THE UNIVERSITY OF ALBERTA

The Stratigraphy and Ichnology of the Upper Devonian Graminia Formation - Toma Creek to Cardinal River Headwaters - Mountain Park, Alberta

by

Cameron W. Fehr

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THE UNDERSIGNED CERTIFY THAT THEY HAVE READ, AND RECOMMEND TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH FOR ACCEPTANCE, A THESIS ENTITLED **THE STRATIGRAPHY AND ICHNOLOGY OF THE UPPER DEVONIAN GRAMINIA FORMATION - TOMA CREEK TO CARDINAL HEADWATERS - MOUNTAIN PARK, ALBERTA**, SUBMITTED BY **CAMERON WELDON FEHR** IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN GEOLOGY.

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Date April 8, 1994

To my Mom and Dad,

love Cam

Abstract

The Upper Devonian Graminia Formation of the Mount [illegible] of three members. Constituent members on the Southesk-Ca[illegible] ude the Calmar Formation (Lower Graminia Member equivalen[illegible] and Upper Graminia Member (Sassenach Formation Equivalent [illegible] in the flanking Jasper Basin includes Lower Graminia Member ("Silt [illegible] dge Basinal Member (upper Mount Hawk equivalent), and Upper Gr[illegible] (Sassenach Formation equivalent).

Storm deposition and associated bedforms dominate the Upper and Lower Members of the Graminia Formation. Carbonate wackestones to grainstones dominate Blue Ridge Member deposition. An isolated carbonate mound at Cardinal Mountain represents Blue Ridge Basinal deposition. Storm activity throughout the Blue Ridge Member depositional stage periodically interrupted carbonate development on the shelf and in the basin. Carbonate deposition continued following cessation of storm activity. A mixed carbonate-siliciclastic system dominated basinal deposition throughout the Graminia Formation.

Biological activity throughout Graminia time destroyed much of the original depositional texture of the sediments. Hummocky cross-stratification and undulatory bedding dominate the physical bedforms. Rare, low angle cross-bedding within the Blue Ridge Member carbonates on the shelf represents sediment movement following cessation of storm activity. Interbedded bioturbated and hummocky bedded siltstones dominate Upper and Lower Graminia deposition at the platform margin. These units represent emplacement of storm deposits and subsequent biological reworking. Preferential weathering of the cyclically bedded and burrowed siltstones create the Lower Graminia Member "Silt Doublet" visible at North Cardinal Pass.

The resident trace fossil suite within the Graminia Formation is a storm influenced mixed *Skolithos-Cruziana* ichnocoenose with a resident *Cruziana* ichnocoenose.

Polykladichnus burrows associated with an opportunistic *Skolithos* assemblage represent the initial documentation of this vertical branching trace fossil within Upper Devonian aged beds

Acknowledgements

The author wishes to express his gratitude to the following organisations for their financial and technical support. Without their assistance this project would not have been possible.

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Stan "the man" Vezina

Table of Contents

List of Tables

List of Figures

List of Plates

page

1.0 INTRODUCTION

1.1 Purpose and Scope

The purpose of this study is to investigate the stratigraphy and ichnology of the Upper Devonian Grammia Formation in the Rocky Mountain Foothills in the area of Mountain Park, Alberta

Sedimentological data document the stratigraphic relationships between the platform units and the basinal equivalents of the Grammia Formation Ichnological data support the stratigraphic and sedimentological interpretations The systematic ichnology formally documents the ichnological framework present within the Grammia Formation of this area.

The study area (Figure 1) encompasses the platform beds of the Toma Creek area to the basinal beds of the Cardinal River Headwaters area. The specific outcrop sections measured were selected based on accessibility and upon previous regional work completed by Ian A. McIlreath (Petro Canada)

1.2 Stratigraphic Nomenclature and Regional Geology

Two sets of stratigraphic nomenclature have been proposed for the Upper Devonian of the Front Ranges primarily in response to independent surface and subsurface studies. Figure 2 is a summary of the correlation of subsurface and outcrop stratigraphic terminology historically used for Upper Devonian of West-Central Alberta (after Shields and Geldsetzer, 1992). This study deals strictly with outcrop Subsurface terminology is adopted for the measured outcrop sections to define precisely the tripartite division observed

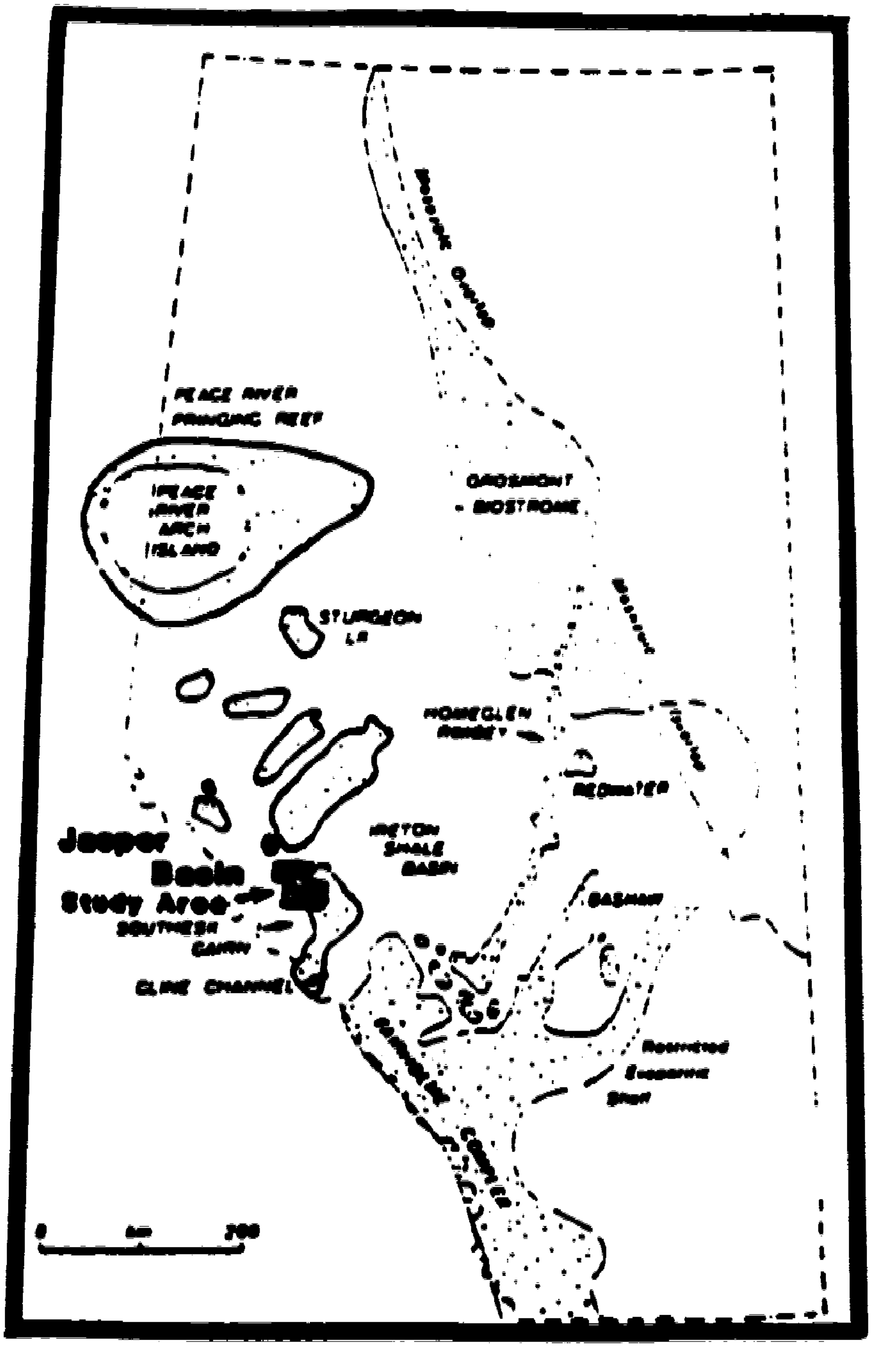


Figure 1 . Area of study and regional palaeogeography of major Devonian reef systems. (modified after Hedinger and Workum, 1989).

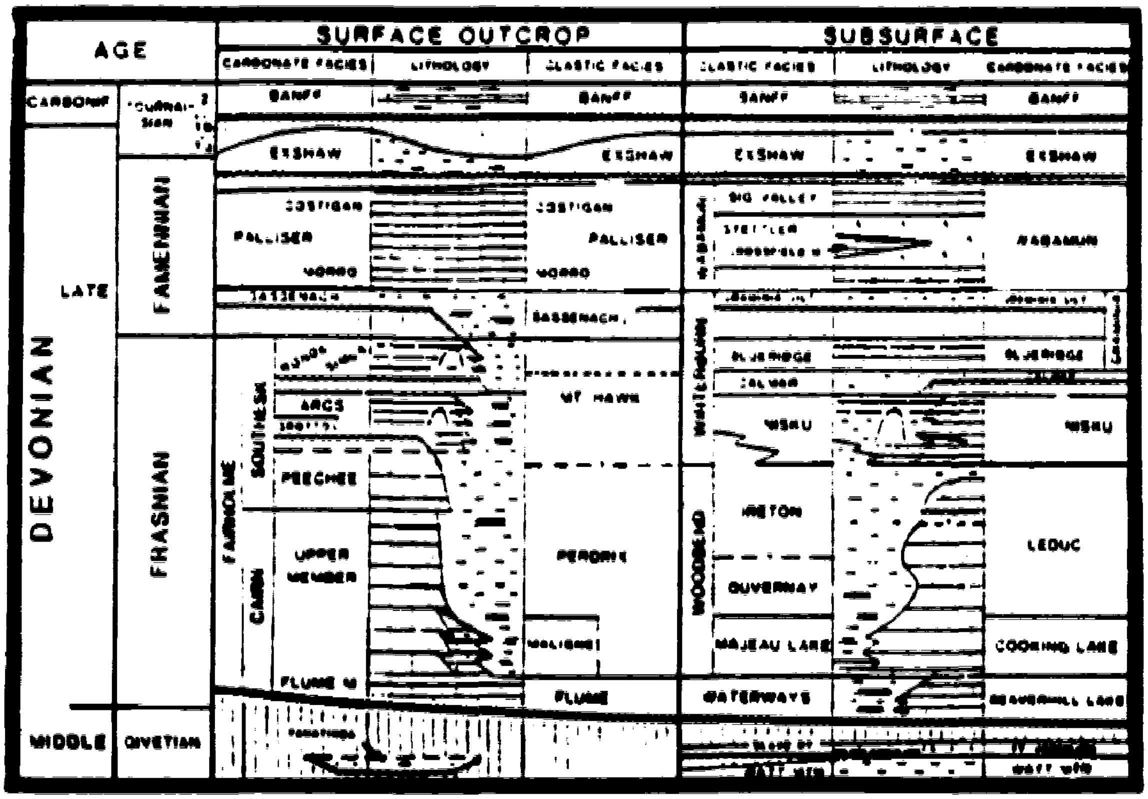


Figure 2. Upper Devonian surface - subsurface correlation chart, this study (modified after Shields and Geldsetzer, 1992)

The Graminia Formation of the Mountain Park area consists of three platform member units and their basinal equivalents. Figures 2 and 3 summarise the units described in this study and their homotaxial subsurface counterparts. These include: Platform: Lower Graminia Member = Lower Ronde Siltstone (Shields and Geldsetzer, 1992), Blue Ridge Member = Ronde Member, Southesk Formation, Upper Graminia Member = overlying Sassenach Formation. Basin: Lower Graminia Member = "Silt Doublet" (Workum and Hedinger, 1987), Blue Ridge basinal equivalents = upper Mount Hawk Formation, (Shields and Geldsetzer, 1992), Upper Graminia Member = overlying Sassenach Formation.

Figure 1 summarises the palaeogeographic distribution of land masses during the Devonian. The upper units of the northwest margin of the Southesk - Cairn complex and basinal equivalents are the focus of this study.

A significant northwest progradation of the platform margin characterises the Graminia Formation which represents the final stage of growth of the Southesk-Cairn carbonate platform (Figure 3) (Shields and Geldsetzer, 1992).

Lower Graminia Member deposition represents the first significant siliciclastic input onto the Mackenzie margin. The "Silt Doublet" and associated silts and sands represent the Lower Graminia Member in the basinal section. Laterally equivalent Calmar Formation beds represent deposition on the Arcs/Grotto Members of the Southesk Formation at Lower Graminia time.

Deposition of the Blue Ridge Member completed the reefal stage of the platform. Isolated carbonate mounds and highly calcareous fossiliferous mudstones of the upper Mount Hawk Formation represent basinal Blue Ridge Member deposition. Deposition of the Upper Graminia/Sassenach Formation concluded the development of this stage of the Mackenzie Margin buildup.

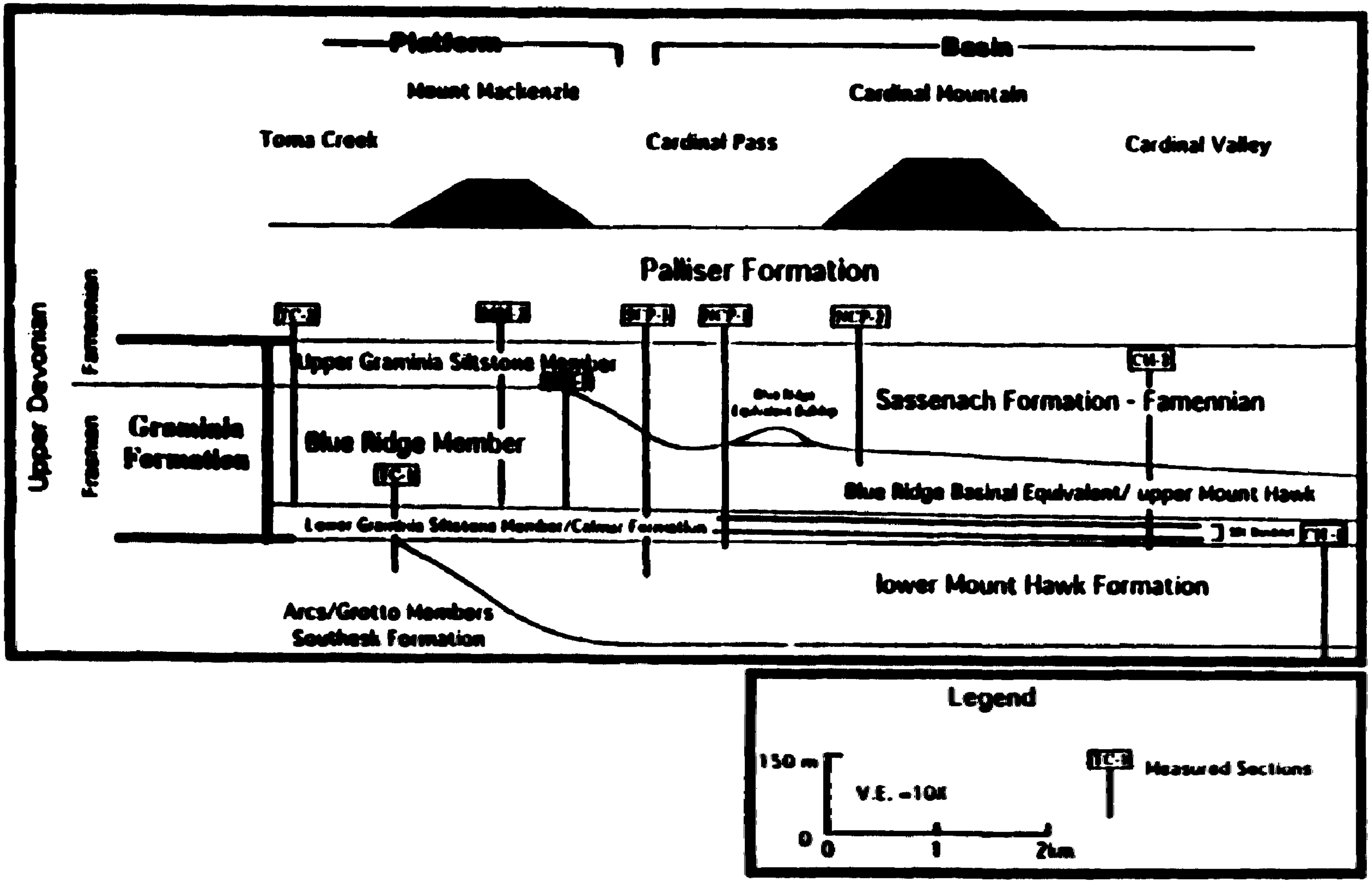


Figure 3 . Schematic cross-section illustrating the relative position of each measured section with respect to major stratigraphic and topographic features View is to the West

No physical evidence was available on the shelf to illustrate the presence of the Frasnian-Famennian boundary. Conodont studies of the area suggest a significant change in the biostratigraphic constituents of the sediments from the top of the Blue Ridge Member to the base of the Sassenach Formation (Shields and Geldsetzer, 1992; Johnston and Meijer Drees, 1993). Interpreted oncolite structures at the upper boundary of the offbank Blue Ridge carbonate mound suggest a possible link to the Frasnian-Famennian extinction event (Shields and Geldsetzer, 1992).

1.3 Study Area and Measured Sections

The study area borders Jasper National park and is within the area of NTS Map Sheet 83 C/14 (Figure 4). All sections measured are within the Rocky Mountain Front Ranges 7-10 km southwest of the abandoned townsite of Mountain Park, Alberta.

There are five areas of interest with a total of 9 outcrop sections described (1200m). Individual areas of study include: Toma Creek, Mount Mackenzie, South Cardinal Pass, North Cardinal Pass, and Cardinal Headwaters (Figure 3, 4).

The Toma Creek area includes two measured sections at $52^{0}50$ N $117^{0}14$ W (Figure 4, Plate 1). The initial section measured (Toma Creek Section 1) includes the upper portion of the Arcs/Grotto Member of the Southesk Formation, the Calmar Formation, the platform equivalent of the Lower Grammia Member and the lower portion of the Blue Ridge Member (Appendix 1). The second of the two measured sections (Toma Creek Section 2) is structurally down dip from section TC - 1 and includes, the Lower Grammia, Blue Ridge, and Upper Grammia Members of the Grammia Formation, the platform equivalent of the Sassenach Formation, and the basal portion of the overlying Palliser Formation (Appendix 1).

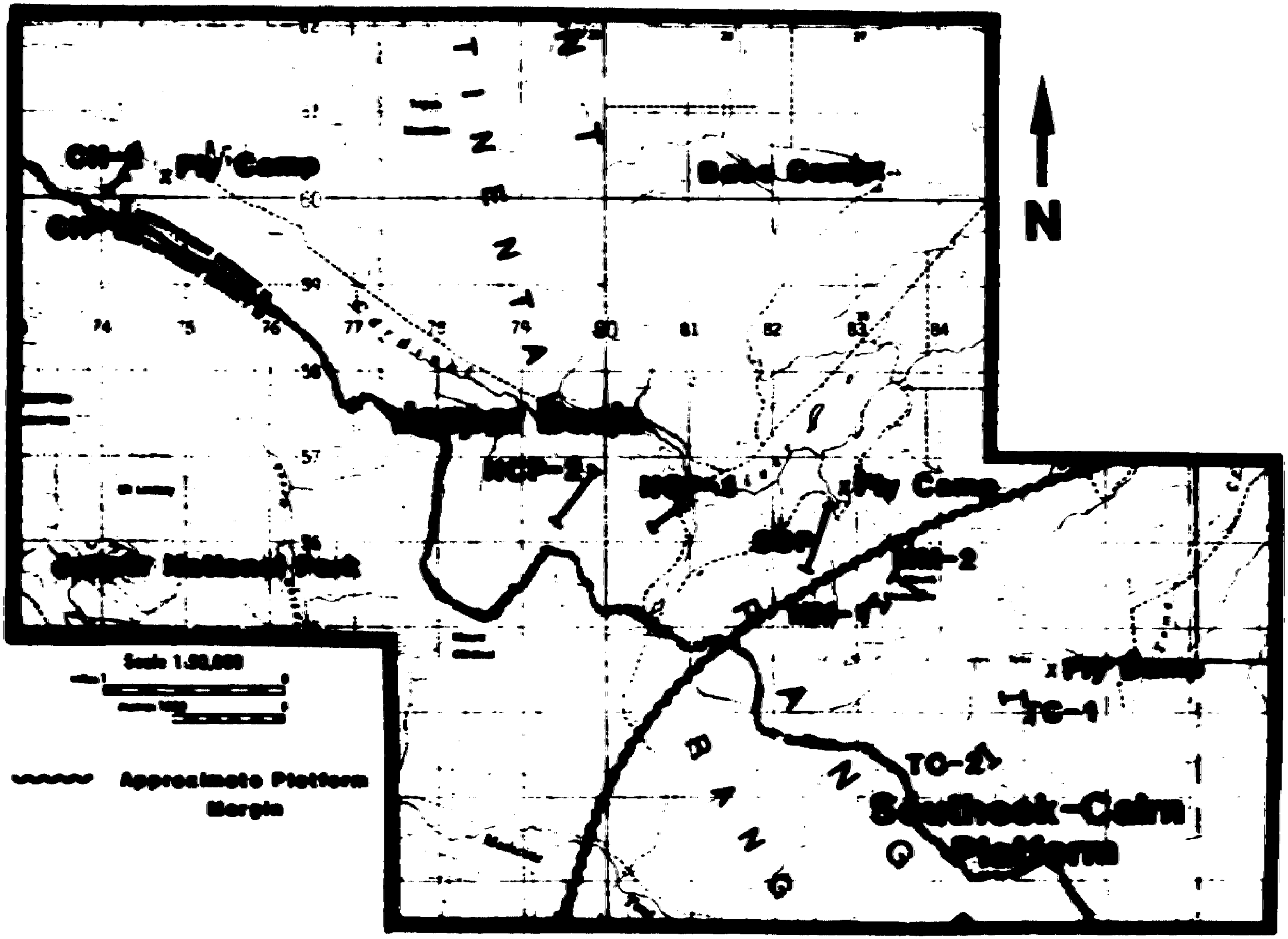


Figure 4. Section location and area topography. Cut lines and access trails indicated by dashed lines. (modified after NTS map 83 C/14)

The Mount Mackenzie area includes two measured outcrop sections at 52°51 N 117°14 30 W (Figure 4 Plate 2) The first section measured (Mount Mackenzie Section 1) included only Blue Ridge Member beds of the Graminia Formation (Appendix 1) The second measured section (Mount Mackenzie Section 2) is structurally up dip from section MM - 1 within a chute on the north face of Mount Mackenzie Units measured include the Blue Ridge Member of the Graminia Formation and overlying Upper Graminia Member/Sassenach Formation (Appendix 1) No relationship to the overlying Palliser or underlying beds was visible in either section due to a large volume of talus obscuring formation contacts

The South Cardinal Pass area includes a single section measured along a rocky spur on the south side of the Cardinal River Valley at 52°51 20"N 117°15 30"W (Figure 4, Plate 3) The entire section includes the upper portion of the Mount Hawk Formation Lower Graminia Member, Blue Ridge Basinal Member, Upper Graminia/Sassenach Formation and the lower portions of the overlying Palliser Formation (Appendix 1)

The North Cardinal Pass area includes two measured sections directly north of the South Cardinal Pass area (Figure 4, Plate 4 and 5) The first section (North Cardinal Pass Section 1) is along the southern shoulder of an east facing Mount Cardinal outcrop containing an inaccessible Blue Ridge equivalent carbonate mound (Plate 6) at 52°51 30"N 117°17 W. Measured units within this section include: upper Mount Hawk Formation, Lower Graminia Member/"Silt Doublet", Blue Ridge Basinal Member, Upper Graminia/Sassenach Formation, and the Lowest portions of the overlying Palliser Formation (Appendix 1) Measured thicknesses of the strata at NCP-1 represent true thicknesses following bed thickness corrections The second of the two measured sections (North Cardinal Pass Section 2) is within a runoff channel 750m north of section NCP-1. Units described from this section include upper Mount Hawk Formation, Lower Graminia Member,

Plate 1. Toma Creek section TC-1. Section TC-2 is approximately 500m to the left of the photograph. The Graminia Formation overlies the Arcs/Grotto Members of the Southesk Formation and is represented by the Lower Graminia/Calmar Formation, Blue Ridge Member and the Upper Graminia Member. View is to the Southwest.

