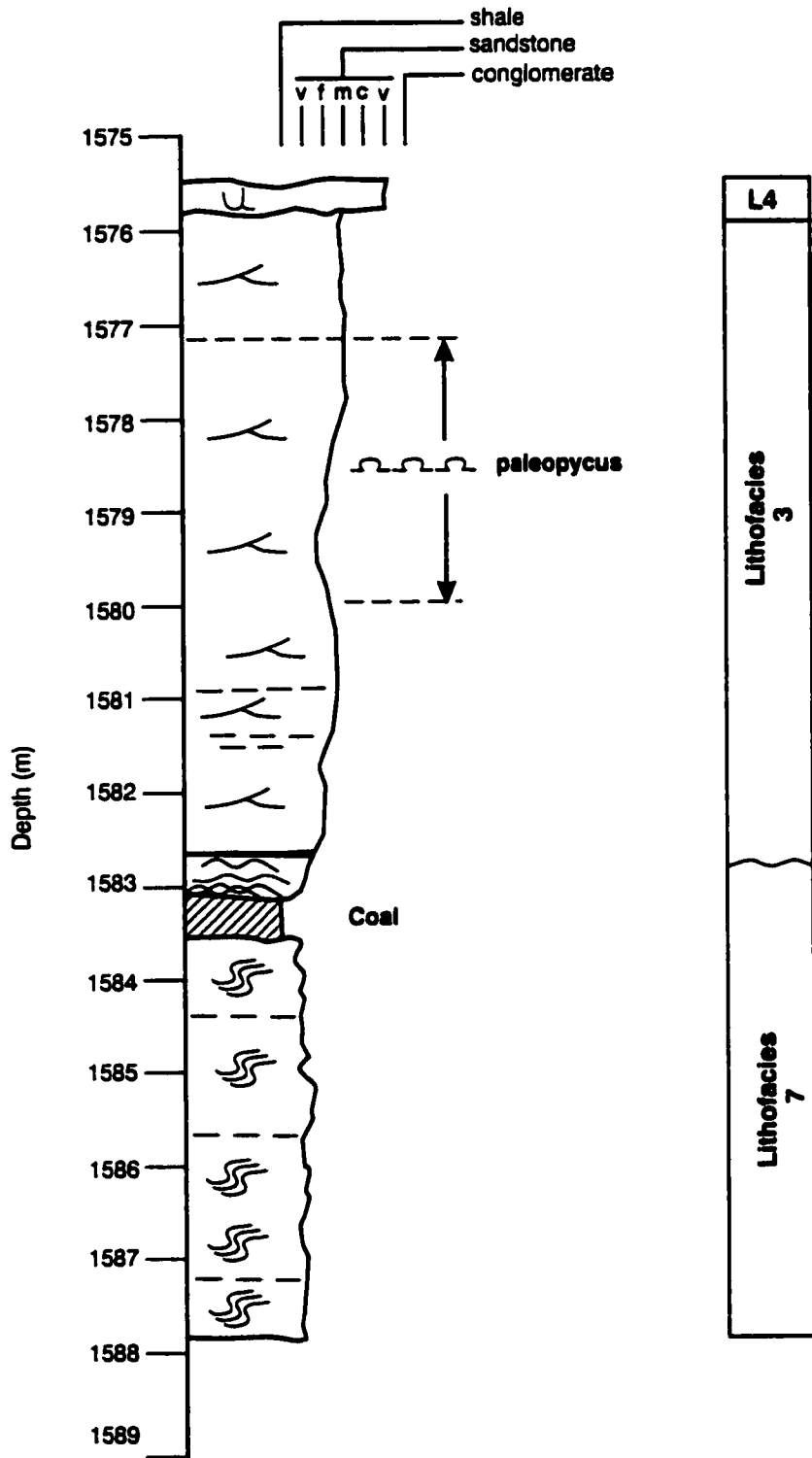


02/14-7-75-8W6

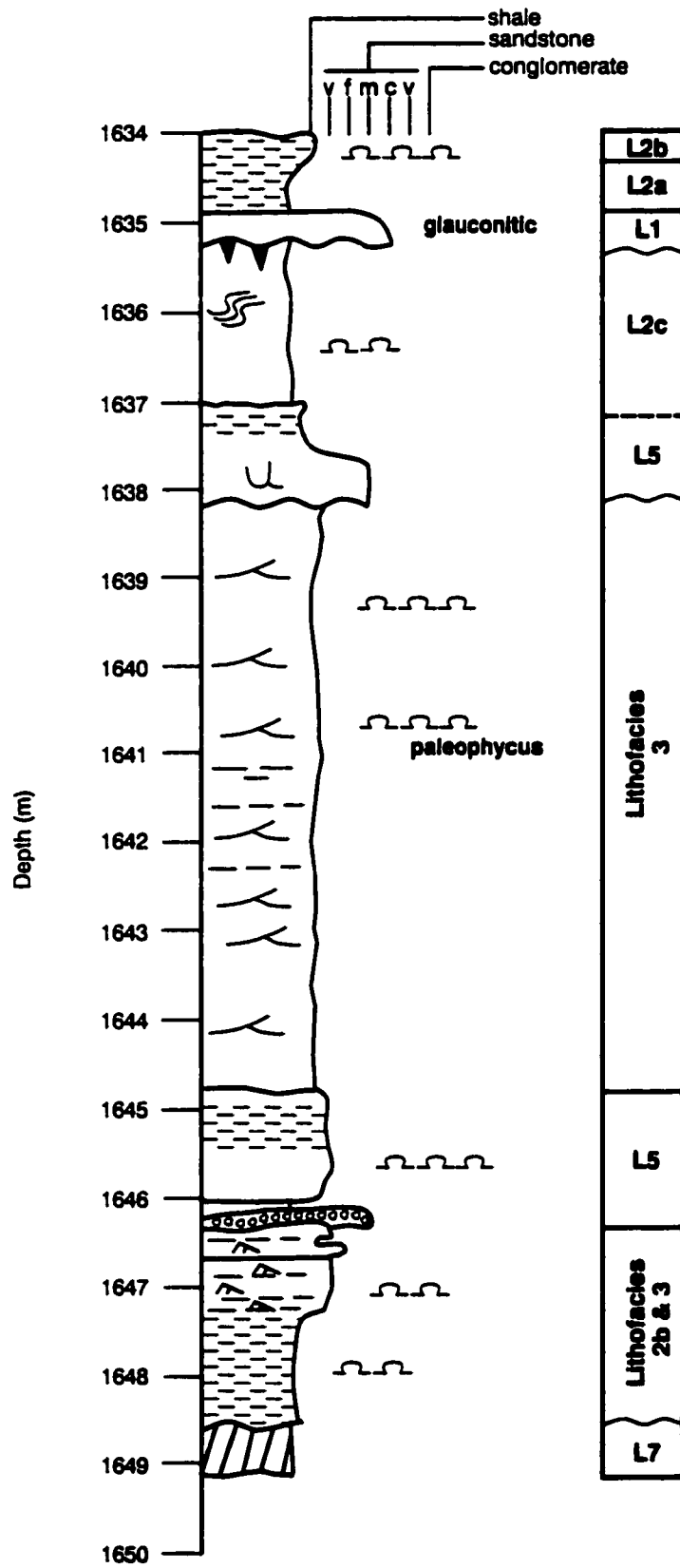