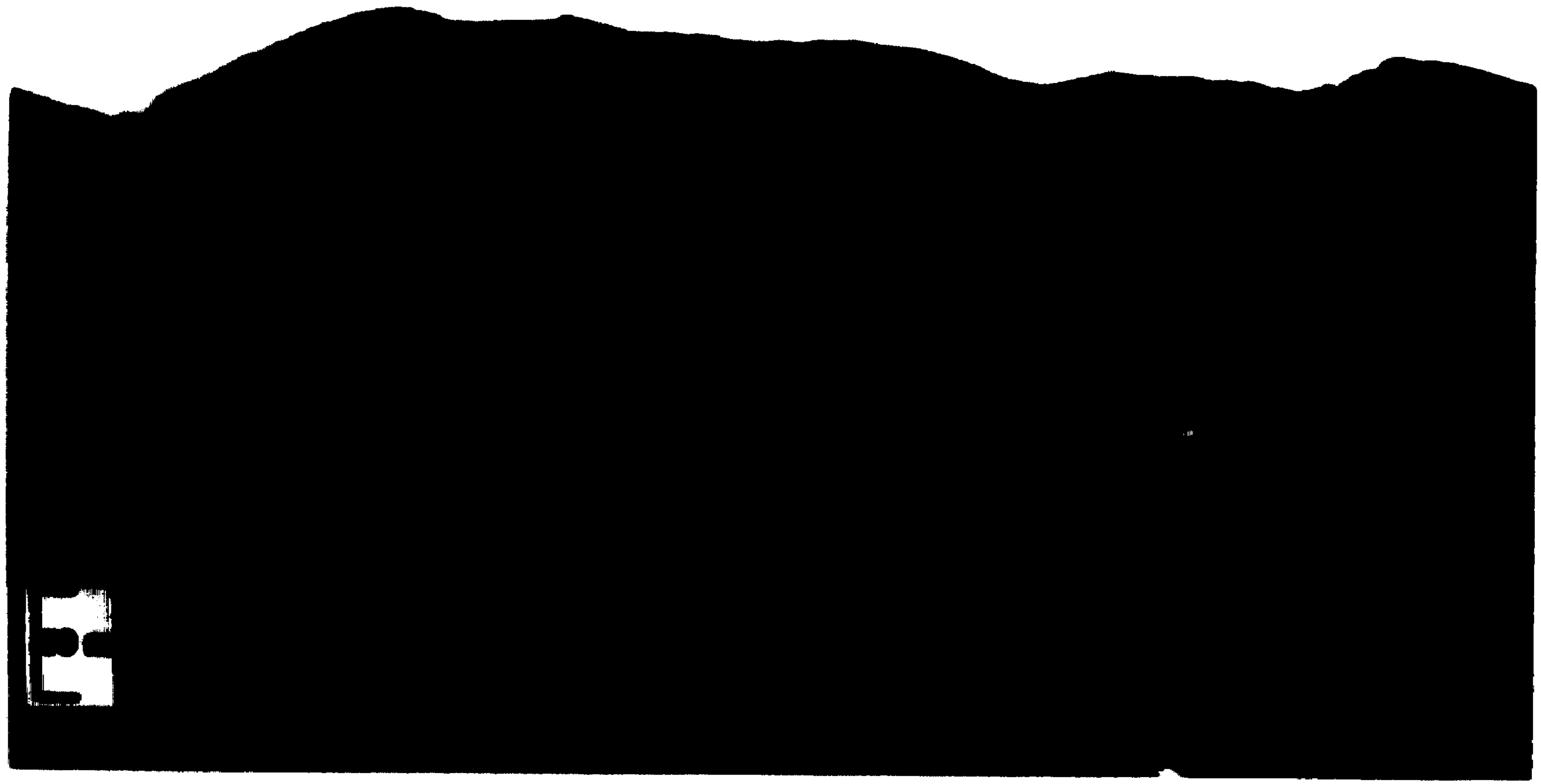


Plate 2. Mount Mackenzie section MM-1. Section MM-2 is approximately 300m to the left of the photograph. Note the scree covered Lower Graminia Member - Blue Ridge contact. Thrust faulting of this section is traceable along strike and is visible as Blue Ridge member beds are thrust over top of Upper Graminia beds. View is to the South

Plate 3. South Cardinal Pass section SCP. The Graminia Formation is represented by the Lower Graminia Member, Blue Ridge Member, and the Upper Graminia Member. View is to the West

and Blue Ridge Basinal Member beds (Appendix 1)

The Cardinal River Headwaters area includes 2 measured sections located near the northernmost extension of the Cardinal River Valley at 52°53 30"N 117°23 W (Figure 4, Plates 7 and 8) The initial section measured (Cardinal River Headwaters Section 1) includes primarily Mount Hawk Formation and possible Lower Graminia-aged beds (Appendix 1) The second section (Cardinal River Headwaters Section 2) is directly up section of section CH-1 and includes lower Mount Hawk Formation, Lower Graminia, upper Mount Hawk/Blue Ridge Basinal Member, and the lower portions of the overlying Sassenach Formation (Appendix 1) Outcrop inaccessibility prevented the measurement of the entire Sassenach interval and the overlying Palliser Formation

1.4 Methodology

Access to the study area was via the forestry trunk road south of Cadomin, Alberta. Individual outcrop sections were accessed using all terrain vehicles along several trails, cut lines and portages A single base camp was established approximately 3km South of the Mountain Park townsite off of the forestry trunk road Subsequent smaller camps were established at the base of the measured sections when daily accessibility to the outcrop sections was not feasible (Figure 4)

1.4.1 Outcrop Description

Approximate regional dip of the strata for individual outcrop sections was measured to facilitate the use of a "Jacob Staff" in the estimation of individual bed thickness Field note descriptions were taken for each interval of the outcrop sections, (Appendix 2) Generalised strip logs for each outcrop were completed utilising the LOGX system software of Geophysical Microcomputer Applications International Ltd. (Appendix 1)

Plate 4. North Cardinal Pass section NCP-1. The Lower portion of the section is approximately 100m to the left of the photograph. Section NCP-2 is approximately 500m to the right of the photograph. The Graminia Formation is represented by the Lower Graminia Member/"Silt Doublet", Blue Ridge Basinal Member and associated carbonate mound and the Upper Graminia Member. View is to the West

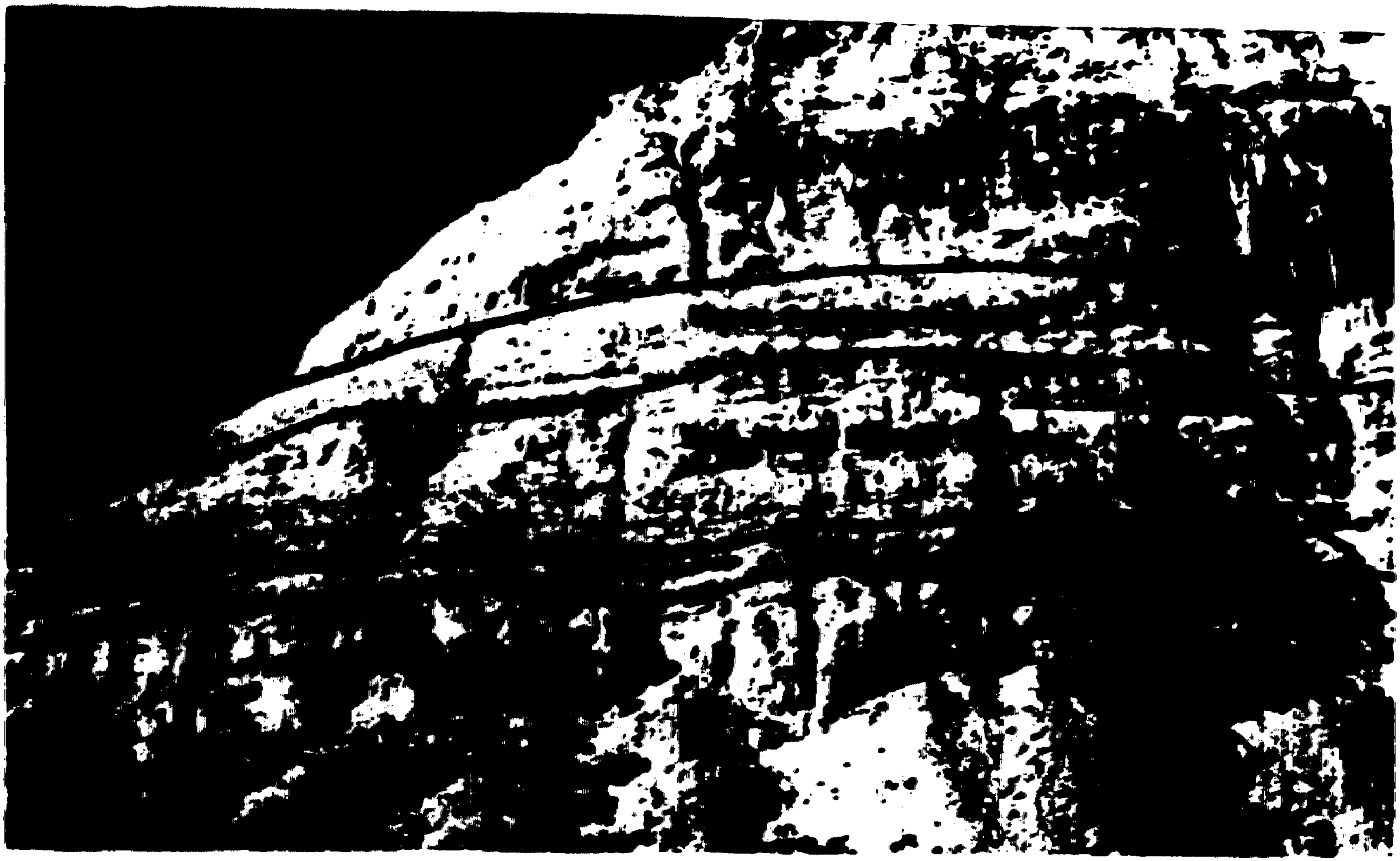


Plate 5. North Cardinal Pass section NCP-1. The Blue Ridge Member carbonate mound is approximately 200m to the right of the photograph. Note the Lower Graminia "Silt Doublet". The Graminia Formation is represented by the Lower Graminia Member/"Silt Doublet", Blue Ridge Basinal Member and Upper Graminia Member. View is to the West.

Plate 6. North Cardinal Pass isolated Blue Ridge carbonate mound between sections NCP-1 and NCP-2. Note sharp base of prominent "Silt Doublet", and abundant debris beds flanking the mound. The Graminia Formation is represented by the Lower Graminia Member/"Silt Doublet", Blue Ridge Basinal Member and carbonate mound, and the Upper Graminia Member. View is to the West.

Plate 7. Cardinal River Headwaters section CH-1 and CH-2. Graminia Formation is represented by the Lower Graminia Member, Blue Ridge Basinal Member, and Upper Graminia Member. View is to the West.

Plate 8. Cardinal River Headwaters section CH-2. The Graminia Formation overlies a Nisku age carbonate mound and is represented by the Lower Graminia Member, Blue Ridge Basinal Member, and the Upper Graminia Member. View is to the West.

Approximately 300 outcrop samples were collected for sedimentological, ichnological and structural data. Sample collection from *in situ* outcrops was of prime concern. However, if no sample was obtainable from the *in situ* outcrop, a nearby and obvious remnant of the outcrop was collected for sample analysis.

1.4.2 Thin Section Petrography

Approximately 75 thin sections were cut from the collected outcrop samples. Complete carbonate staining techniques were carried out on each thin section as outlined by Dickson, (1966). Subsequent description and point counting of the stained samples yielded detailed lithologic data discussed in Chapter 2 of this study. Individual point counts consist of 300 counts per slide and are summarised in Appendix 3 for each of the formations and members described.

Samples were classified based on Dunham's (1962) classification scheme of carbonate rocks, (Figure 5). The occurrence of a major proportion of silt in many of the samples made strict adherence to this classification scheme problematic. Classification of the samples was completed employing clastic terminology (sandstone, siltstone, mudstone) where use of the Dunham system was inappropriate.

1.4.3 Scanning Electron Microscopy

Four outcrop samples from each of the dominantly clastic members of the Graminia Formation were partially dissolved using 10% HCl to separate the constituent clastic material from the carbonate matrix. The samples were then cleaned in a 10% HCl acid wash before being mounted and gold plated in preparation for examination in the SEM laboratory. Description of the samples is summarised in Appendix 4.

1.4.4 X-Ray Radiography

Several outcrop samples appear to yield little or no direct biological or physical structures X-Ray radiography of selected samples was used to analyse any possible structures present in what appear to be homogeneous rocks under visible light The techniques utilized in this study are summarised in Hamblin (1962), Bouma (1969, and Hill *et al.* (1979)

No new evidence was available from the X-ray radiographs The homogeneous nature of the samples x-rayed is attributed to a complete biological churning of the sediments at the time of deposition or the lack of minerals with different densities in distinct layers (Wittenberg, 1992)

1.4.5 Ichnofossil Identification

Ichnofossil identification was carried out as extensively as possible at each outcrop locality. Trace fossils not identified in the field were photographed and sampled where possible. Photographs of each structure observed were taken with the trace *in situ* Subsequent sampling of the structures in question often resulted in damage to the main portion of the sample. The photographic record was utilized in sample identification to supplement the sometimes damaged structures A detailed description of each sample structure and formal identification was completed in the laboratory

<table>
<tr><th colspan="5">DEPOSITIONAL TEXTURE RECOGNIZABLE</th><th rowspan="5">DEPOSITIONAL TEXTURE NOT RECOGNIZABLE</th></tr>
<tr><td colspan="4">Original Components Not Bound Together During Deposition</td><td rowspan="4">Original components were bound together during deposition... as shown by intergrown skeletal matter, lamination contrary to gravity, or sediment-floored cavities that are roofed over by organic or questionably organic matter and are too large to be interstices.</td></tr>
<tr><td colspan="3">Contains mud
(particles of clay and fine silt size)</td><td rowspan="3">Lacks mud and is grain-supported</td></tr>
<tr><td colspan="2">Mud-supported</td><td rowspan="2">Grain-supported</td></tr>
<tr><td>Less than 10 percent grains</td><td>More than 10 percent grains</td></tr>
<tr><td><u>Mudstone</u></td><td><u>Wackestone</u></td><td><u>Packstone</u></td><td><u>Grainstone</u></td><td><u>Boundstone</u></td><td><u>Crystalline Carbonate</u>

(Subdivide according to classifications designed to bear on physical texture or diagenesis.)</td></tr>
</table>

Figure 5 . Classification of carbonate rocks, (modified after Dunham, 1962).

2.0 STRATIGRAPHY

2.1 Introduction

The Grammia Formation is defined formally by Glass (1990) as the uppermost unit in the Winterburn Group. In Central and Northern Alberta it is subdivided into three constituent members. These include: 1) the Lower Siltstone Member, which is laterally equivalent to the Calmar Formation, 2) the Blue Ridge Member, equivalent to the upper Mount Hawk, and 3) the Upper Siltstone Member equivalent to the Sassenach Formation. Plates 1-8 illustrate the measured outcrop sections within each area and the identified member units of the Grammia Formation.

Although no detailed conodont sample identification was completed for this study, conodont biostratigraphy is used by several authors to define the stratigraphic boundaries in the Front Ranges of this area. These include: Johnston and Meijer Drees, (1993), Johnston and Chatterton, (1991), Weissenberger, (1988), and Clark and Ethington, (1965). Figure 6 illustrates the conodont biostratigraphic position of the Frasnian and Famennian members of the Grammia Formation.

2.2 Calmar Formation

Within this study area the Calmar Formation is defined by a massive to thickly bedded, green, silty claystone, unconformably overlying the Arcs/Grotto Members of the Southesk Formation. The Calmar Formation is correlative with the Lower Grammia Member of the Grammia Formation, however no direct basinal equivalent is identifiable.

2.2.1 Sedimentology and Palaeontology

Detailed sampling of the Calmar Formation green claystone completed by R.W. Workum during a 1988 PetroCanada field party yielded several X-Ray diffraction (XRD) samples. Table 1 illustrates the results of these tests and the resulting mineralogy of the

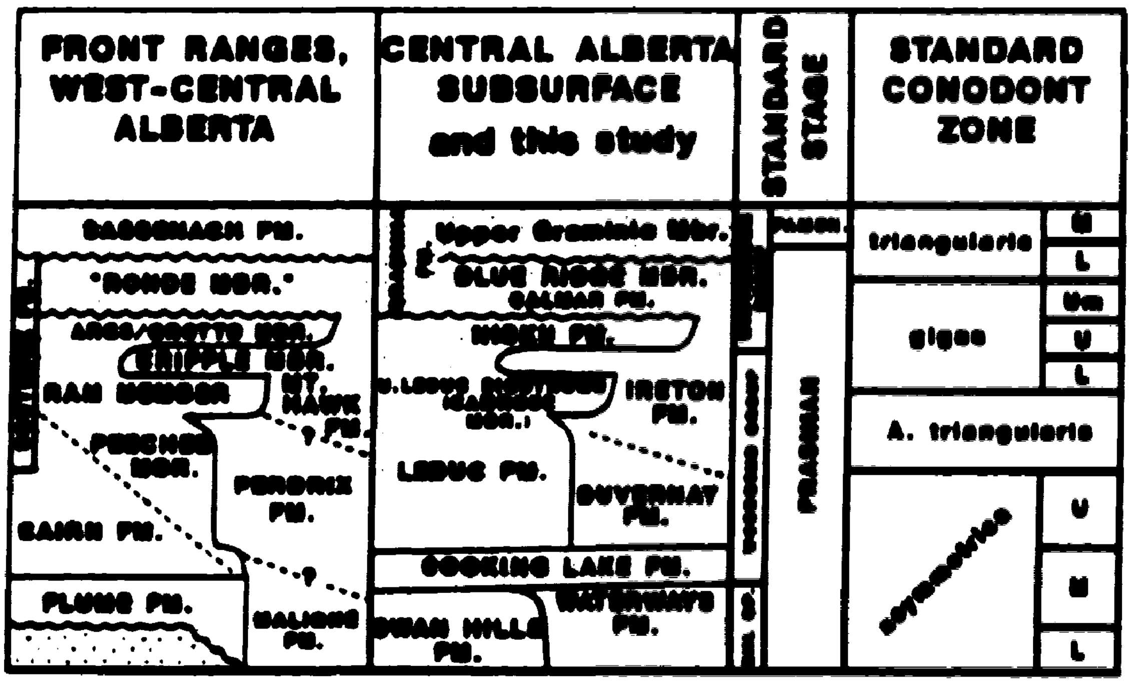


Figure 6 . Surface to subsurface correlations and standard conodont biozones of the Upper Devonian, West-Central Alberta, (modified after Weissenberger, 1994).

Sample	Percentage	Constituents
SW-88-A2	49%	Quartz-SiO_2
	23%	Illite-Clay mineral-Hydrous alumino silicate
	12%	Mixed layer clays
	6%	Anatase-TiO_2-authigenic derivative from Fe,Ti-Bauxite
	6%	Jarosite - K,Fe silicate hydroxide
	4%	Orthoclase-K feldspar
SW-88-2-4	54%	Quartz-SiO_2
	23%	Illite-Clay mineral-Hydrous alumino silicate
	8%	Goethite-FeOOh
	7%	Orthoclase-K feldspar
	4%	Chlorite
	4%	Anatase-TiO_2-authigenic derivative from Fe,Ti-Bauxite
	tr	Dolomite
SW-88-2-5	48%	Illite-Clay mineral-Hydrous alumino silicate
	21%	Quartz-SiO_2
	19%	Goethite-FeOOh
	12%	Chlorite
	tr	Anatase-TiO_2-authigenic derivative from Fe,Ti-Bauxite

Table 1. Mineralogy of selected X-Ray Diffraction samples from the Calmar Formation/Lower Grammia Member Sampling completed by R W Workhum, sample analyses by Jenny Wong - I.S.P.G., (pers comm I A McIlreath, 1990).

green shale. (pers comm , I A McIlreath, 1990)

Thin section analysis generated similar mineralogical results with all samples yielding a relatively large percentage (up to 15%) of unidentifiable opaque mineral grains. Plate 9 is representative of the mineralogy of the Calmar Formation green shale. The opaque material represents iron, titanium and aluminum oxides and hydroxides identified in the XRD samples.

Detailed mineralogy reveals that the Calmar of the study area is composed primarily of quartz, dolomicrite, and illitic clays with significant percentages (up to 15%) of opaque iron and aluminum oxides and hydroxides. Detailed heavy mineral identification or thick sectioning is not included in this study. However, possible mineralogy may include rutile (TiO_2), ilmenite ($FeTiO_3$), or limonite (FeO(OH)).

Minor constituents of the green clays and silts include mixed layer clays (e.g. smectite), orthoclase (potassium feldspar), chlorite, and weathering derivatives of the aforementioned minerals. These include jarosite (potassium, iron silicate hydroxide - authigenically derived from the weathering of feldspars and clays), goethite (iron hydroxide formed under oxidising conditions at the expense of iron-bearing minerals), (Skoog and West, 1986, Berry, Mason and Dietrich, 1983), anatase (TiO2 - authigenic derivative from the weathering of titanium bearing sediments)

The alteration series producing anatase begins with the weathering of a titanium-bearing rock (igneous or volcanic). Anatase is formed authigenically as an early oxide of titanium under metastable sedimentary conditions such as fluctuating water chemistry. (Skoog and West, 1986, Berry, Mason and Dietrich, 1983) Subsequent weathering, transport, and concentration of the previously deposited titanium-bearing sediments results in significant accumulations (up to 8%)of titanium oxide within the Calmar clays.

A

B

Plate 9 . A) Calmar Formation calcareous siltstone. Section TC-1 a)opaque heavy minerals. b) angular to subangular quartz grain with pitted grain surface. c) interstitial micrite. Crossed polars.

B) Calmar Formation calcareous siltstone. Section TC-1 Grain to grain contacts of opaque material and quartz are completely sutured. a) opaque material with sharp grain boundary. b) angular quartz grain

The quartz is most often preserved as silt sized (<65 microns) grains with varying percentages of quartz overgrowths The quartz grains are sub-rounded to angular The overgrowths may display varying degrees of rounding due to abrasion Pitting and/or pocking of the quartz surfaces is common and may represent grain to grain contact during transport or chemical dissolution in an aqueous environment

Plates 10,11, and 12 illustrate scanning electron photography of quartz grains separated from the green clays of the Calmar Formation Plate 10 illustrates a quartz grain completely enveloped by clay minerals Plates 11 and 12 illustrate a set of spore casts within a quartz overgrowth These samples were collected from the hummocky stratified silt layers within the Calmar and may be indicative of siliciclastic deposition on the platform during storm events Subsequent lithification and development of quartz overgrowth cement appears to have "trapped" the reproductive spores of a terrestrial plant.

Structures at the top of the Calmar Formation suggest a karst setting. Overlying sediments from Blue Ridge Member infill the large structures of the Calmar Formation created by surface weathering and subsequent chemical dissolution Plate 13 illustrates Blue Ridge mudstones infilling a 5-10 cm wide void in the underlying sediments

No biological structures are identifiable within the Calmar Formation of this study area. Two, five centimetre intervals of silt to fine sand are the only indications of bedding These zones are parallel to sub-parallel bedded and show indications of wavy to hummocky stratification The remainder of the unit is massive with peculiar surface weathering structures in the form of 1-10 cm "holes" in the outcrop surface (Plate 14).

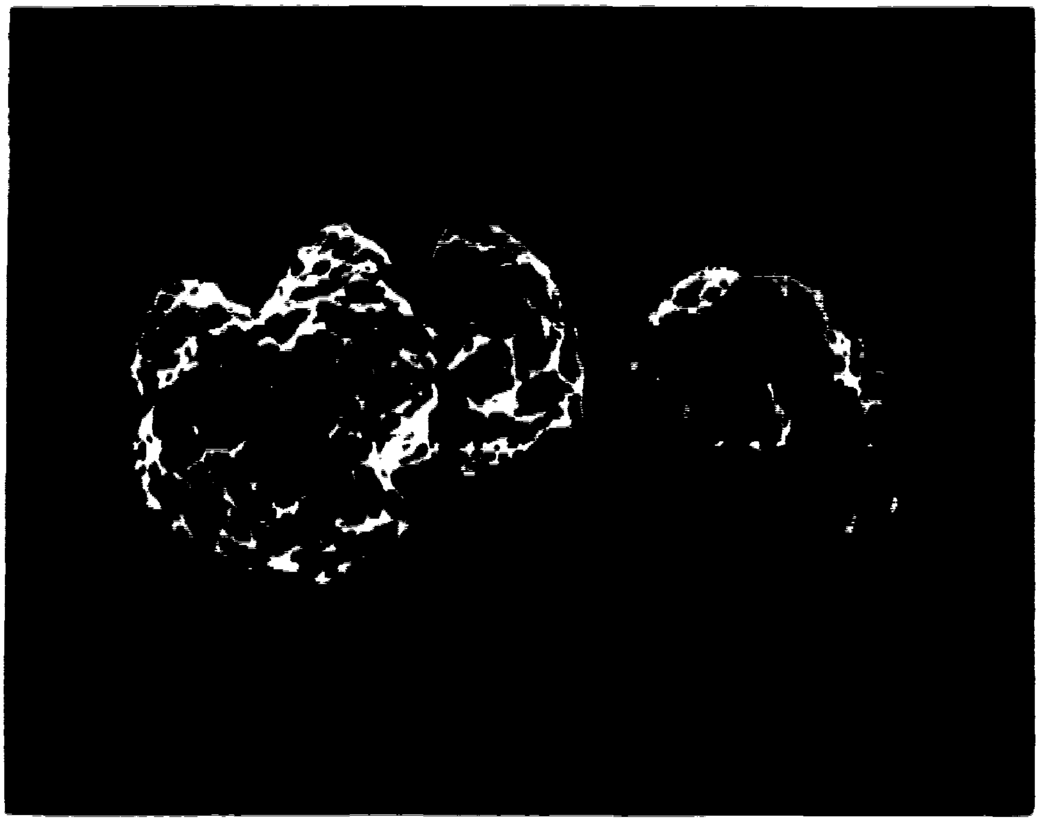


Plate 10. Scanning electron microscope photograph of a Calmar Formation silt grain. Quartz grain is completely encased in illitic clays. Section TC-1

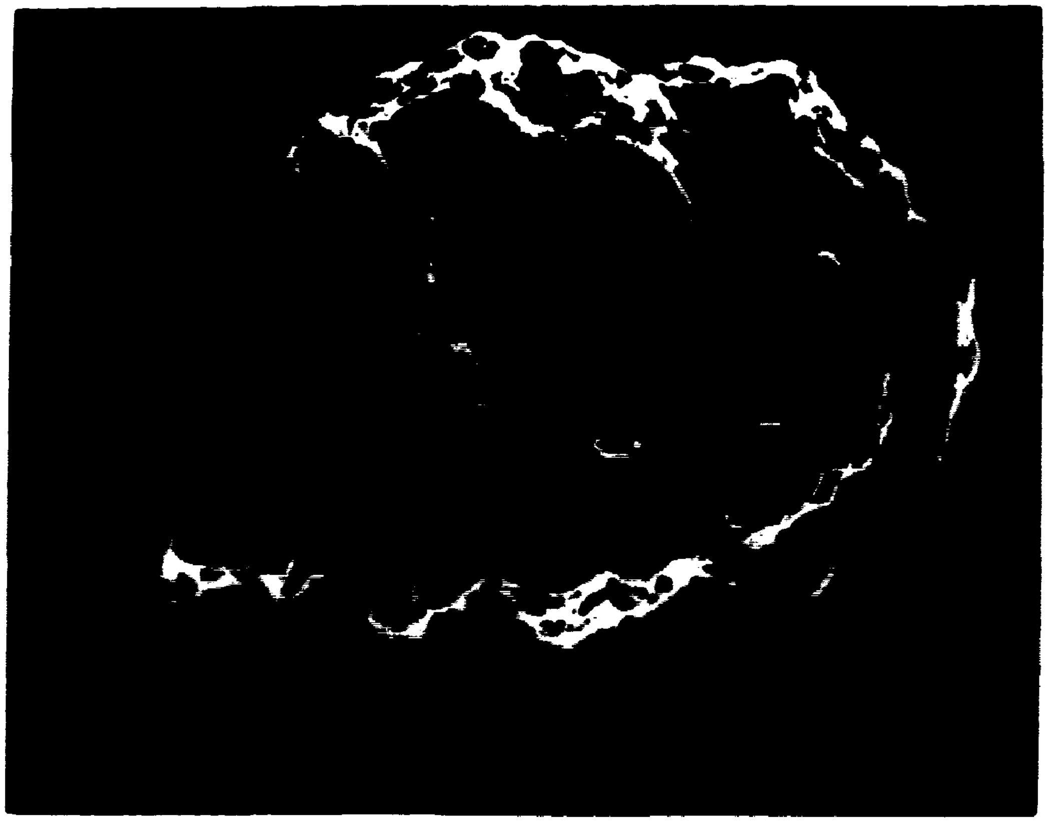


Plate 11 . Scanning electron microscope photograph of a Calmar Formation silt grain. Section TC-1. Quartz grain with quartz overgrowths. a)Peculiar round structures within quartz overgrowth.

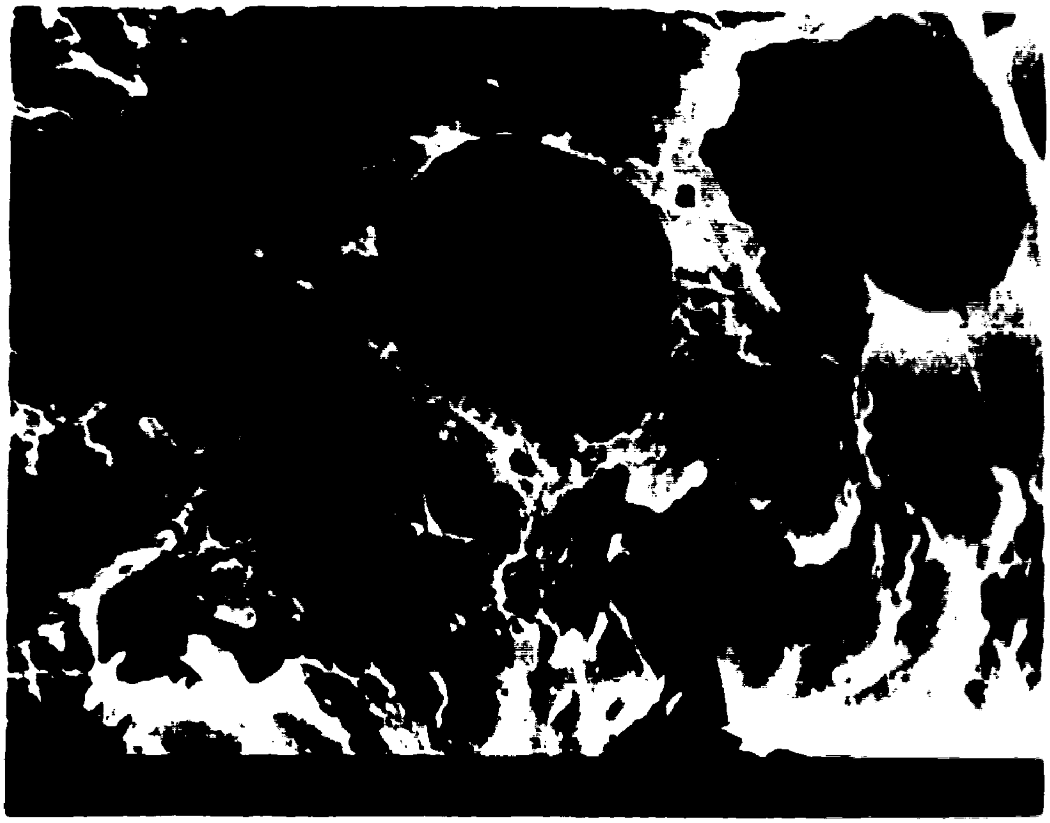


Plate 12. Scanning electron microscope photograph of a Calmar Formation silt grain. Close up of Plate 11. a) round structures are lined with hexagonal pattern and represent molds of spores.

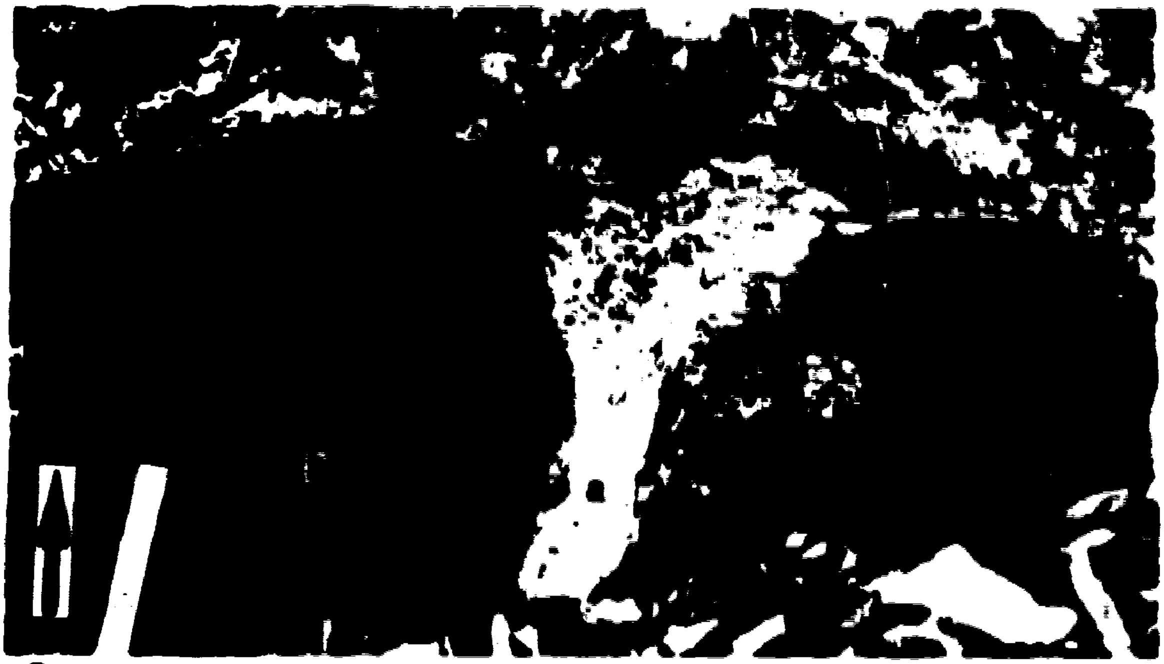
2.2.2 Calmar Formation Discussion

The green claystones and siltstones of the Calmar are widely documented and are reported at various stratigraphic levels within the Middle to Upper Devonian, (Machel, 1984, Wendte and Stoakes, 1982, and Leavitt, 1968). Previous studies have interpreted these green clays to be the residual soil of palaeoexposure surfaces, (Leavitt, 1968). More recent work by Machel, (1984), and Wendte and Stoakes, (1982), suggest that the green clays are the products of storms and that the fine grained sediments were transported to the shelf from a source external to the reef complex.

The relatively large percentage of illite may have at least four origins as discussed by Velde, (1977). These include 1) material crystallised during weathering, 2) reconstructed degraded mica, 3) mica formed at hydrothermal temperatures, and 4) "unaffected" illite redeposited from sedimentary rocks. The green illites of the Nisku Formation are reported to have formed in a mildly oxidising marine environment, (Machel, 1984)

The sediments analysed in the discussion by Machel (1984) have little or no quartz or feldspathic silt or chlorite. The paucity or absence of these minerals is interpreted by Machel to be indicative of a marine setting, remote from any shoreline or having a windblown origin for the clays. X-Ray diffraction results of the green claystones from the Calmar Formation discussed in this study have an abundance of the aforementioned minerals, (Table 1) suggesting a somewhat different environment of deposition.

A lack of biological structures and the presence of hummocky stratified quartzose silts to fine sands within the Calmar of the study area suggests that its origin may be a combination of several processes. The authigenic oxides and presence of spore casts within the Calmar Formation (Plates 11 and 12) may indicate a terrestrial influence. Terrestrial debris (spores) and iron-bearing siliciclastic material is periodically deposited into



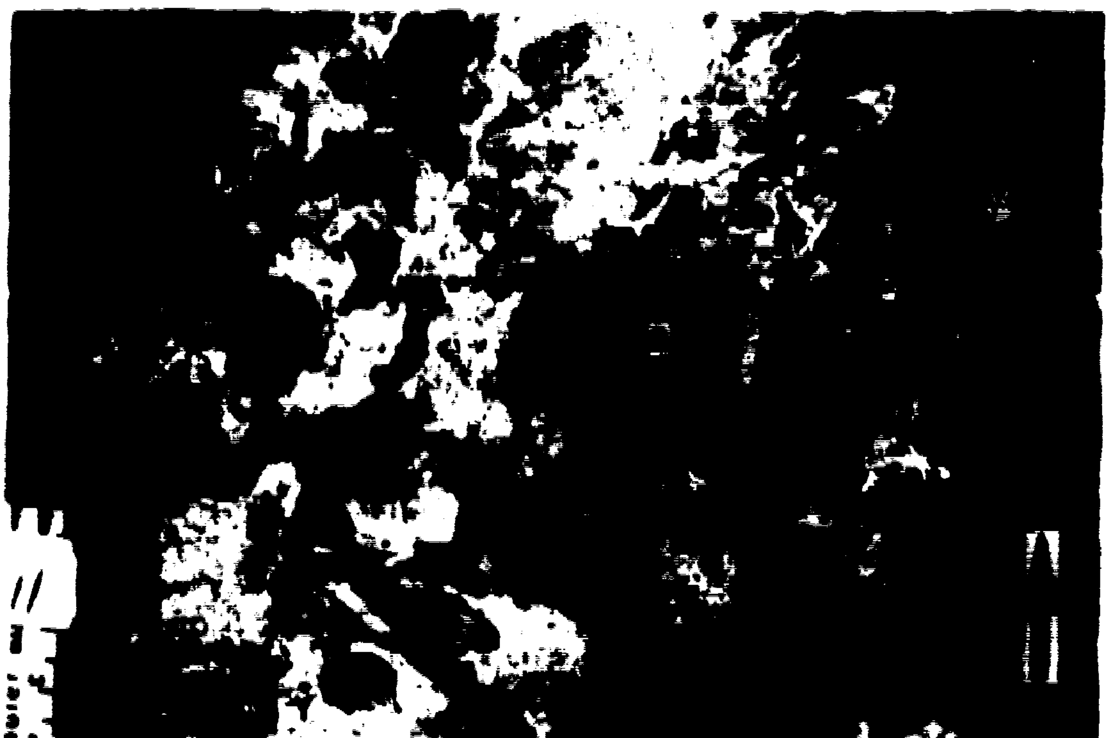
A

B

Plate 13 A) Blue Ridge Member carbonate mudstone deposited into a large (10cm) crevice/karst feature in the underlying Calmar Formation. Section TC-1. a)Blue Ridge Member carbonate mudstone, b) green clays of the Calmar Formation.

B) Closeup of the Blue Ridge Member massive carbonate mud (a) deposited into karst feature of the Calmar Formation green shales (b).

A



B

Plate 14. A) Calmar Formation green clays. Section TC-2. Peculiar weathering pattern as large fossil material is leached (a).
B) Close up of Calmar Formation green clays and peculiar weathering pattern. a) leached fossil material.

a shallow submarine environment during major storm events Burrowing marine organisms are not able to populate the extremely stressful environment because of repeated dessication Resumption of normal fair weather conditions completes the preservation of the physical sedimentary structures

Karsting of the upper surface of the Calmar Formation suggests a drop in sea level preceded Blue Ridge deposition Exposure of the platform and subsequent dewatering of the clay fraction would partially lithify the Calmar sediments Partial lithification of the sediments would increase their susceptibility to surface weathering and create structures observed in the upper surface of the Calmar Formation (Plate 13) Blue Ridge Member sediments are deposited into the voids created by chemical dissolution (karst)

To summarise, the Calmar Formation consists of a silty green claystone with a mineralogical and biological makeup reflecting a subaerial exposure surface The presence of siltstone beds in unburrowed illite and alumino-silicate rich sediments indicates periodic influxes of siliciclastic sediments into a shallow, subaerially influenced environment

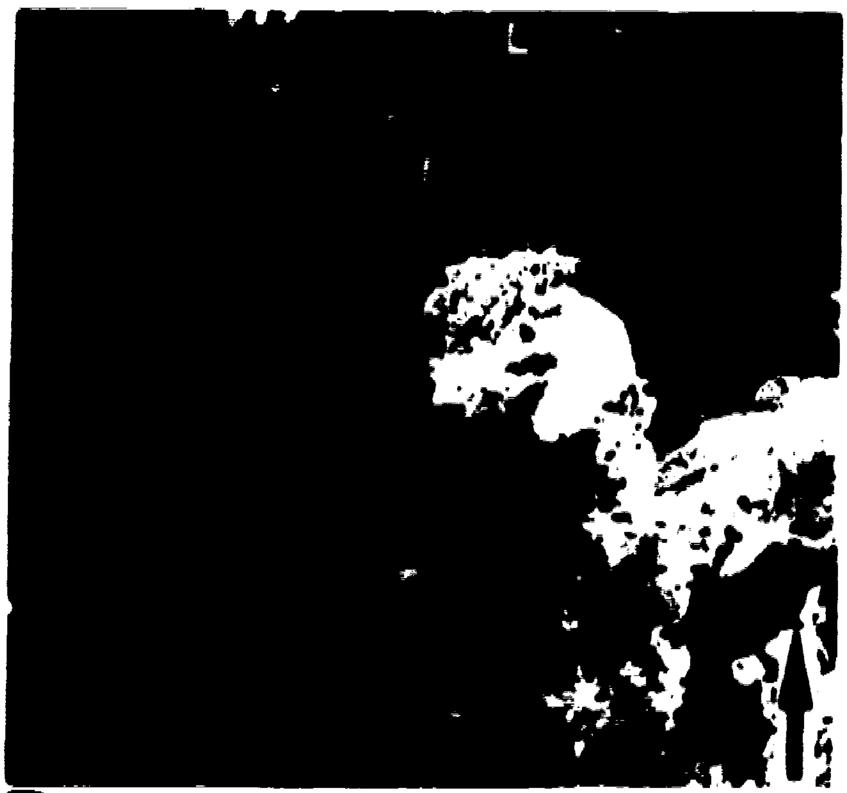
2.3 Lower Graminia Member - Graminia Formation

Within the study area the base of the Lower Graminia Member is defined by the occurrence of a relatively thin series of westward dipping siltstone/sandstone beds Lower Graminia Member hummocky stratified siltstones are absent on the Southesk-Cairn platform, but are correlative with the Calmar Formation In the Jasper Basin, (off-bank) the Lower Graminia Member is represented by the "Silt Doublet" and conformably overlies the calcareous shales of the lower Mount Hawk Formation

2.3.1 Sedimentology and Palaeontology

At its base the Lower Graminia Member consists of rhythmically bedded calcareous

A



B

Plate 15. A) Hummocky cross-stratification of an unburrowed Lower Graminia Member siltstone. Section NCP-1 a) scour surface.

B) Hummocky cross-stratification in a Lower Graminia Member siltstone. a) scour surface. Section SCP. Photo is approximately 1.5m across.