6-10-75-8W6

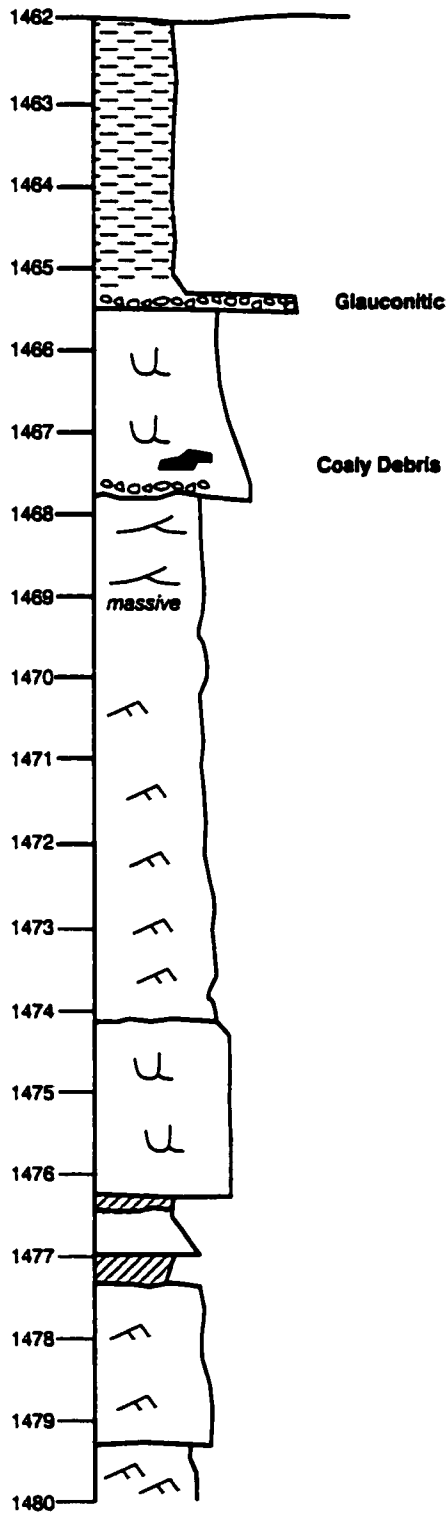
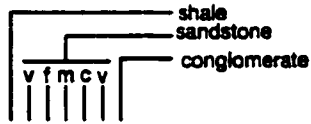
Core 2



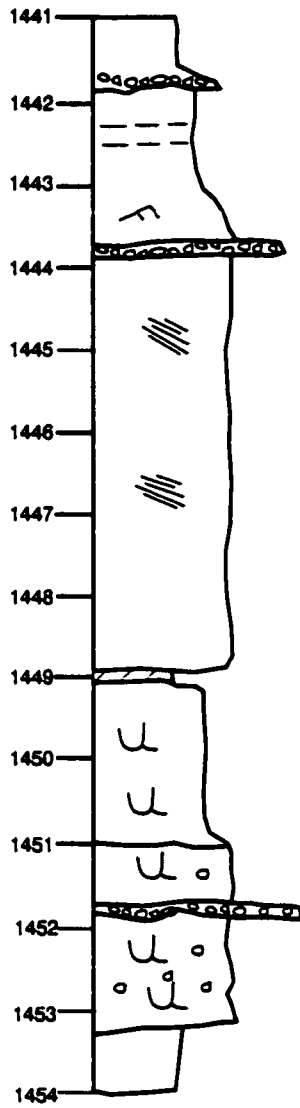
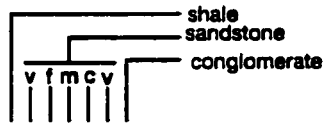
02/8-33-75-8W6