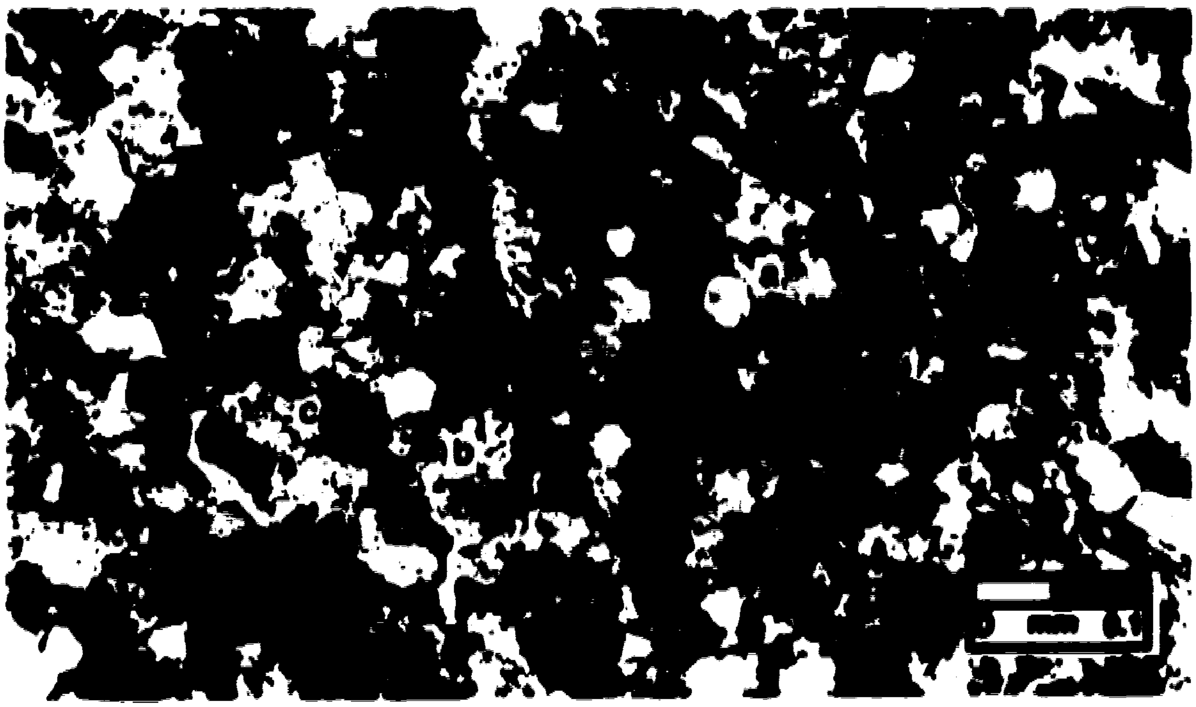
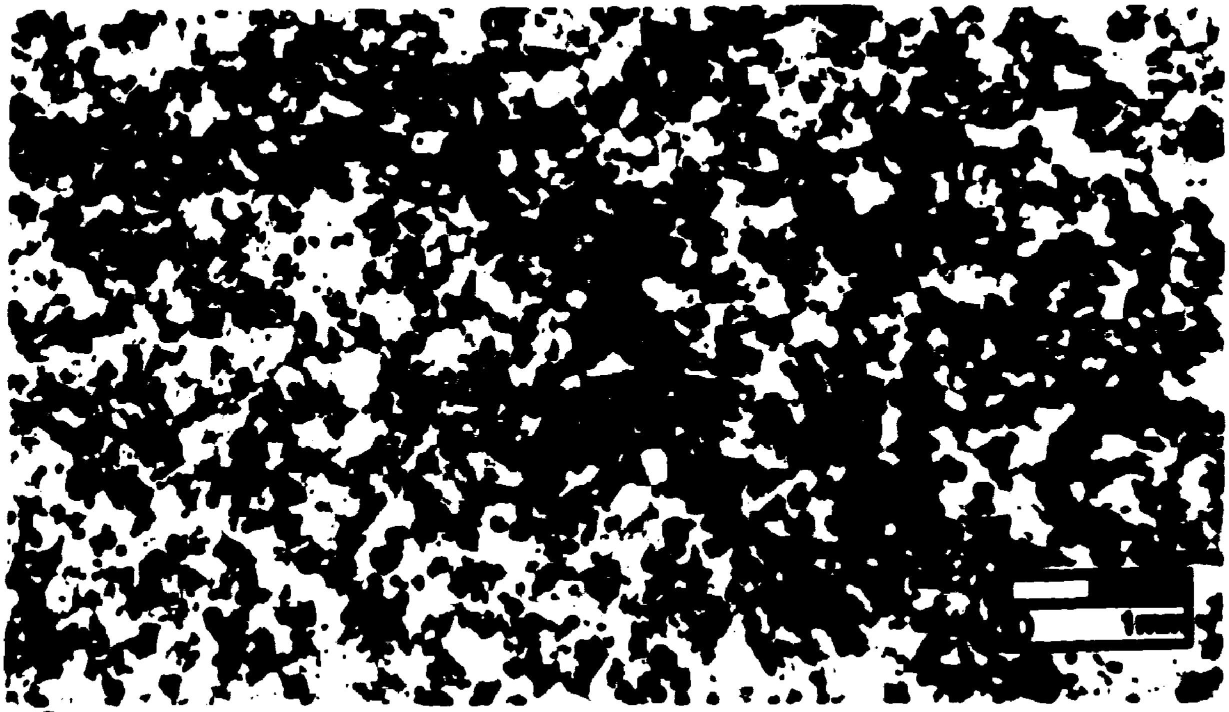
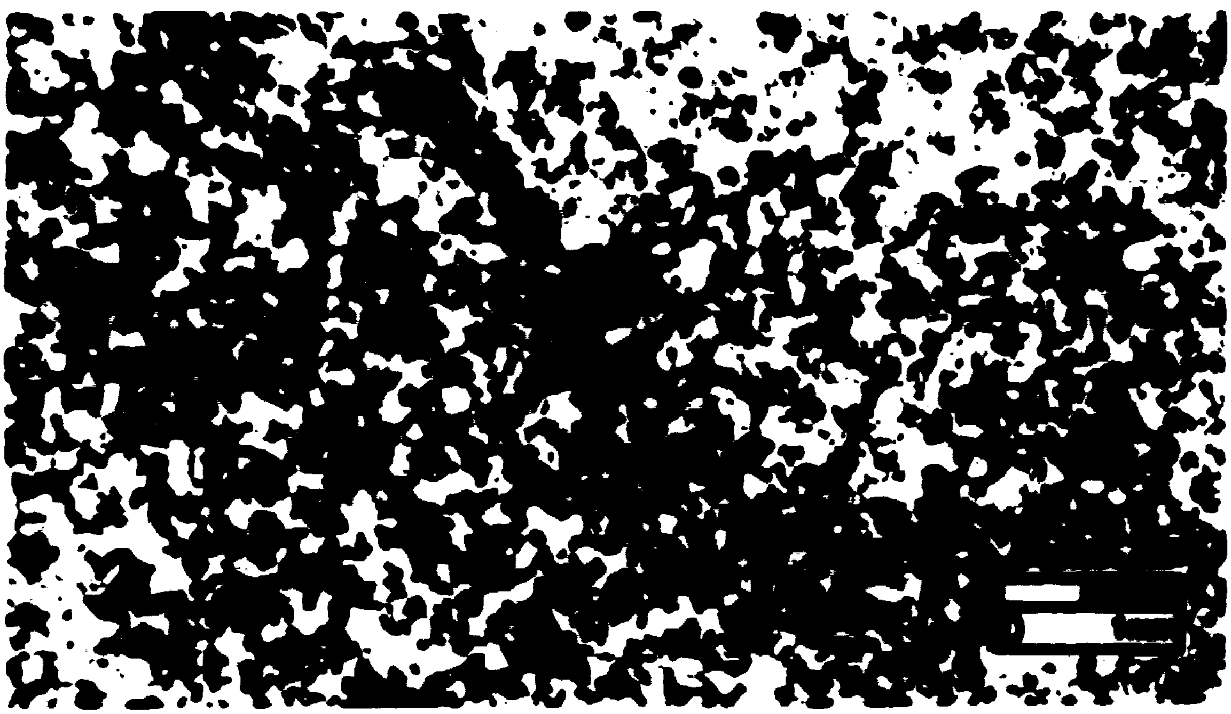


Plate 16. Photomicrograph of Lower Gramma Member calcareous siltstone from burrowed section of storm unit Section SCP Little or no argillaceous material a) rounded quartz grain with pitted surface. b) blocky dolomite cement. c)pellet structure Crossed polars



A



B

Plate 17. A) Photomicrograph of Lower Graminia Member silty carbonate mudstone. Section SCP. Quartz grains are rounded to subrounded. Crossed polars. B) Photomicrograph of Lower Graminia Member silty carbonate mudstone. Section SCP. Heavy mineral fraction up to 10%. Plane light.

silts and sands and silty carbonates (Plates 15, 16, and 17). Petrography and point count analysis yield high percentages (10-20%) of micrite and dolomicrite matrix, and sand and silt sized quartz grains (30-40%). Additional mineralogical components include dolomite cement (10-20%), opaque heavy minerals (10-15%), clays (5-10%), and iron oxide staining suggesting high initial amounts of iron bearing minerals. (Plates 16 and 17)

The quartz grains are rounded to angular with occasional quartz overgrowths. These overgrowths are not rounded indicating lack of transport. However pitting and pocking of the surfaces is common suggesting grain to grain contacts and associated chemical dissolution (Plate 16). The detrital heavy minerals are angular and closely associated with iron oxide staining. Detailed heavy mineral identification or thick sectioning is not included in this study. Possible mineralogy may include rutile (TiO_2), ilmenite ($FeTiO_3$), or limonite ($FeO(OH)$).

Micrite and dolomicrite are interstitial to the detrital grains in each thin section analysed. High percentages of finely crystalline carbonate matrix suggests the depositional system was predominantly carbonate. External clastic detritus may have been continually introduced into the system and reworked through physical (storm) and biological (burrowing) processes.

Deposition of Lower Graminia Member/Calmar Formation sediments did not occur on the underlying raised platform margin of the Southesk Formation (Shields and Geldsetzer, 1992). All Lower Graminia units measured in the study area exhibit undulating (hummocky) bedding on different scales. Small scale hummocky stratification (5-10 cm) is the dominant physical bedform proximal to the platform (Plate 15). However, a large percentage of the Lower Graminia bedding structures in the area proximal to the platform have been destroyed through biological activity (Plates 18, 19B, and 20). The thickness and frequency of hummocky stratification increases into the Jasper Basin away from the

A

B

Plate 18. A) Intensely burrowed Lower Graminia Member siltstone. Section SCP. a) *Thalassinoides*.

B) Intensely burrowed Lower Graminia Member siltstone. Section SCP. *In situ Teichichnus*.

A

B

Plate 19. A) Lower contact of Blue Ridge Member carbonate. Section TC-2. Jacob's staff for scale is 1.5m. Lower Graminia Member is absent at sections TC-1 and TC-2. Calmar Formation is correlative.
B) Intensely altered Lower Graminia Member silty carbonate. Section SCP. No trace fossils visible. Dolomite predominates.

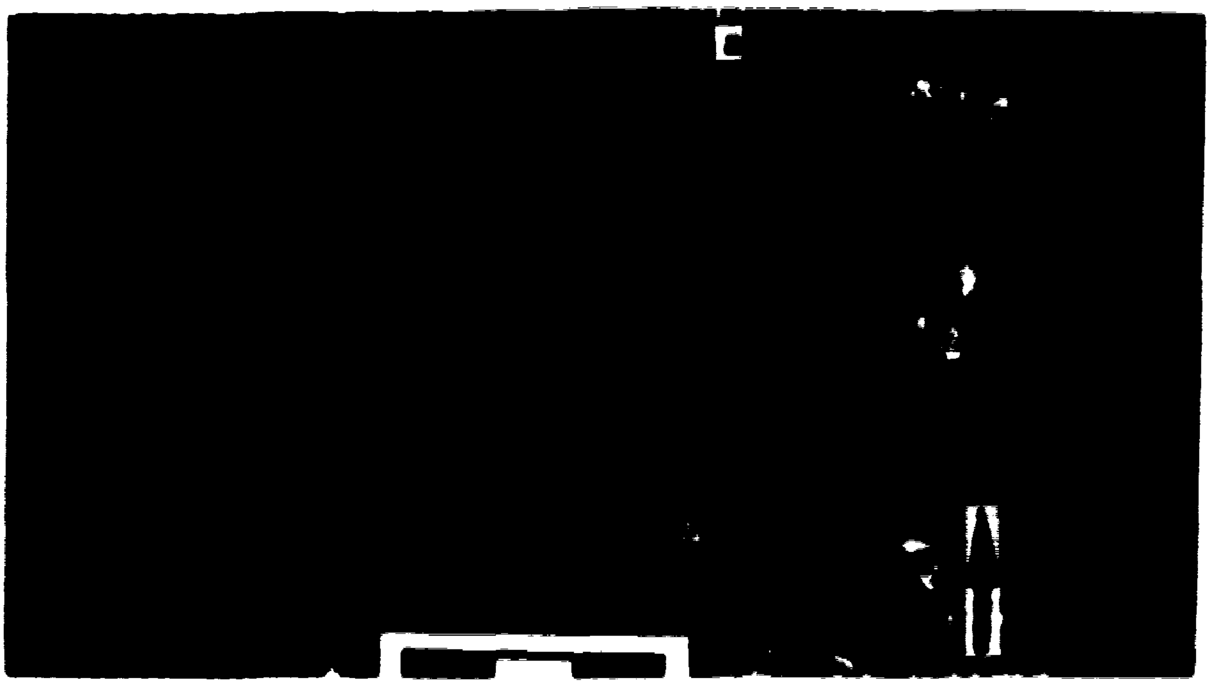


Plate 20. Lower Gramınia Member recessive burrowed siltstone interbedded with unburrowed parallel laminated siltstone. Section SCP. Represents one complete storm cycle deposition. 1) deposition 2) colonization 3) burrowing 4) subsequent storm deposition. a) scour surface, b) gradational contactbetween burrowed sand and unburrowed sand, c) *Palaeophycus*. Scale bar is 3cm

Southesk-Cairn platform In the Cardinal Headwaters section biological activity has destroyed most of the physical bedforms

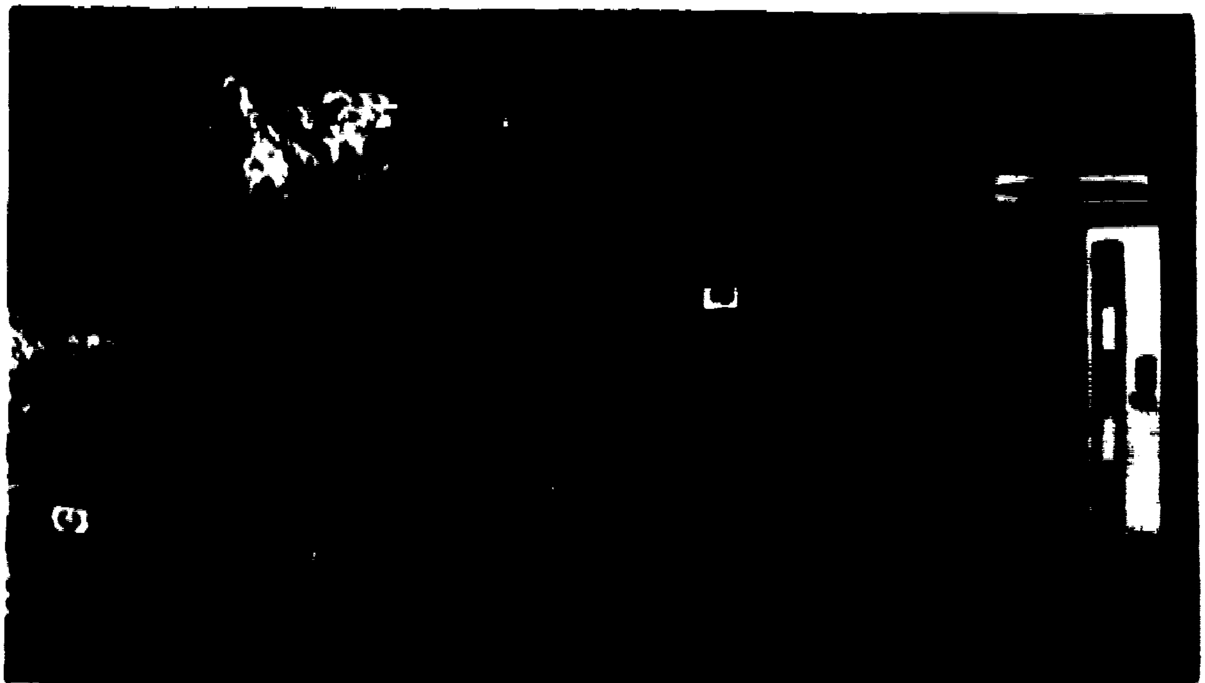
Large scale Lower Graminia Member sedimentary structures in the area of the South Cardinal Pass Section alternate between hummocky bedded strata and highly burrowed sediments The highly burrowed beds are generally more recessive than the unburrowed hummocky bedded units This recessive/prominent cyclicity is evident in Plates 21 and 22

At a more basinward location at North Cardinal Pass, the Lower Graminia is identified by a set of two prominent hummocky siltstone beds Shields and Geldsetzer (1992), and Workum and Hedinger (1987), identified this set of siltstone beds as the "Silt Doublet" Plates 4,5, and 6 illustrate the nature and thickness of the "Silt Doublet" in the area of North Cardinal Pass Section 1

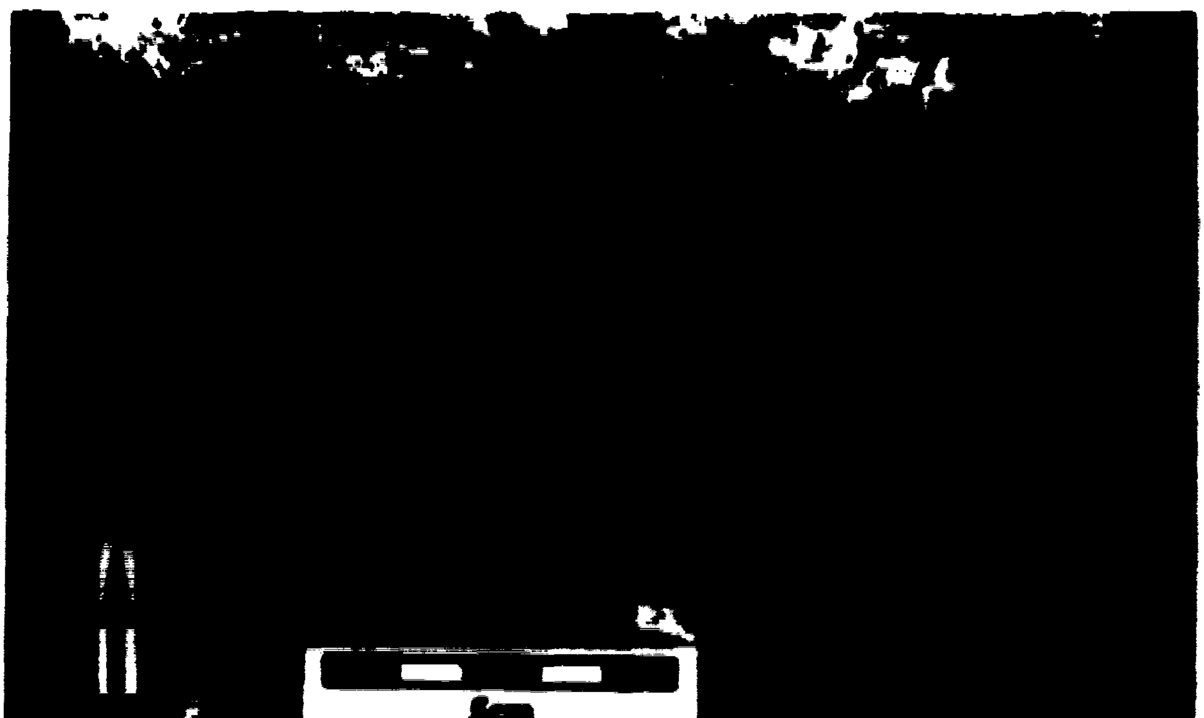
Detailed investigation of the "Silt Doublet" reveals it to be a pair of prominent hummocky cross-bedded siltstones interbedded with at least three intensely burrowed more recessive siltstone units (Figure 7) The lowermost unit appears entirely burrowed and is truncated by the overlying bedded unit. The overlying unit is entirely burrowed in the upper 2 -3 meters with burrow intensity decreasing downward and gradually disappearing into the underlying hummocks This succession of bedded and burrowed beds is repeated in an overlying set of siltstones The result of this cyclicity is similar to the cyclically bedded and burrowed units at South Cardinal Pass Subsequent preferential weathering on the outcrop of these exposed siltstones has created the prominent and recessive "Silt Doublet" beds (Figure 7)

Several authors have indicated that the ratio of bedded to burrowed bed thicknesses indicates the frequency and severity of storm events (Howard 1975 Dott

Plate 21. Lower Grammia Member siltstone. Section SCP. Prominent parallel laminated to hummocky bedded siltstones overlying recessive, intensely burrowed siltstones. Sample represents burrowed storm siltstones overlain by younger storm deposited siltstones. a) *Thalassinoides*, b) scour surface.



A



B

Plate 22. A) Complete Lower Graminia Member storm depositional cycle. a) storm deposited parallel laminated to hummocky bedded siltstone. b) intensely burrowed upper portion of storm beds. c) subsequent storm beds of overlying storm event. Section SCP.
B) Close up view of Lower Graminia Member burrowed storm unit. a) scour surface. b) *Thalassinoides*. Section SCP.