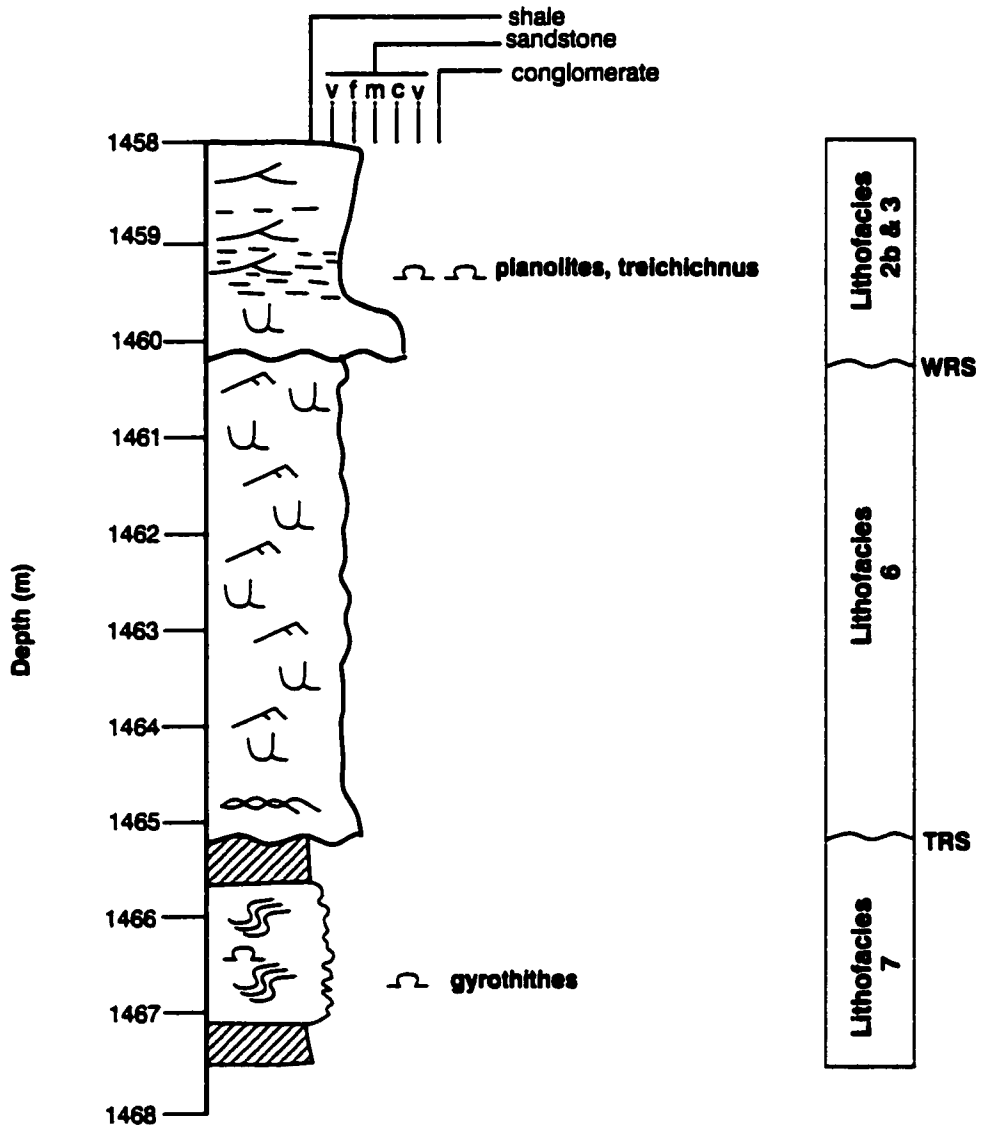
16-06-76-7W6



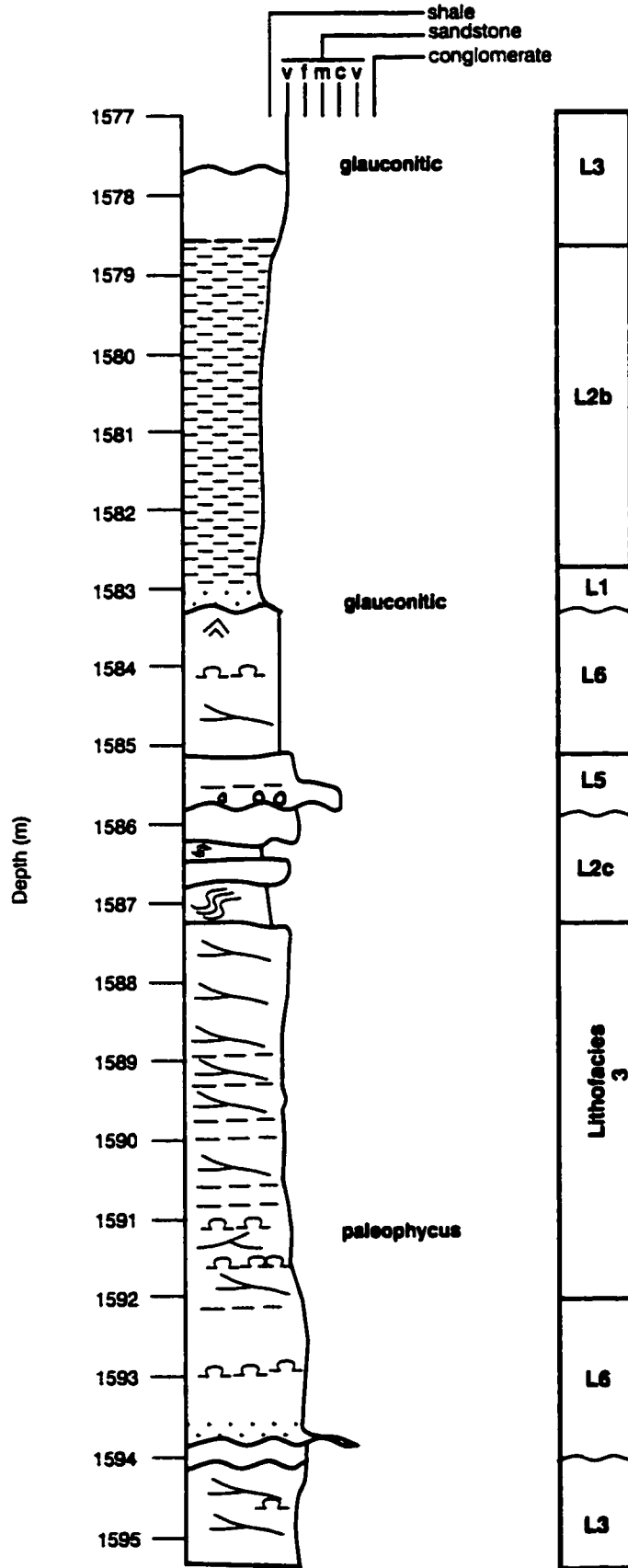
14-07-76-7W6



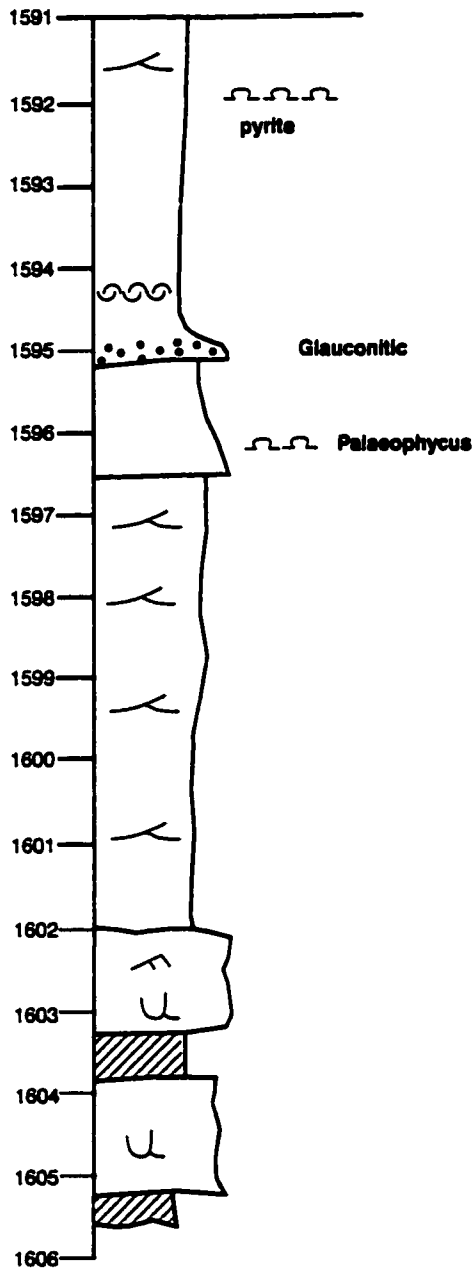
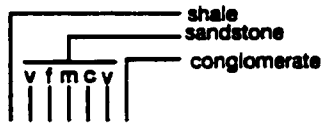
9-22-76-8W6