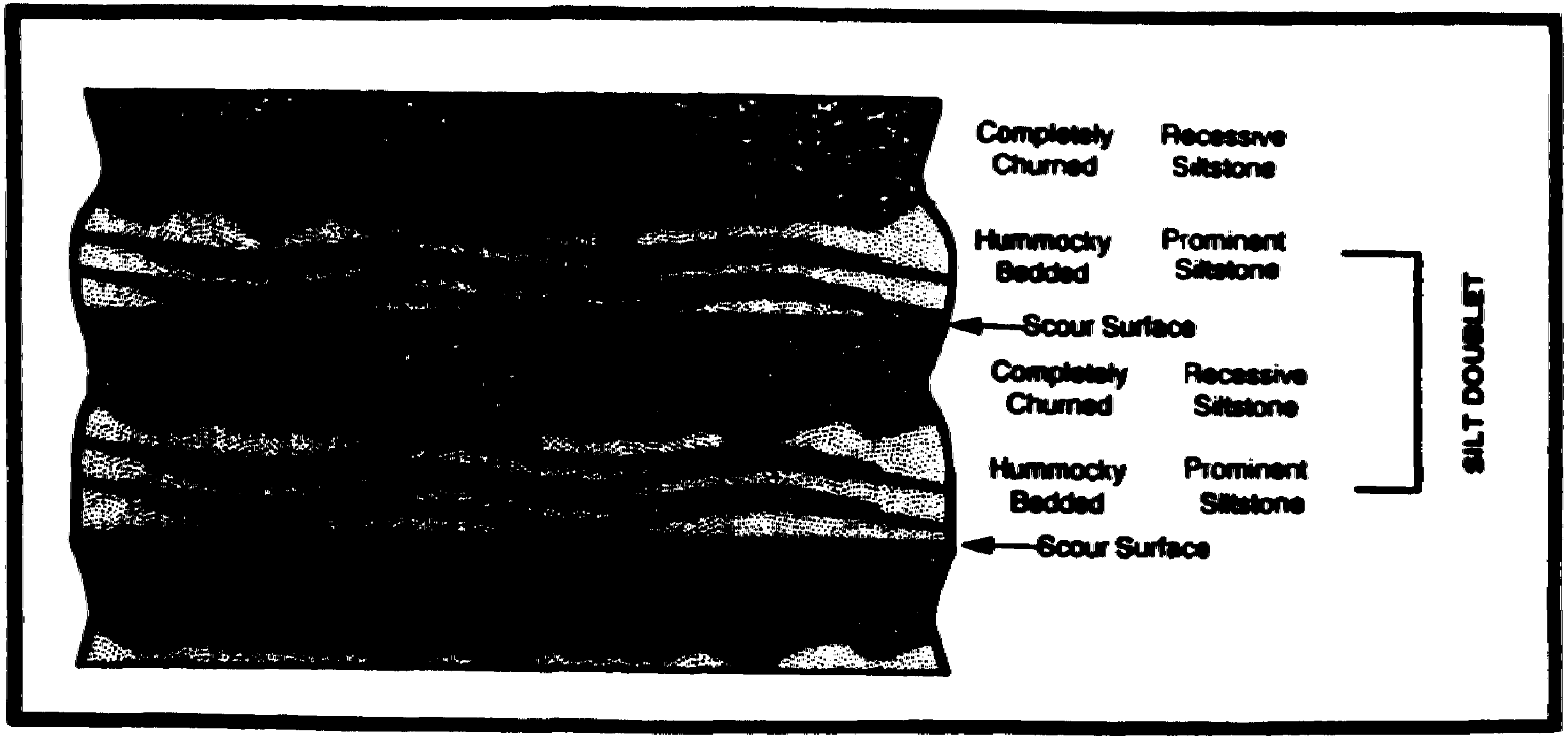


Figure 7 . Schematic diagram illustrating the mode of formation and preservation of the Lower Grammia "Silt Doublet" No scale is implied "Silt Doublet" is approximately 10 m in total thickness

1988, and Pemberton *et al.*, 1992). Pemberton *et al.* (1992) pointed out that the intensity of sediment reworking has three connotations: 1) population density and rate of activity by the organisms, 2) degree of modification of primary physical sedimentary structures, and 3) rate of deposition of sediments. Depositional rate is perhaps the most important (Pemberton *et al.*, 1992). As a result, thicker burrowed sections indicate extended periods of time between individual storm events in which opportunistic organisms are able to burrow the sediments. The longer the period of time in which burrowing occurs, the deeper the penetration by the organisms into the sediment. The result is a thinner preserved stratified unit (Wheatcroft, 1990, Pemberton *et al.* 1992).

Thicknesses for all available individual storm beds were measured in the field. Storm frequency as calculated by burrowed : bedded thickness is variable. However, no accurate time frame could be calculated for individual events because of the unavailability of a depositional rate for the Lower Graminia Member sediments.

Basinward, towards the northwest, the Lower Graminia Member becomes increasingly more burrowed and the "Silt Doublet" is no longer recognisable (Plate 23). The Lower Graminia Member calcareous silts and silty carbonates measured at the Cardinal Headwaters Section 2 are entirely reworked and no physical structures remain (Plate 24).

Bioclastic sediments are common throughout the entire Lower Graminia section, but the abundance and diversity of fossils is generally low. Brachiopod debris, algal structures, crinoid ossicles and indistinguishable coral fragments are the only visible allochems in the basinal sections at Cardinal River Headwaters and North Cardinal Pass Section 2. Proximal to the exposed Arcs/Grotto platform the fossil abundance increases, however diversity remains low. Gastropods, rare solitary coral debris and bivalves are identifiable in addition to brachiopod and crinoid debris.

Plate 23. Cardinal River Headwaters section approximately 1.5km South of section CH-2. The "Silt Doublet"/Lower Gramina coalesces into a single unit. The Gramina Formation is represented by the Lower Gramina Member, Blue Ridge Basinal Member, and the Upper Gramina Member. View is to the Southwest.

Plate 34. Cardinal River Headwaters section approximately 0.5km South of section CH-2. The Graminia Formation is represented by the Lower Graminia Member, Blue Ridge Basinal Member, and the Upper Graminia Member. View is to the West.

Ichnofossils are relatively abundant throughout the entire interval. Trace fossils identified are most abundant in the burrowed interbeds of the Upper and Lower Members. These units include *Skolithos*, *Thalassinoides*, *Palaeophycus*, *Teichichnus*, *Planolites*, *Chondrites*, *Teichichnus*, *Cruziana*, *Palaeophycus*, escape traces and rare *Polykladichnus*. All forms are generally small with the exception of *Thalassinoides*. Recolonisation of newly deposited storm beds is rapid in a relatively non-competitive environment. Subsequent storm events reworked the previously burrowed sediments and burrows within the upper regions of the beds are destroyed.

2.3.2 Lower Graminia Member Discussion

The calcareous silts of the Lower Graminia appear to have been deposited in a shallow off bank environment below fair weather wave base and within storm weather wave base. Highly burrowed strata are relatively thick and show excellent preservation of cyclicity. The depositional system appears to have been predominantly carbonate with a dominant siliciclastic source supplying quartz and heavy minerals. The carbonate mud matrix and clastic debris were subsequently reworked by storm activity and biological processes.

Thin section analysis and scanning electron microscopy identified rounded quartz overgrowths and heavily etched grains (Plates 25 and 26). This suggests the source was a previously lithified sedimentary rock reworked and redeposited during Lower Graminia time. Potential areas capable of supplying this type of sediment include: 1) Peace River Arch, 2) Canadian Shield, 3) West Alberta Ridge, 4) as yet unidentified western source.

A mechanism of transport for the siliciclastic sediment into the study area remains problematic. Possible sediment supply mechanisms include: fluvial systems, aeolian systems, or submarine currents. No original, depositional structures within the siliciclastic material remain because of the continual reworking of the sediments by storm and biological processes during Lower Graminia time.

2.4 Blue Ridge Member - Graminia Formation

Within the study area the Blue Ridge Member is present exclusively on the Southesk-Cairn platform. Off of the buildup the upper Mount Hawk Member of the Mount Hawk Formation is correlative to the Blue Ridge Basinal Member. The Blue Ridge is defined by the occurrence of a prominent carbonate ridge directly overlying the Calmar Formation (Plate 19A). Much of the contact between the Blue Ridge Member and the underlying Lower Graminia Member is obscured by scree.

The Blue Ridge Member represents the final growth stage of the Southesk-Cairn platform and is characterised by a significant progradation of the platform margin environment. The presence of biostromal buildup material suggests the locus of platform margin deposition during Blue Ridge time was at Toma Creek. Subsequent progradation of the platform margin shifted the depocentre towards the north in the direction of Mount Mackenzie. (Shields and Geldsetzer, 1992)

2.4.1 Sedimentology and Palaeontology

Mineralogically the Blue Ridge and Blue Ridge Basinal Members consist of variably dolomitized grainstones, wackestones, and mudstones. Replacement dolomite appears to decrease upward and bankward (Southeast) in the measured sections. Two separate phases of coarsely crystalline dolomite cement represents the final phase of lithification. Pelletal structures, oncolites, skeletal material and rounded lithoclasts are the predominant allochemical constituents (Plate 27). Silt sized quartz and feldspar grains are also present in specific horizons on the platform and in the Blue Ridge Basinal Member (Plates 28, 29, and 30).

Physical structures within the Blue Ridge Member are restricted to the relatively thin quartz and feldspar rich horizons dispersed throughout the unit. Ripple cross-lamination and undulatory bedding predominate within these 10-50 *cm* thick units. The

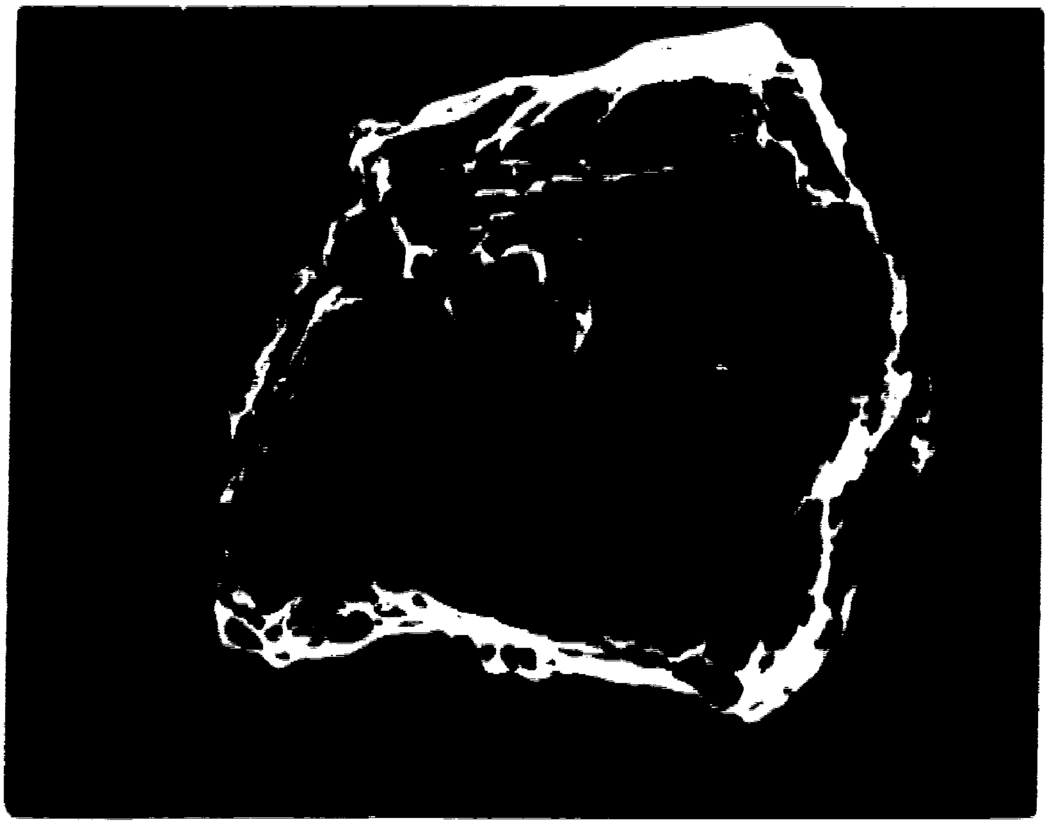


Plate 25. Scanning electron microscope photograph of a Lower Graminia Member ("Silt Doublet") silt grain. Section NCP-1. Heavily etched quartz grain and quartz overgrowth. a) casts of dolomite crystals within quartz overgrowth.

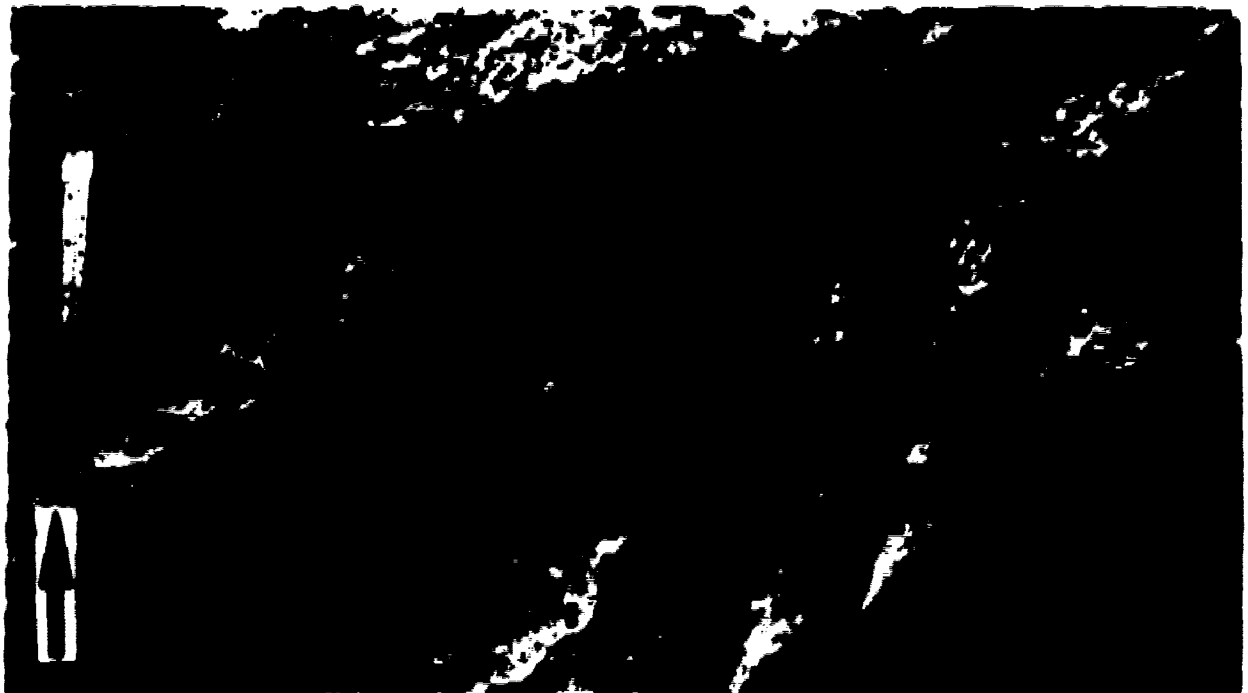
Plate 26. Scanning electron microscope photograph of a Lower Grammia Member ("Silt Doublet") silt grain. Clean quartz overgrowths on quartz grain.

remainder of the platform is a series of massive biostromes interbedded with skeletal grainstones.

The Blue Ridge Member at Toma Creek Section 2 is composed of interbedded pelletal grainstones and mudstones with rare skeletal wackestones (Plates 32 and 33). Rare fossil debris and skeletal wackestones are also recognized in association with thin (<10cm) silt sized quartz rich horizons (Plate 28A,B, Plates 38 and 39). These horizons may represent storm deposition into a dominantly low energy carbonate platform interior environment.

Ichnofossils within the Blue Ridge and Basinal Blue Ridge Members are characterised by low species diversity, low population, and small size despite the large percentage (up to 30 %, Plate 27B) of biologically generated pelletal grains. Narbonne (1984) suggests that the greater susceptibility of carbonates to early and late diagenetic processes greatly reduces the preservation potential of a trace fossil suite developed within a carbonate sediment. Ichnofossils identified within the platform and basinal Blue Ridge carbonates include *Monocraterion*, *Bergaueria*, and *Lockeia*. Escape traces in conjunction with hummocky cross-stratified silts indicate catastrophic storm deposition and the responsive behaviour of the organisms present.

Macrofossils in life position (corals) and articulated bivalves are common within the platform Blue Ridge Member. Basinal sections contain abundant bioclastic detritus. Life position fossils are generally restricted to the platform interior and includes gastropods (Plate 32B) and *Megalodont* bivalves (Plate 33A,B). At the platform margin stromatoporoids are abundant and include spherical, bulbous (Plate 34B), laminar, and encrusting. Corals are also abundant on the open marine platform margin and include rugose, and rare *Alveolites* (Plates 33A,B,34B).



A

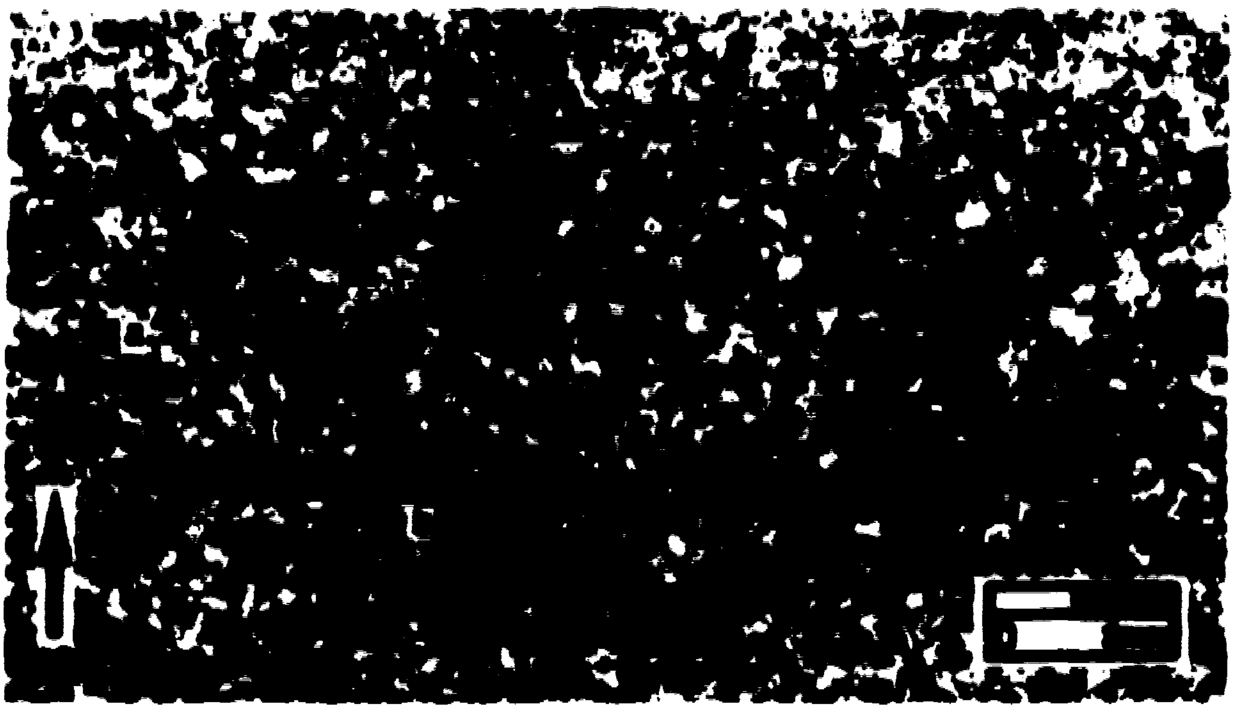
B

Plate 27. A) Typical weathering surface of a Blue Ridge Member pelleted carbonate wackestone.

B) Photomicrograph of Blue Ridge Member carbonate wackestone in A).

a) pellet structures, b) calcite (stained red) cement.

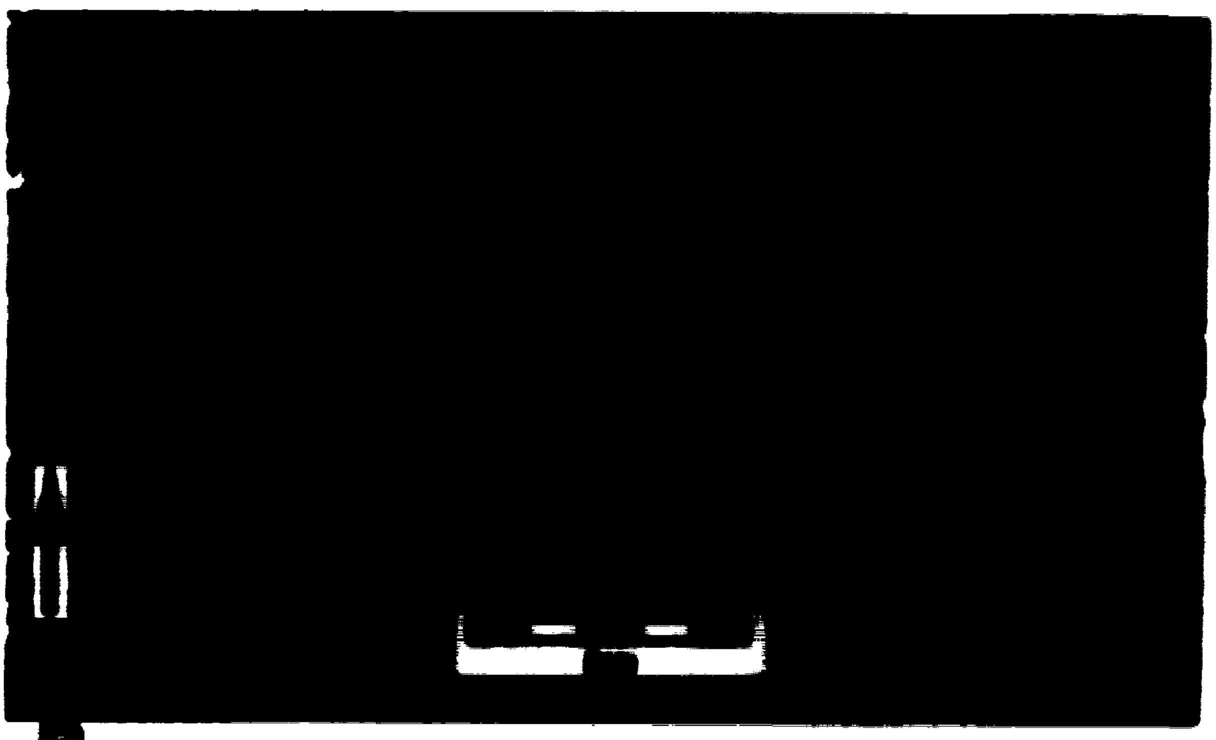
A



B

Plate 28. A) Silts within Blue Ridge Member carbonate. Section TC-2. a) low angle cross-stratification, b) slumping of silts into carbonate mud.
B) Photomicrograph of a 2-3mm siltstone bed within Blue Ridge Member Carbonate. Section TC-2. a) siltstone, b) carbonate matrix. Tops indicated by decrease in silt percentage upward (waning flow).