13-4-76-9W6

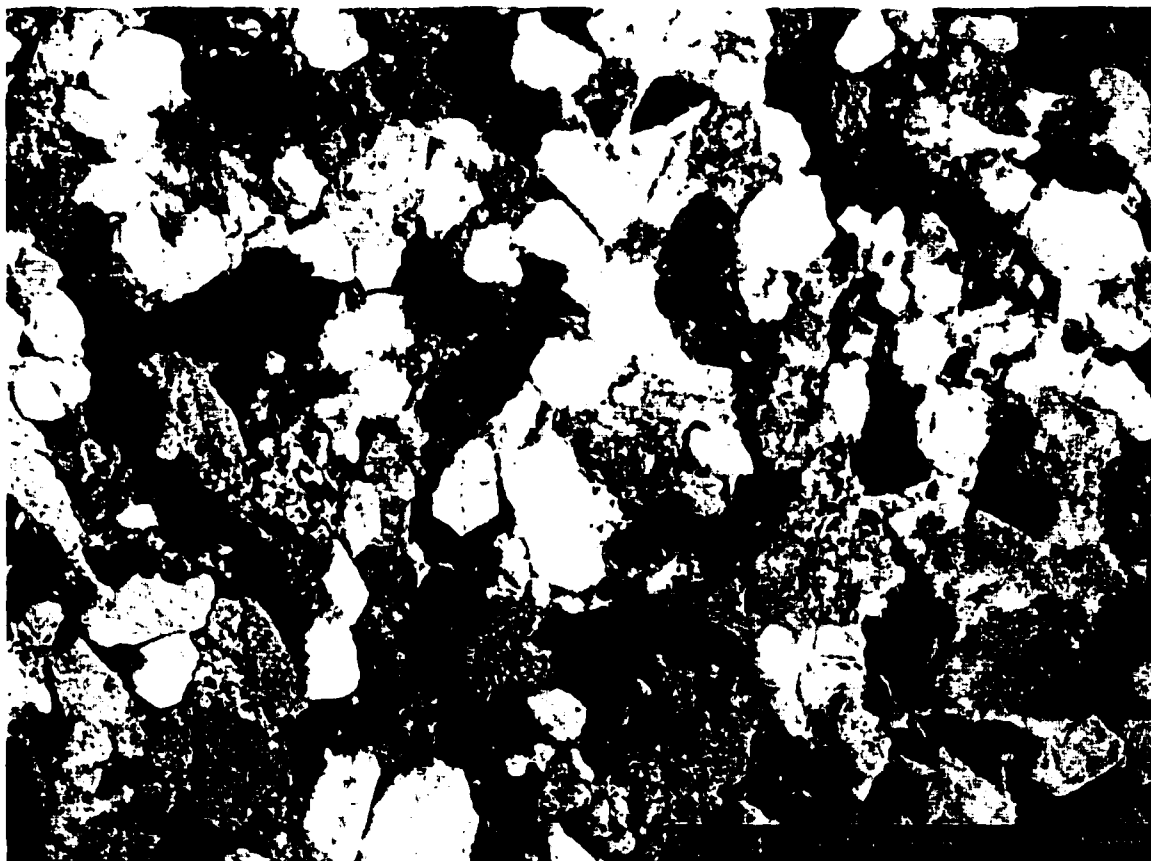


06-14-76-9W6
Core 1



Appendix B: Sandstone Petrography

UWI	Depth	Facies
8-23-74-7W6	1563.50m	Lithofacies 1: Upward fining Glauconitic Conglomerate to Sandy Shale



General: Fine to medium grained poorly sorted sublitharenite (Folk, 1968)

Matrix:

Quartz:	30%
Chert:	45%
Opaques:	10%
Glauconite:	5%

Quartz: Subangular, moderate sphericity, some overgrowths

Chert: Subrounded, mottled light brown

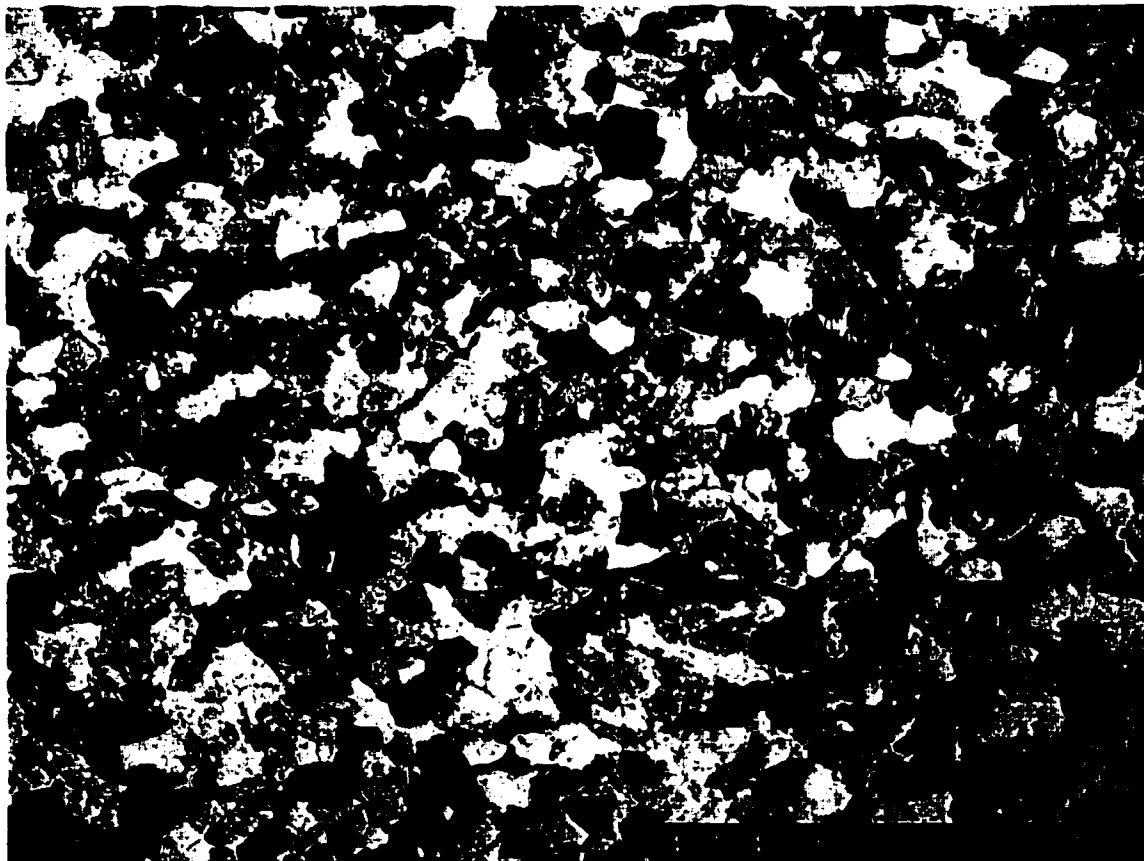
Opaques: Angular to ductile, low sphericity, occasionally fractured

Glauconite: dark green, subrounded to ductile

Cements:

Quartz Overgrowths	30%
Clay	70%
Calcite	Trace

UWI	Depth	Facies
14-21-74-7W6	1580.00m	Lithofacies 3: Upper very fine grained, low angle cross-stratified sandstone



General: Very fine grained moderately sorted sublitharenite (Folk, 1968)

Matrix:

Quartz:	50%
Chert:	35%
Opaques:	10%
Misc.:	5%

Quartz: Subangular, moderate sphericity

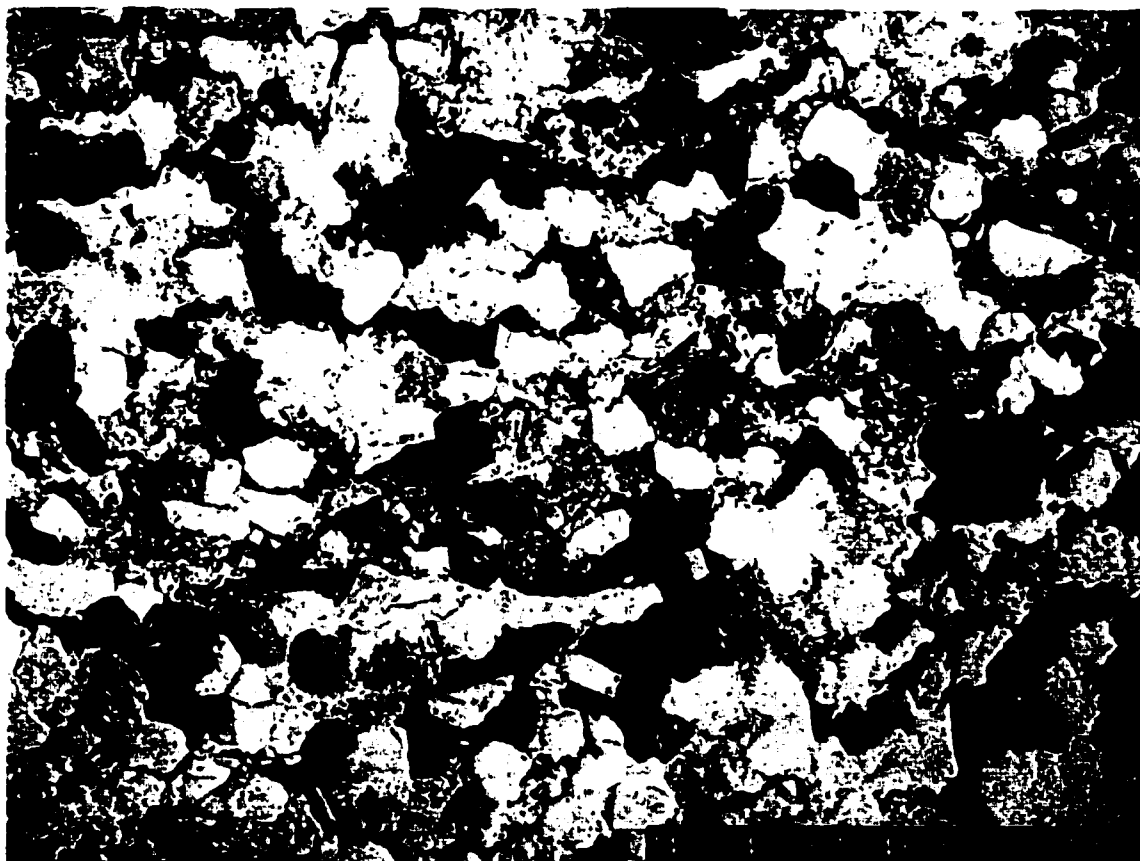
Chert: Subrounded, mottled light brown=

Opaques: Angular to sub angular, low sphericity, occasionally fractured

Cements:

Quartz Overgrowths	40%
Clay	40%
Calcite	20%

UWI	Depth	Facies
14-21-74-7W6	1574.60m	Lithofacies 6:Blocky fine to medium sandstone



General: Fine to medium grained poorly sorted sublitharenite (Folk, 1968)

Matrix:

Quartz:	60%
Chert:	20%
Opaques:	10%
Clay:	10%

Quartz: Commonly overgrown, suture contacts, subrounded, high sphericity

Chert: Subrounded, mottled light brown

Opaques: Angular to sub angular, low sphericity, occasionally fractured

Clays: ductile laminae to granular, dark brown

Cements:

Quartz Overgrowths	60%
Clay	40%