A

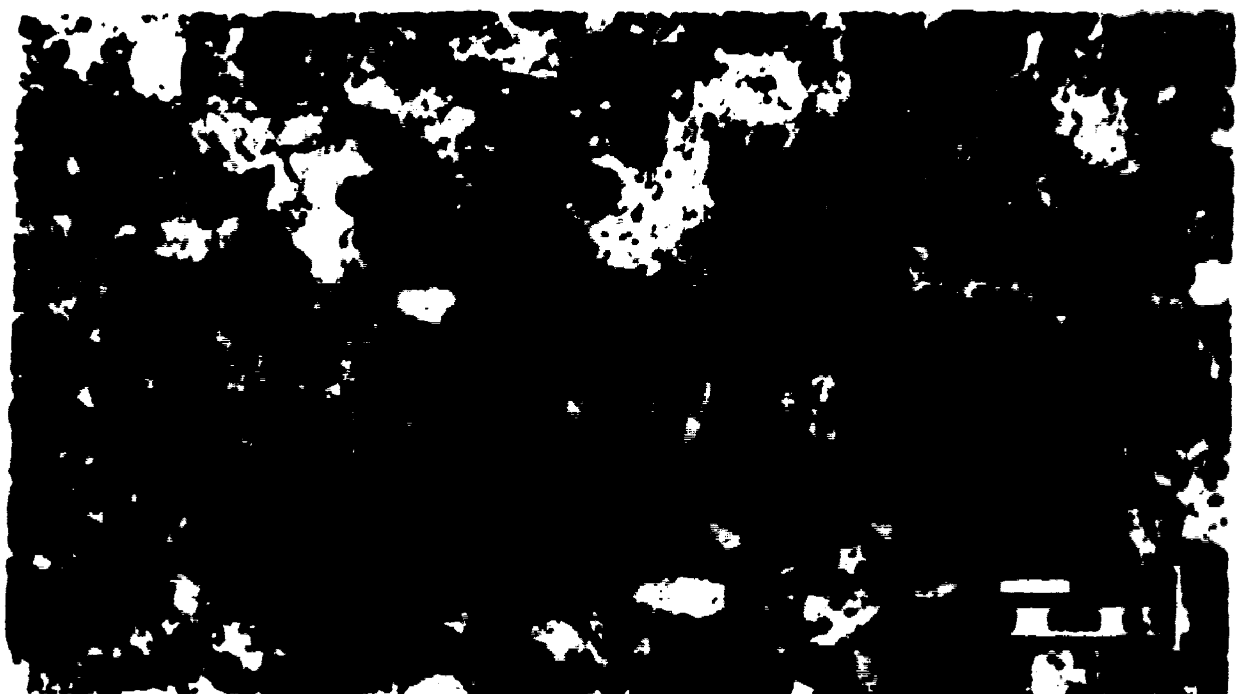


B

Plate 29. A) Blue Ridge Member siltstones within massive carbonate mudstones. Section TC-2. a) scour surface. b) low angle cross-stratification indicates bedform migration offshore. (to the right of the pphotograph).

B) Blue Ridge Member siltstone within massive carbonate mudstone. Section MM-2. a) *Skolithos*. b) *Arenicolites*. c) escape trace. d) scour surface and overlying parallel laminated siltstones.

A



B

Plate 36. A) Interbedded calcareous siltstone and silty carbonate of upper portion of Blue Ridge Member. Section MM-2. a) low angle cross-stratification in silty bed.

B) Photomicrograph of Blue Ridge Member silty carbonate. Section MM-2

A

B

Plate 31. A) Carbonate mudstone of the Blue Ridge Basinal Member. Section NCP-1. Small percentage of fossil debris.

B) Photomicrograph of Blue Ridge Basinal Member. Section CH-2. a) subangular to subrounded quartz grains with pitted surfaces in micrite matrix. b) articulated brachiopod filled with dolomite cement.

A

B

Plate 32. A) Highly fossiliferous Blue Ridge Member carbonate. Section TC-2. Matrix is pelleted lime mudstone. a) leached articulated bivalves. B) Photomicrograph of Blue Ridge Member carbonate wackestone - packstone. Section TC-2. a) gastropod, b) pellets, c) bivalve filled with dolomite cement.

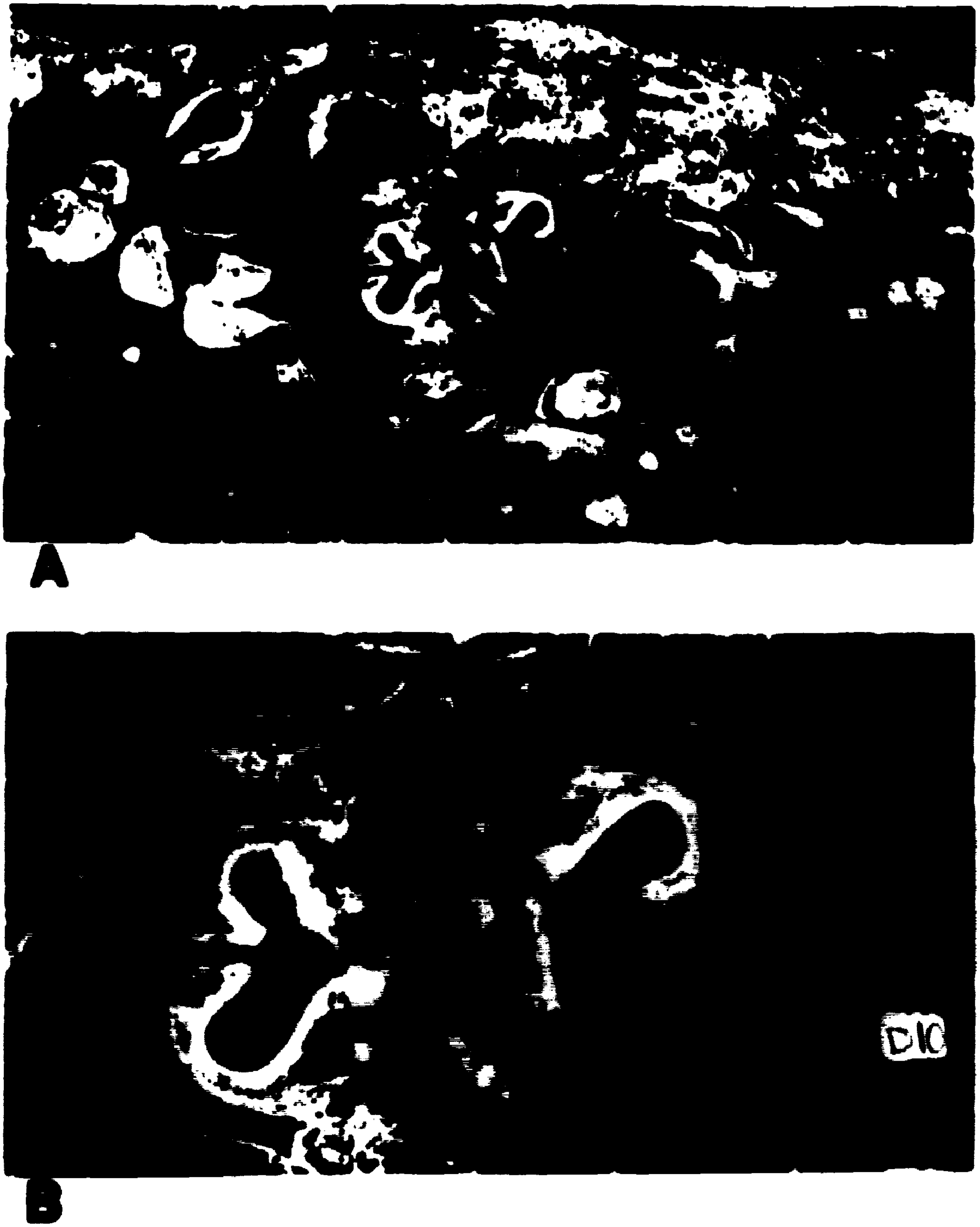


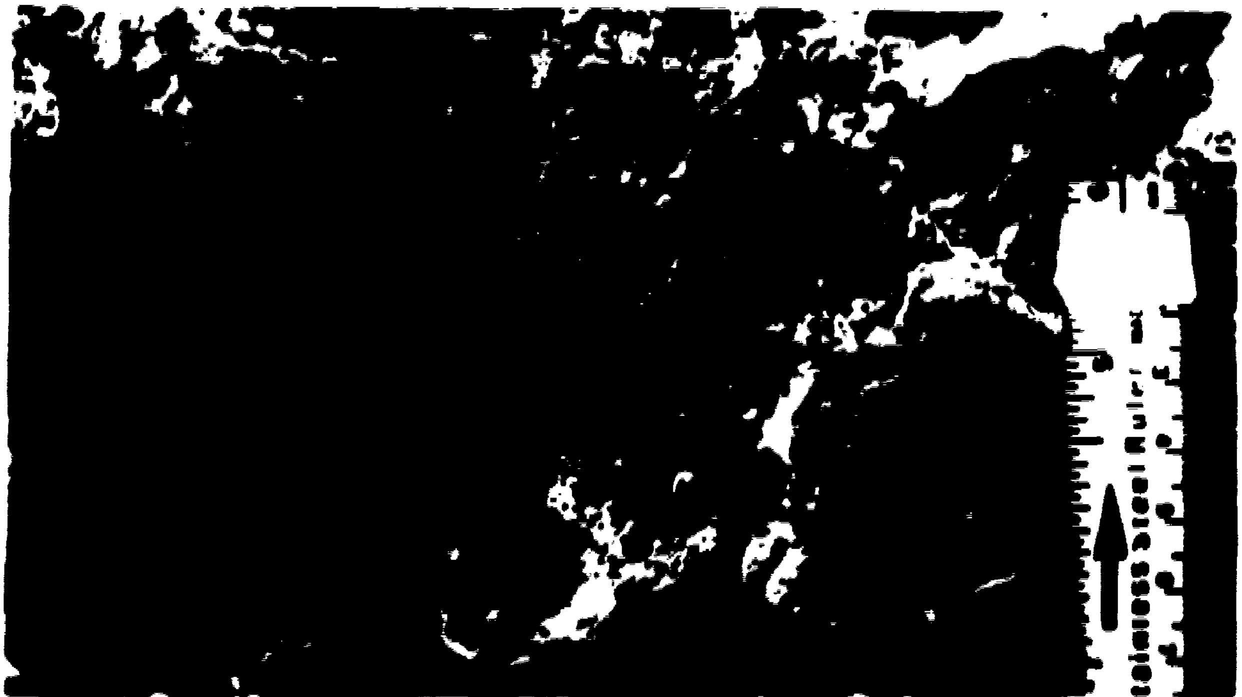
Plate 38. A), B) Conspicuous articulated *Megalodont* Bivalve bedding surface of Blue Ridge Member. Section TC-2. Matrix is carbonate wackestone to packstone.

Seaward of the platform margin fossil debris becomes more disarticulated and includes brachiopods, crinoids, bryozoans, and rugose coral debris (Plate 31A). The foreslope environment of the North Cardinal Pass Sections 1 and 2 is characterised by a carbonate mound approximately 120m wide and 40m thick (Plate 6). The buildup is inaccessible, however associated debris beds contain large stromatoporoids and disarticulated colonial corals derived from the area of the buildup.

Basinward of the buildup at North Cardinal Pass Section 2 a conspicuous oncolite bed is developed in the uppermost Blue Ridge Basinal Member (Appendices 1 and 2). The oncolites range up to 5cm in diameter and exhibit excellent textural preservation. Shields and Geldsetzer (1992) suggest the occurrence of the oncolite beds at the upper contact of the Blue Ridge may be related to the Frasnian-Famennian extinction event. No evidence is available in this study to validate or refute this suggestion. However, conodont biostratigraphy suggests the Frasnian-Famennian boundary is present at the lower contact of the Sassenach/Upper Grammia with the Blue Ridge Basinal Member of the Grammia Formation (Johnston and Meijer Drees, 1993; Weissenberger, 1988).

2.4.2 Blue Ridge Member Discussion

The Blue Ridge Member of the Grammia Formation represents latest Frasnian carbonate deposition at the Southesk-Cairn platform margin. Correlative Blue Ridge Basinal Member sediments are equivalent to the upper Mount Hawk Formation and are also dominated by carbonate sedimentation. The increased carbonate mud content and decreased abundance of skeletal allochems in the basinal sediments suggests that these deposits represent quiet water off-bank deposition. The platform interior is represented at the Toma Creek Section by pelletal grainstones and mudstones deposited in a restricted setting which was periodically influenced by storm activity.



A

B

Plate 34. A) Coral wackestone of Blue Ridge Member Carbonate. Section SCP. Corals (*Alveolites*) are close to life position and are surrounded by carbonate mudstone matrix.

B) Stromatoporoid within a Blue Ridge Member Carbonate grainstone. Section TC-2.

A

B

Plate 35. A) Carbonate debris bed of Blue Ridge Basinal Member proximal to the basinal carbonate mound a)dark lithoclasts show good rounding. Quarter for scale

B) Photomicrograph of sample from carbonate debris (A). Rounded lithoclasts contain a) calcispheres, b) ooids, c) pellets, and are cemented by d) druey dolomite cement, and e) blocky carbonate cement.

Thin siliciclastic dominated intervals at Toma Creek section 2 illustrate the interpretation that catastrophic events affected the platform interior Rounded carbonate lithoclasts in the region of North Cardinal Pass section 1 (Plate 35A B) illustrate the interpretation that these catastrophic events also affected the deeper water off bank regions Carbonate deposition on the platform and in the basinal section was not terminated by the input of siliciclastics and was quickly resumed following cessation of individual storm events

Sources of the siliciclastics are similar to the sources of the Lower Graminia Member silts The presence of quartz and feldspar grains (Plates 36 37 38 and 39) and the absence of dissolved feldspar grains in the form of clays suggests these sediments were not transported great distances before being deposited Chemical dissolution and physical abrasion during extended transport will generally destroy feldspar grains and significantly abrade quartz grains The resulting sediments are often clay rich and have little feldspar remaining This suggests a proximal source for the siliciclastic material

Abundant robust skeletal material (*Megalodont* bivalves, *Alveolites*) within measured Blue Ridge sections suggests a normal marine environment periodically interrupted by storm activity Basinal deposition includes development of off-bank carbonate mounds. Debris beds associated with the buildup suggest it may have undergone early lithification Oncolite beds deposited at the upper contact of the Blue Ridge buildup may represent basin depositional response to the events responsible for the Frasnian-Famennian extinction

2.6 Upper Graminia Member - Graminia Formation

Within the study area, the base of the Upper Graminia Member is defined by the occurrence of a thin series of westward dipping siltstone beds unconformably overlying the Blue Ridge Member on the Southesk-Cairn platform In the Jasper Basin (off-bank) the

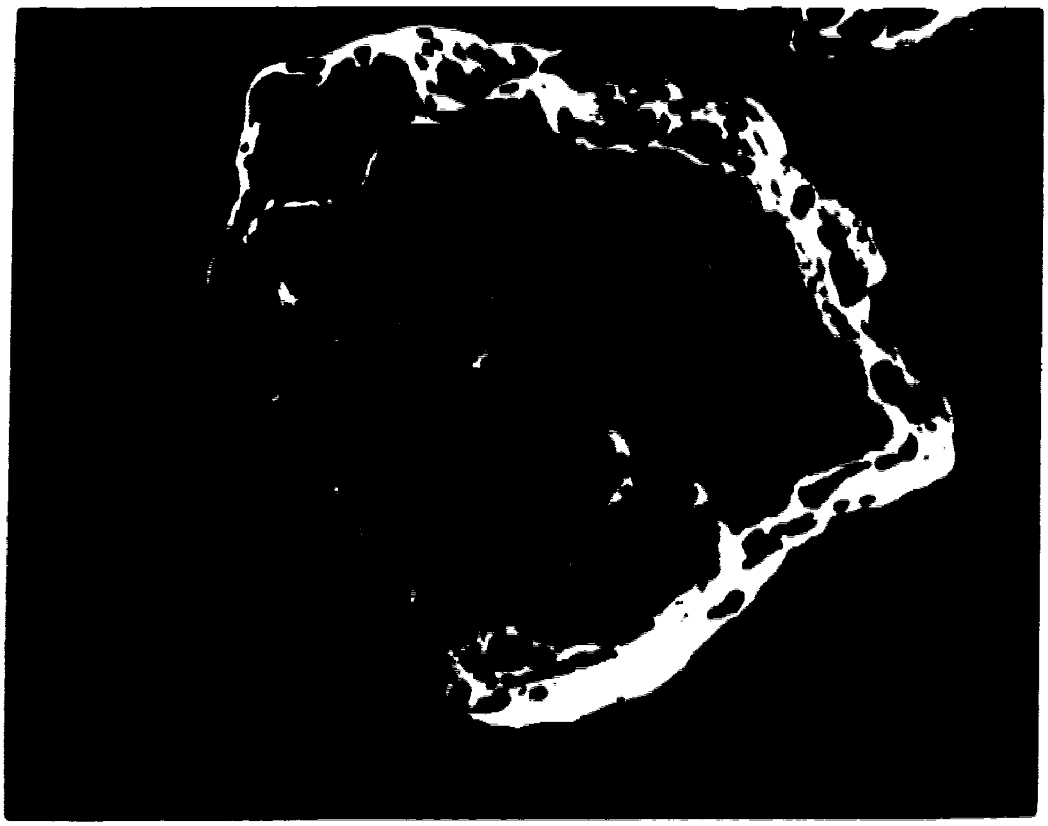


Plate 36. Scanning electron microscope photograph of Blue Ridge Member silt grain. Heavily etched potassium feldspar grain with potassium feldspar overgrowths.

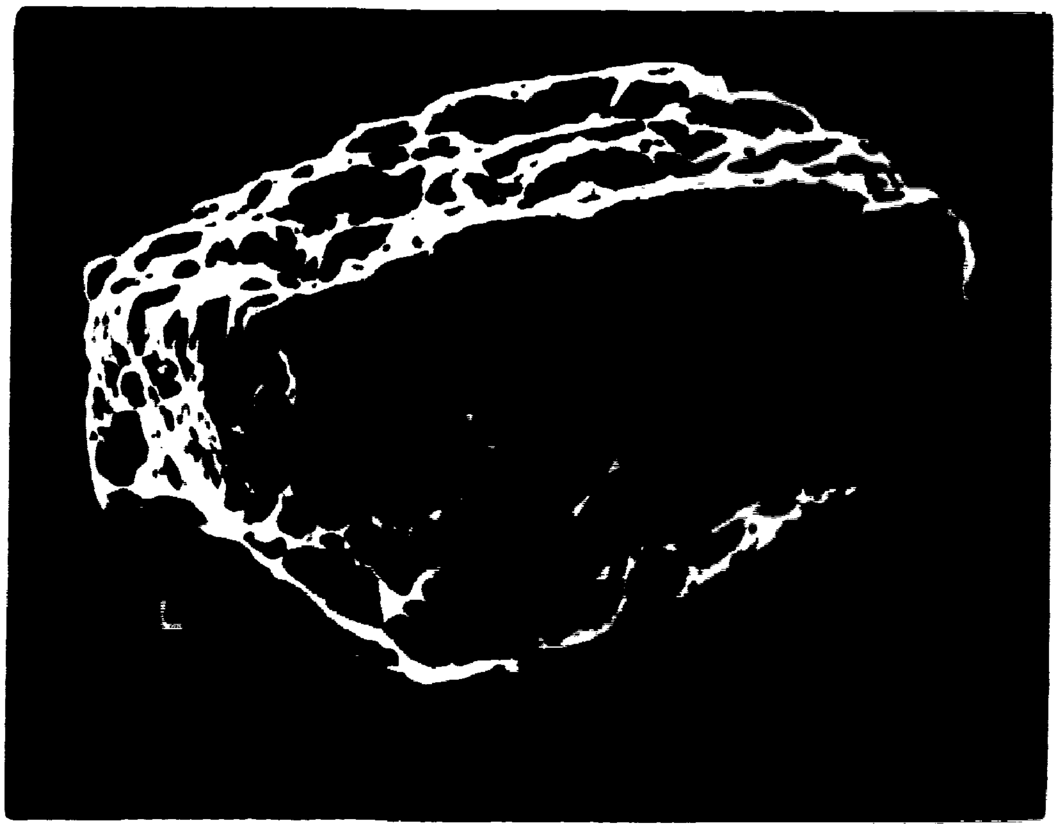


Plate 37. Scanning electron microscope photograph of Blue Ridge Member silt grain. Feldspar grain with heavily etched feldspar overgrowth. a) twinning on feldspar grain

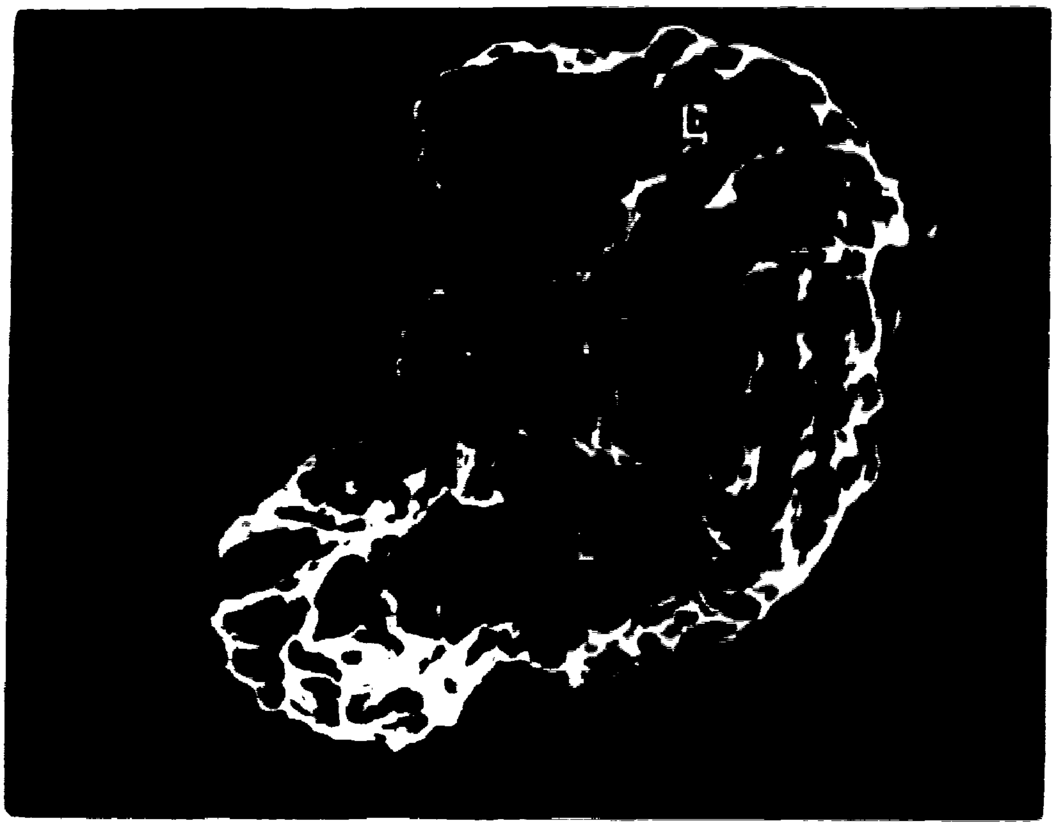


Plate 38. Scanning electron microscope photograph of Blue Ridge Member silt grain. a) subrounded quartz grain, b) heavily etched and rounded quartz overgrowth

Plate 30. Scanning electron microscope photograph of Blue Ridge Member silt grain. Quartz grain has heavily etched quartz overgrowth. a) negative crystals (molds) of dolomite crystals in quartz overgrowth

Upper Grammia is equivalent to the Sassenach Formation and conformably overlies the Blue Ridge Basinal Member

2.5.1 Sedimentology and Palaeontology

On the Southesk-Cairn platform the Upper Grammia Member consists of rhythmically bedded calcareous siltstones and bioturbated calcareous siltstones. In the Jasper Basin (off-bank) the ratio of bedded siltstones to burrowed siltstones decreases basinward.

Thin section identification and point count analysis yielded high percentages of quartz (50-60%) consisting of well rounded to angular grains with abraded and euhedral overgrowths (Plates 40,41,42, and 43). Scanning electron microscopy of the siliciclastic portion of the Upper Grammia sediment also reveals relatively high percentages (5-10%) of feldspar grains with overgrowths (Plates 44, 45, and 46). The remainder of the sediment is predominantly clays (5-10%- products of the weathering of feldspars) (Plate 47), micrite and dolomicrite (10-20% - interstitial to grains), and calcite and dolomite cement (5-10%) (Plate 45). Opaque minerals and associated iron oxide staining are also identifiable in small percentages (<5%).

Hummocky cross-stratification is the predominant bedform in the Upper Grammia Member (Plates 48, 49, 50A). Parallel lamination is also present, but is only observable in hand sample (Plate 51B). These samples represent only a fraction of the hummocky bedded unit. Intensely burrowed siltstones are interbedded with the hummocky bedded strata (Plates 50B and 51A). Preferential weathering of these beds clearly illustrates highly burrowed strata similar to those described in the Lower Grammia Member. The scale of the highly burrowed beds is variable and may range from only a few centimetres to several meters in thickness (Plate 50B and 51A). Individual storm events are represented by a lower laminated/hummocky cross-stratified unit with a scoured base gradually giving way to

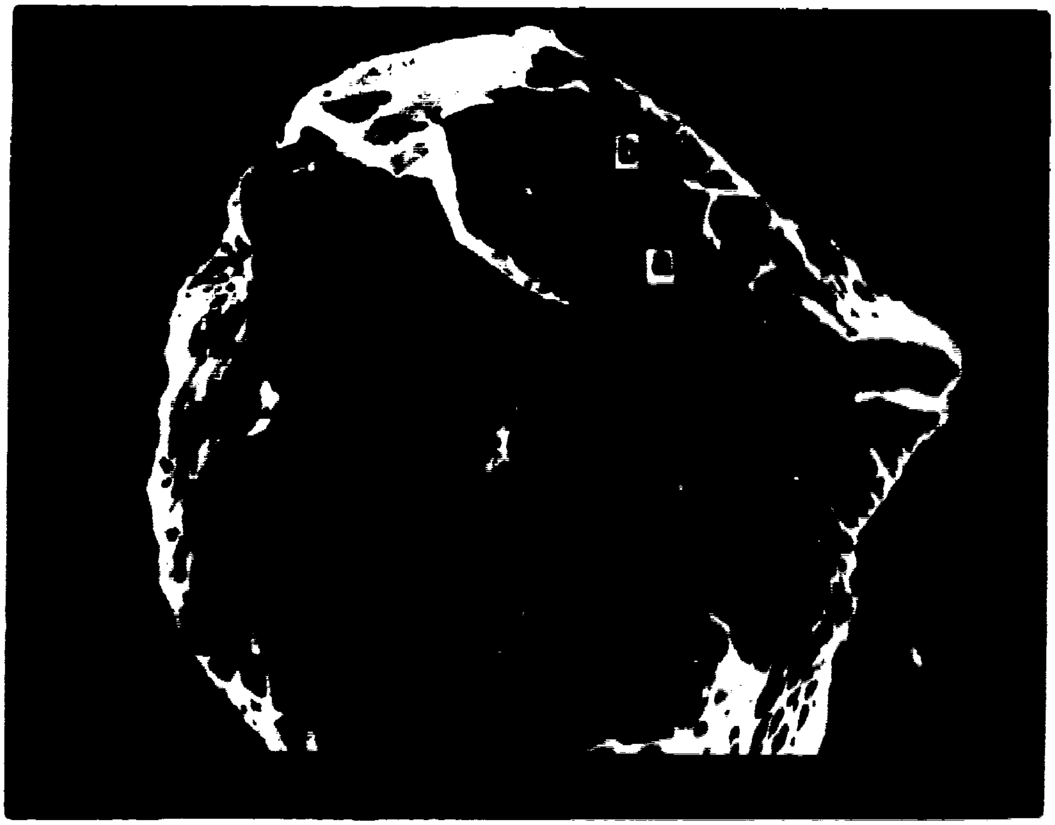


Plate 40. Scanning electron microscope photograph of an Upper Graminia Member silt grain. Section NCP-1. Well rounded quartz grain and overgrowth a) hexagonal cast in quartz overgrowth preventing complete overgrowth of quartz grain. b)dolomite rhomb cast within larger hexagonal cast

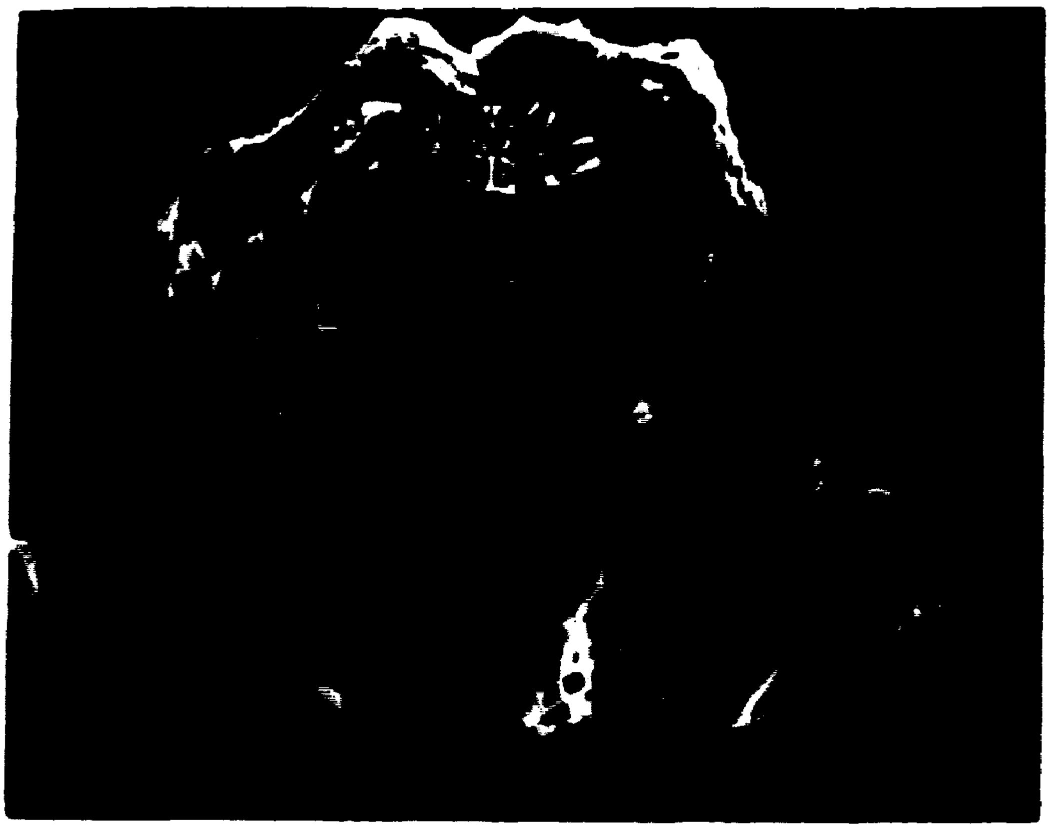
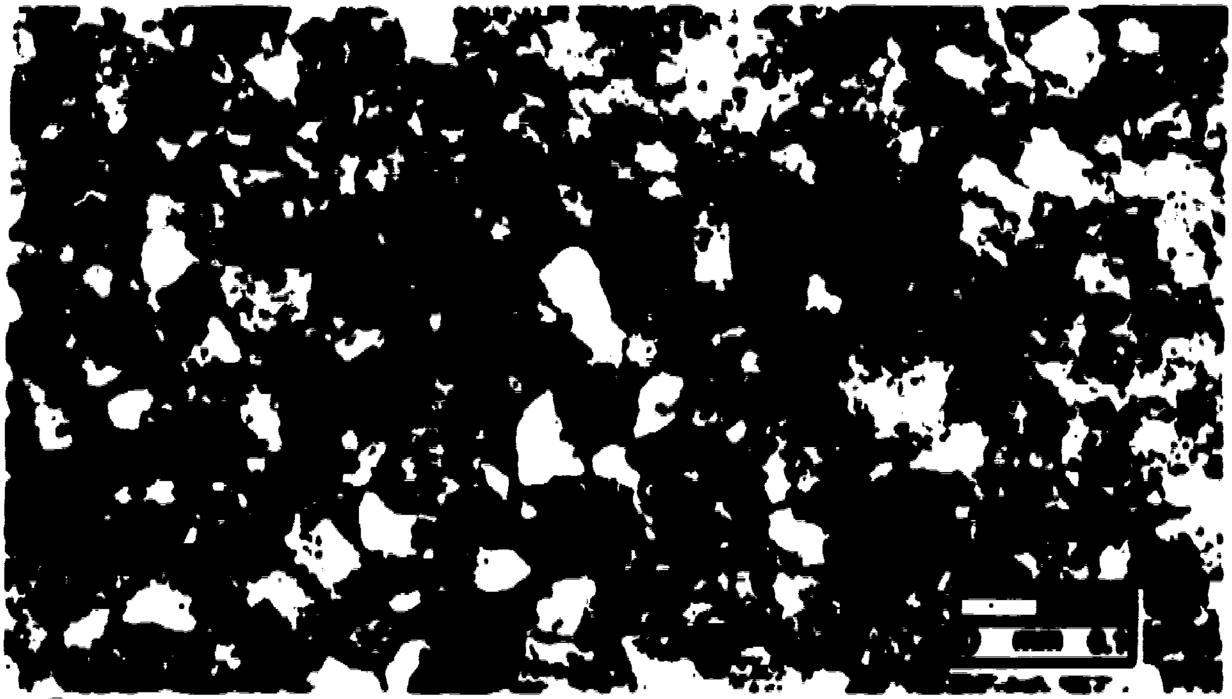
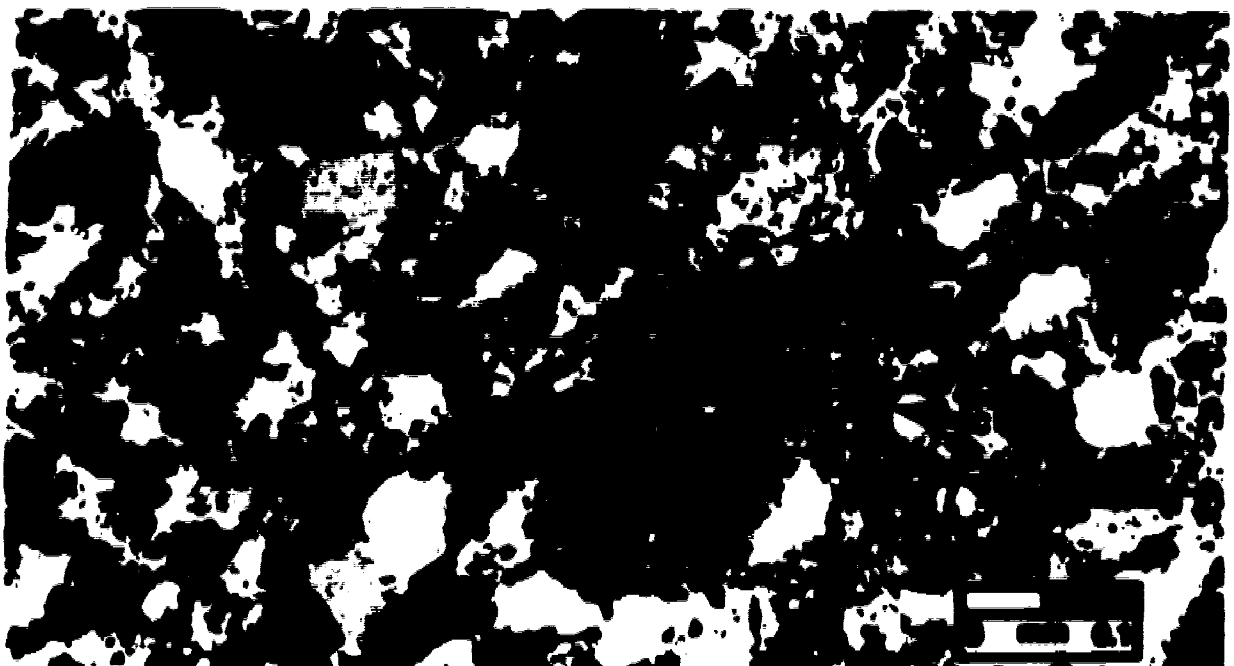


Plate 41. Scanning electron microscope photograph of an angular quartz grain with quartz overgrowth and associated clay. Upper Graminia Member section MM-2. a) pitting of surface of quartz grains.

Plate 42. Scanning electron microscope photograph of an Upper Gramina Member silt grain. Section MM-2. Angular to subangular quartz grain with quartz overgrowth. a) heavy etching pattern, b) dolomite rhomb casts in quartz overgrowth



A



B

Plate 43. A) Photomicrograph of Upper Graminia Member calcareous silt. Section NCP-1. Note angularity of quartz grains and interstitial carbonate mud. B) Photomicrograph of Upper Graminia calcareous silt. Section MM-1. a) rounded quartz overgrowth on rounded quartz grain, b) angular quartz with no overgrowths, c) interstitial carbonate mud.

Plate 44. Scanning electron microscope photograph of subangular to subrounded feldspar grain with detached feldspar overgrowth. Upper Gramma Member silt grain. Section MM-2.

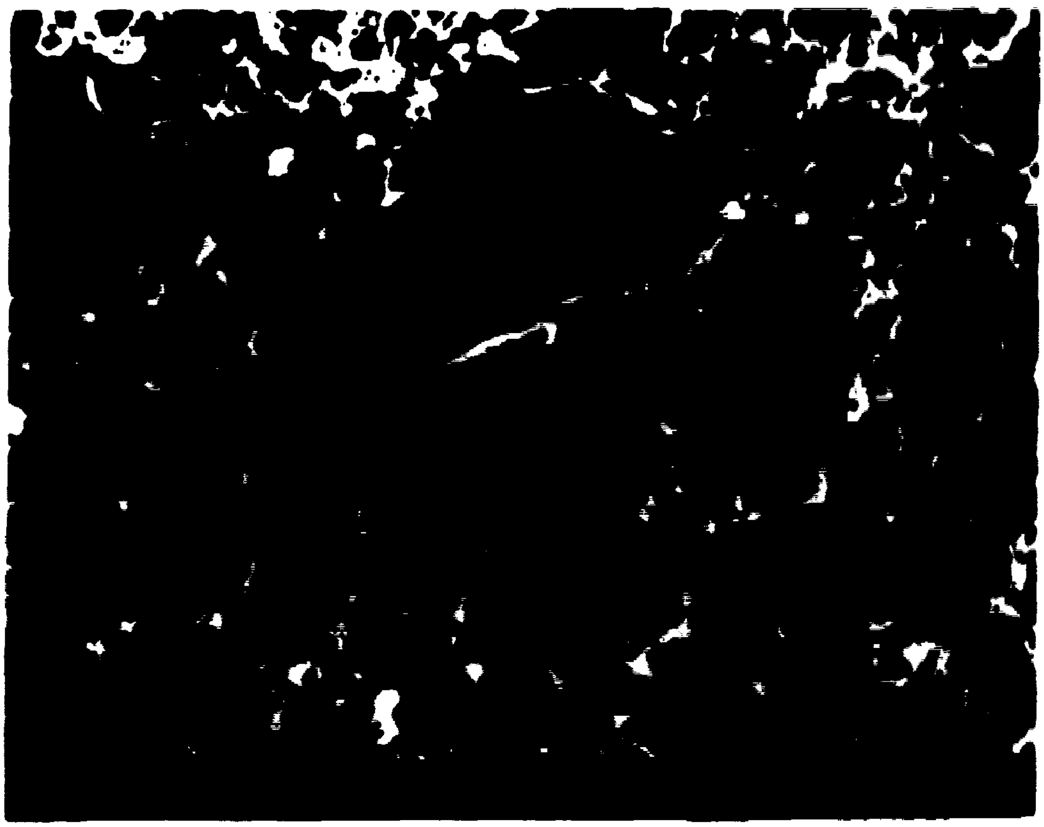


Plate 46. Scanning electron microscope photograph of a subrounded potassium feldspar grain completely encased in calcite cement. Upper Graminia Member section MM-2

Plate 46. Scanning electron microscope photograph of an Upper Graminia Member silt grain. Section MM-2. Heavily etched quartz and feldspar grains with quartz overgrowth. a) quartz grain, b) feldspar grain.

Plate 47. Scanning electron microscope photograph of an Upper Graminia Member silt grain Section MM-2. Quartz grain with associated clay material and calcite. a) clay material, b) quartz grain

an overlying bioturbated bed

The occurrence of the highly burrowed strata is most prominent in the Upper Grammia Member at both the South Cardinal Pass and North Cardinal Pass sections Basinward from these sections towards the Cardinal Headwaters section the bedded units disappear Only extreme low frequency storm events affected the sediments in this area This ultimately decreases the ratio of bedded to burrowed bed thicknesses to zero Continuous burrowing at or below storm wave base in the area of Cardinal River Headwaters results in the development of a completely churned sediment (Plate 50B)

Dessication or mud cracks are also distinguishable at Mount Mackenzie Section 2 (Plate 52A B) These are attributed to periodically developed exposure surfaces and represent non-deposition following storm cessation Decreasing energy levels on the bank following a storm event allows deposition of the suspended sediment load Restricted waters will ultimately evaporate and dessicate the upper few centimetres of mud Deposition on the shelf during a subsequent storm event will infill the mud cracks and preserve the dessication structures (Plate 53B)

Skeletal material occurs throughout the entire Lower Grammia section, but the abundance and diversity of fossils is generally low Brachiopod fragments, crinoid ossicles and coral fragments are the only visible allochems in the basinal sections at Cardinal River Headwaters and North Cardinal Pass Section 2

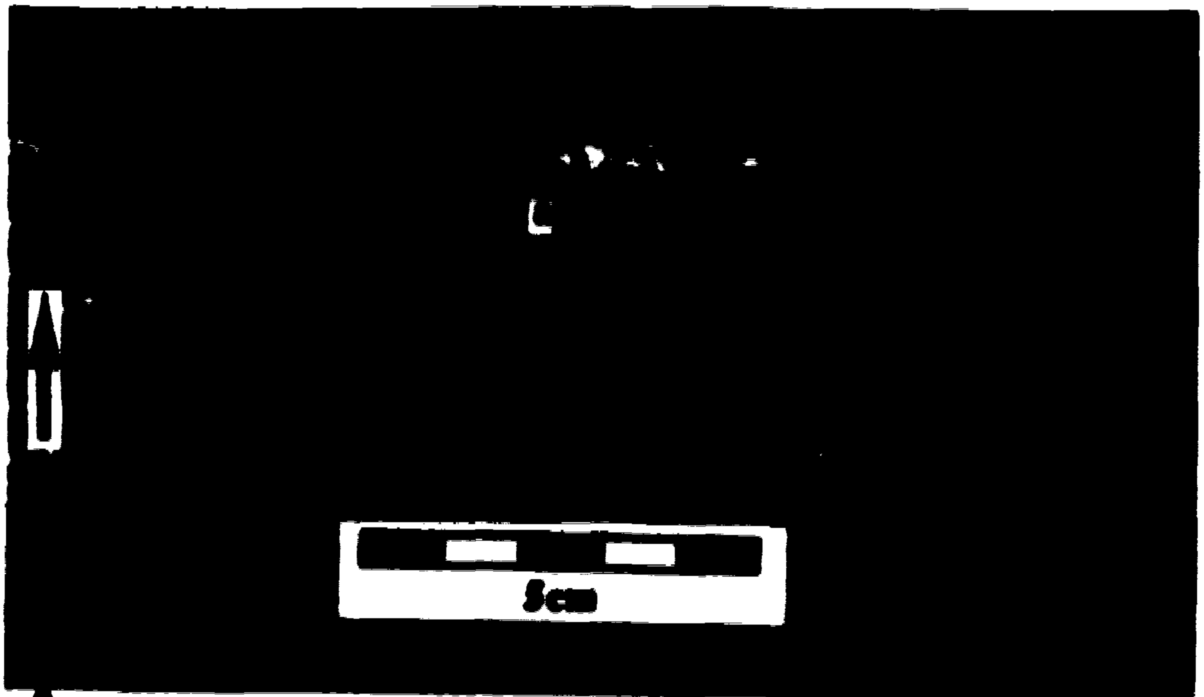
Ichnofossils are relatively abundant throughout the entire Upper Grammia interval. Trace fossils identified in the areas proximal to the platform edge are most abundant in the highly burrowed interbeds of the storm beds The highest burrow frequency within the Upper Grammia Member is within the thin siltstones deposited on the platform at Mount Mackenzie Section 2

Plate 46. A) Upper Grammia hummocky cross stratified siltstone. Section CH-2. a)truncation surface, b)overlying hummocky bedding.
B) Parallel laminated to hummocky bedded Upper Grammia Member calcareous siltstone. Section MM-2.

A

B

Plate 49. A) Thinly bedded Upper Gramina Member siltstones. Section NCP-1. Undulating surfaces indicate hummocky bedding.
B) Hummocky cross-stratification within Upper Gramina Member silts. Mount Mackenzie section MM-2.



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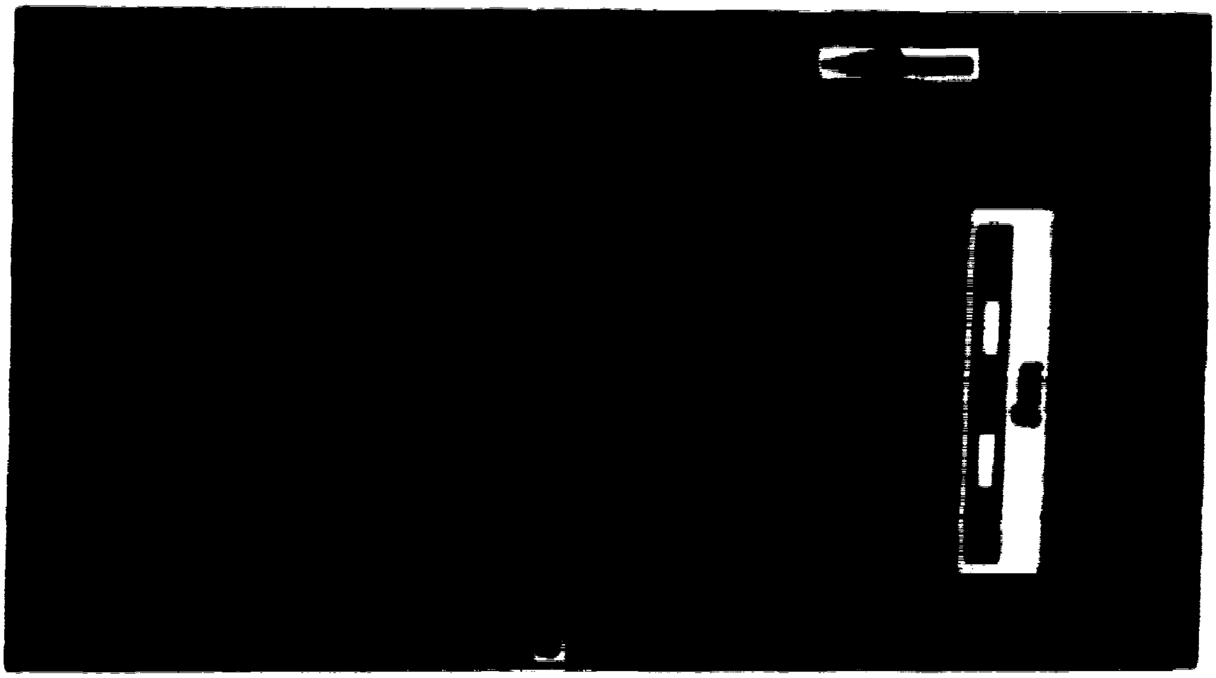


B

Plate 60. A)Parallel laminated Upper Graminia Member siltstone. Section MM-2.
a) low angle cross stratification overlying flat to undulating (hummocky) bedding. No visible trace fossils.
B) Thinly laminated Upper Graminia Member calcareous siltstones overlying churned silt beds. Section MM-2. a) scour surface.
b) *Planolites*.

A

B

Plate 51. A) Upper Grammia siltstone. Section MM-2. a) *Dactyloidites*. b) *Chondrites*

B) Thinly bedded Upper Grammia Member calcareous siltstone. Section MM-2.

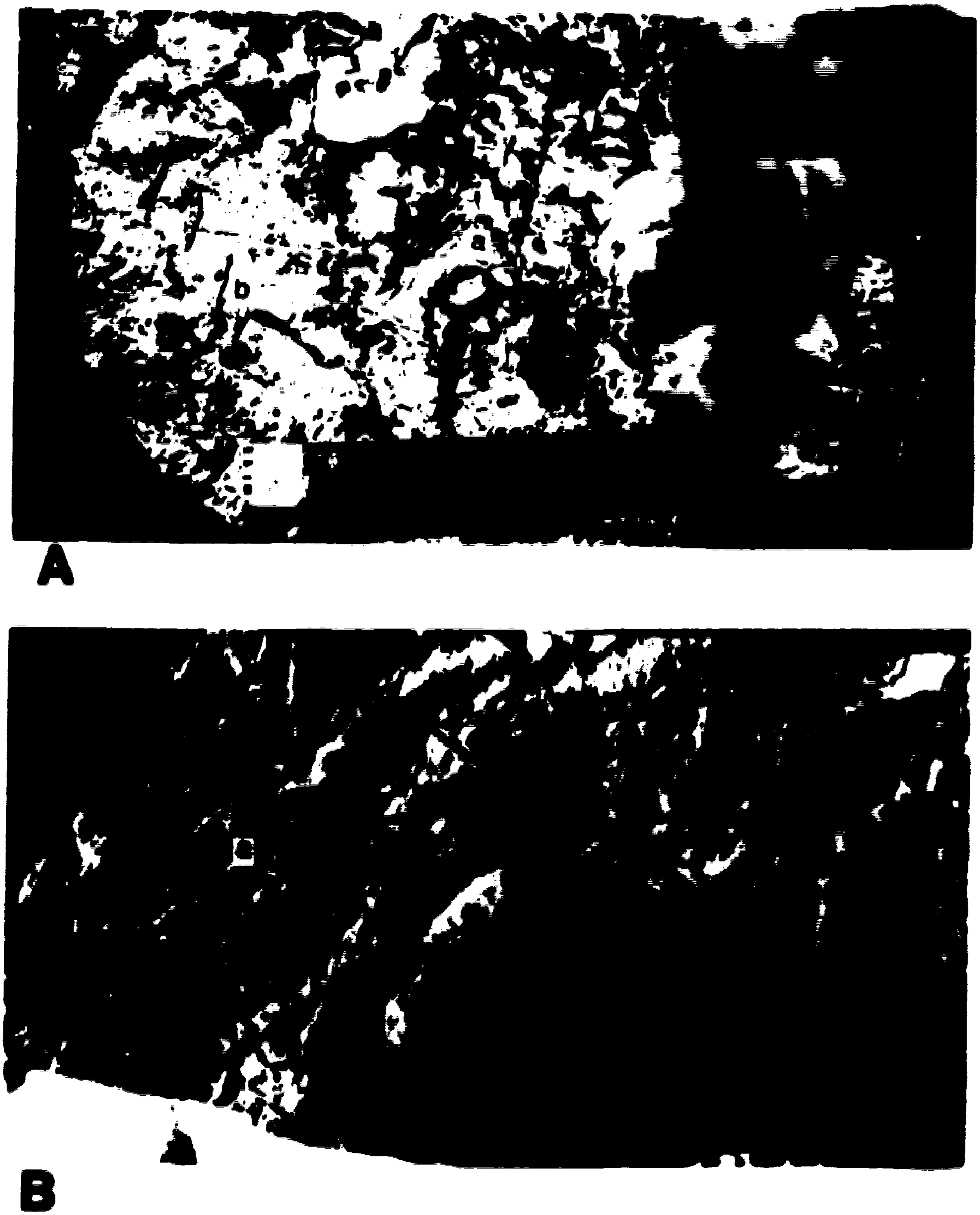


Plate 52. A) Bedding plane of Upper Graminia Member silty carbonate mud. Section MM-2. a) solitary coral. b) molds of mud cracks shown by tapering, discontinuous sand bodies.
B) Bedding plane of Upper Graminia Member silty carbonate mud. Section MM-2. a) molds of mud cracks.

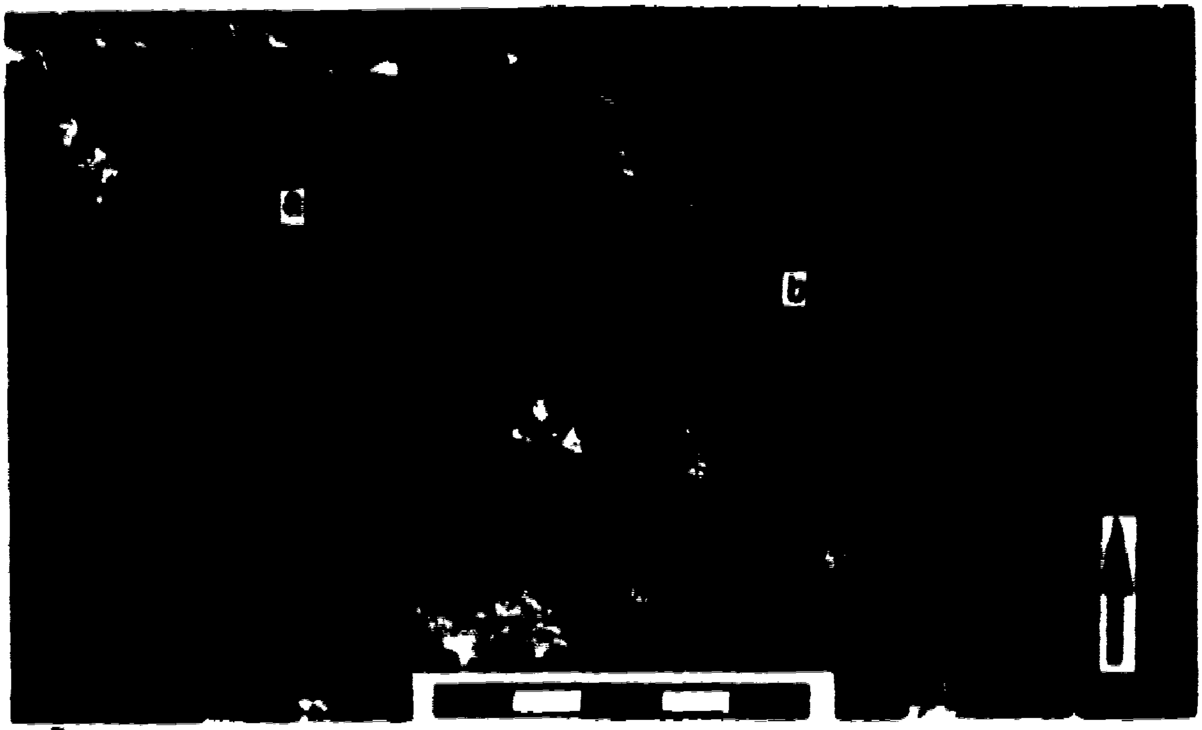
Ichnofossils identified within the Upper Graminia Member include *Skolithos*, *Dactyloidites* escape traces *Thalassinoides*, *Palaeophycus*, *Teichichnus*, *Arenicolites*, *Lockeia*, *Cruziana*, *Chondrites*, *Planolites*, *Palaeophycus*, rare *Polykladichnus*, as well as completely churned beds attributed to intense and relatively continuous biological activity. All forms are generally small with the exception of *Thalassinoides*.

2.5.2 Upper Graminia Member Discussion

The Upper Graminia Member is similar to the Lower Graminia Member in that both were deposited in a shallow marine environment. Infilling of the off-bank regions and smothering of carbonate deposition by siliciclastic input in the Upper Graminia is indicated by the presence of storm dominated (hummocky bedded) silts and sands on the Southesk-Cairn-Blue Ridge platform. Intense biological activity has destroyed most of the primary structures in this unit. Basinal deposition was above storm weather wave base and below fair weather wave base as is indicated by hummocky bedding and lack of fair weather bedforms.

The Upper Graminia Member is slightly different from the Lower Graminia Member in terms of dominant lithologies. In the Upper Graminia Member siliciclastic deposition predominates. Carbonate mudstones and wackestones were deposited intermittently and the entire sediment column was subsequently reworked by storm events and biological activity.

Key variations between the Upper Graminia Member sediments and the Lower Graminia Member are the decreased quantities of heavy mineral grains and the increased quantity of feldspar grains in the Upper Graminia Member. The prevalence of angular feldspars in these sediments suggests relatively minimal transport before redeposition.



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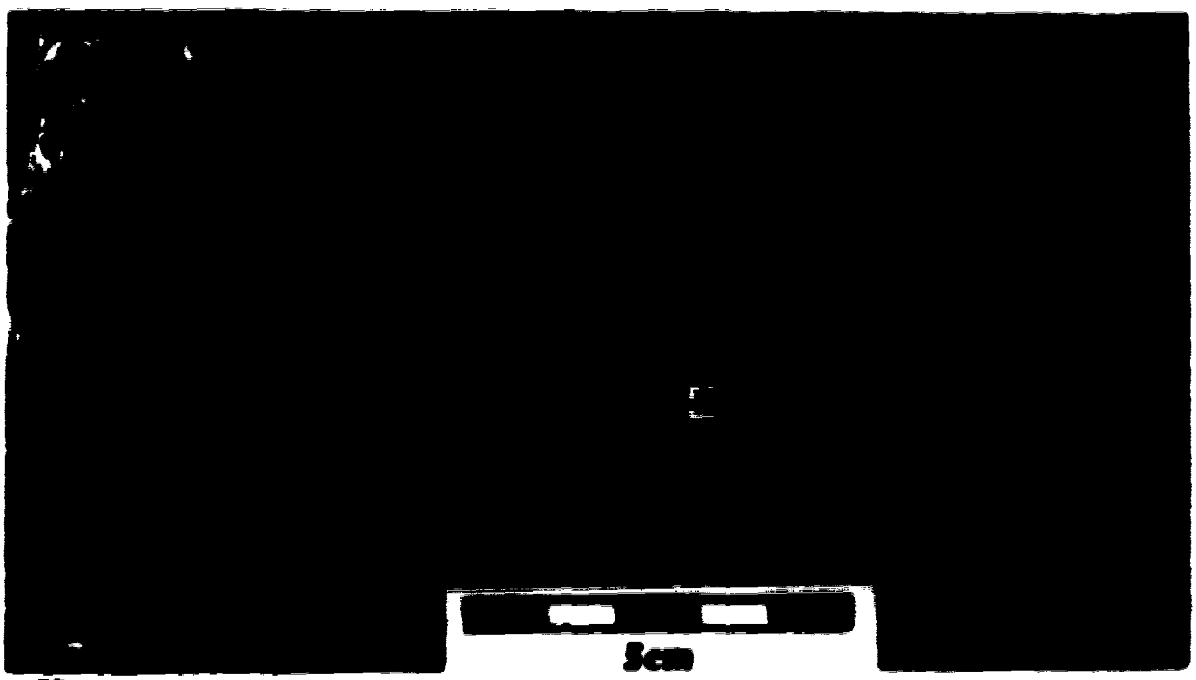


B

Plate 53. A) Massive carbonate mudstone overlain by thinly bedded siltstones. Upper Graminia Member section MM-2. a) scour surface, b) wedge of churned sediment within massive muds.
B) Bedding plane view of sample A). a) mud cracks.

2.6 Graminia Formation Discussion

The Graminia Formation of the study area is differentiated into three constituent members. Platform members include Calmar Formation/Lower Graminia Member, Blue Ridge Member, and Upper Graminia Member/Sassenach Formation. Basinal members include Lower Graminia/"Silt Doublet", Blue Ridge Basinal Member, and Upper Graminia Member/Sassenach Formation.

The overall depositional environment for the Graminia Formation was a carbonate and siliciclastic dominated mixed system and is summarised in Figure 8. Individual formation members reflect slightly varying dominance of the two principal lithologies. The Calmar Formation/Lower Graminia Member was dominated by clastic input into a carbonate dominated basin (Jasper Basin). Calmar Formation beds represent shallow marine deposition in a shallow marine environment periodically influenced by storm activity. Exposure of the underlying Arcs/Grotto prevented deposition at the platform margin during Lower Graminia Member time.

The Blue Ridge and Blue Ridge Basinal Members are dominated by carbonate deposition. The Blue Ridge Basinal Member is equivalent to the upper Mount Hawk Member of the Mount Hawk Formation. Periodic influxes of siliciclastic sediment during Blue Ridge Member deposition are evident on the platform in the form of hummocky cross-stratified siltstones, and on the platform margin by a series of interbedded silts and carbonates. The influx of clastic material into the basin at Blue Ridge time only interrupted carbonate production but did not completely drown carbonate deposition.

The Frasnian-Famennian boundary is present at the top of the Blue Ridge Member of the Graminia Formation (Johnston and Meijer Drees, 1993; Shields and Geldsetzer, 1992; and Weissenberger, 1988). A thin (<1 m) oncolite horizon at the top of the Blue Ridge Basinal Member in the area of North Cardinal Pass is the only "macro-evidence"

DEPOSITIONAL STAGES - Graminia Formation

Toma Creek to Cardinal River Headwaters,
Mountain Park, Alberta.

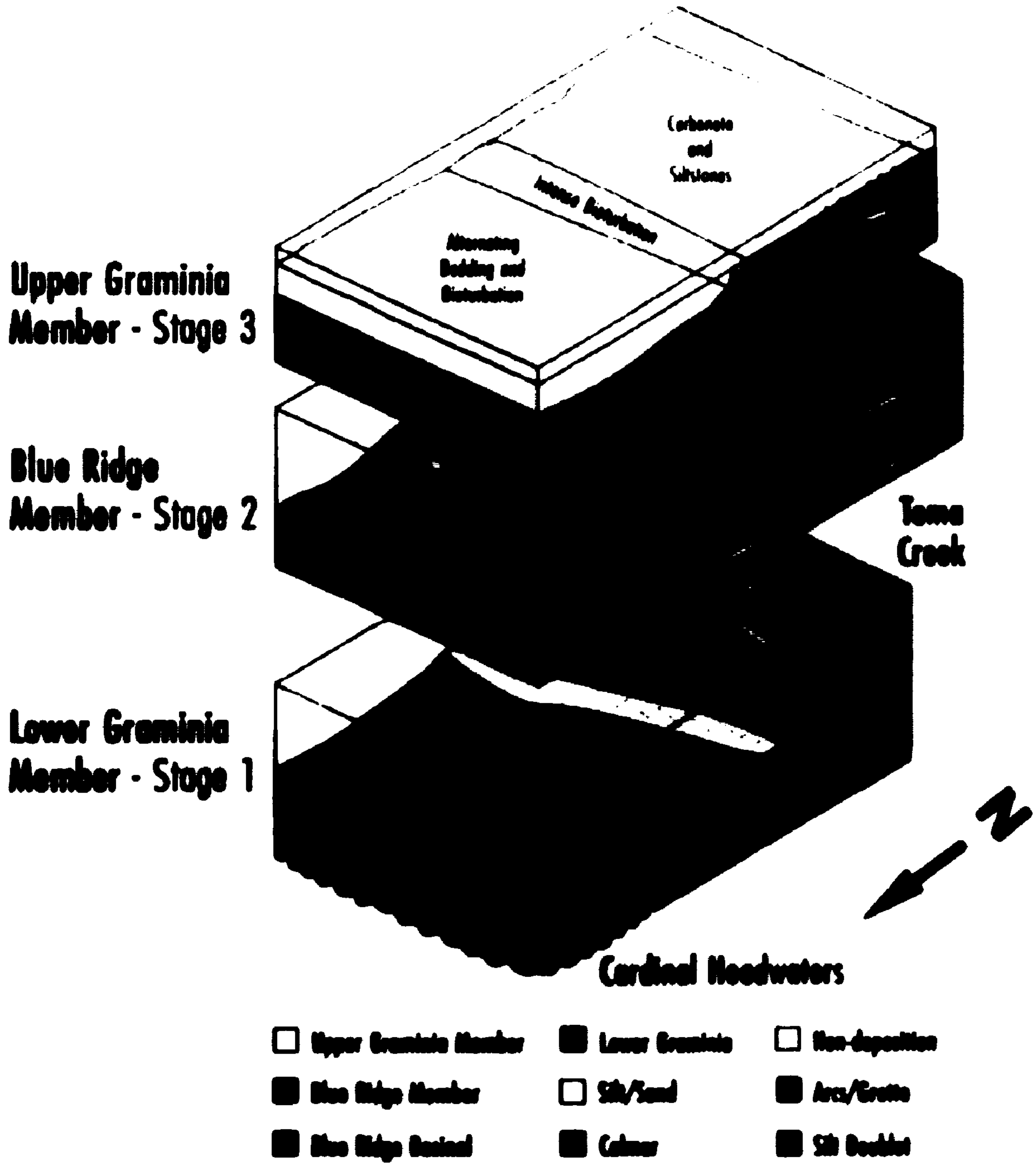


Figure 8. Schematic block diagram of Graminia Formation depositional stages Stage 1 - Lower Graminia Member/Calmar Formation, Stage 2 - Blue Ridge Member, Stage 3 - Upper Graminia Member

available to suggest the presence of this boundary

Upper Grammia deposition smothers the Blue Ridge bank and represents a return to a siliciclastic, storm dominated system. Cyclical hummocky cross-stratified and bioturbated siltstones are the characteristic sedimentary succession in the area of the platform margin. Deposition on the drowned platform is characterised by parallel laminated to hummocky bedded storm deposits and interbedded bioturbated beds. Basinal Upper Grammia Member siltstones are predominantly bioturbated with no remnant primary structures

Although the provenance for the Grammia Formation siliciclastics remains problematic, the siliciclastic sediments were not transported a great distance before being redeposited in the study area. Source beds must have been quartz and feldspar rich with appreciable amounts of heavy minerals. Clay material and authigenic substances (anatase, jarosite, and goethite) are the products of the weathering of the principal source constituents. Sediment provenance was likely to be in the areas of the Peace River Arch, Canadian Shield, West Alberta Ridge, or from an as yet unidentified western source

3.0 PROCESSES AND STRUCTURES OF STORM DEPOSITS

3.1 Introduction

The shelf and shallow marine setting is a complex depositional environment with many sub-environments, each with a vast number of internal processes. Recent studies of these environments have shown a general lack of the seaward gradation of grain size traditionally held to be characteristic of a shelfal environment. Studies completed in the past fifteen years have continued to illustrate the complexity of both bedform geometry and sediment type and have given insight into the processes acting on the shelf at any one time. (Pemberton *et al.*, 1992, Duke *et al.*, 1991, Haines,1988, Duke 1985a,b,c, Kreisa, 1981, etc.)

Four main current types are believed to be operating on the shelf: 1) intruding ocean currents, 2) tidal currents, 3) storm (meteorological) currents and 4) density currents (Swift *et al.* 1971). In general, shelves and shallow marine settings are subdivided into intruding ocean current-dominated (5% of modern shelf environments, *e.g.* Southwest African Shelf,), tide-dominated (15% of present day shelves, *e.g.* North Sea), and storm dominated (80% of modern shelves, *e.g.* North American Atlantic Shelf) (Swift and Niedoroda, 1985). Density currents, if actually present on shelves, are believed to be storm-induced (Walker, 1984) and constitute part of the storm-dominated setting. As in the case of most sedimentary systems, most shelves typically possess characteristics of several environments.

Cyclical, catastrophic events such as storms have similar characteristics (Barron, 1989; Leckie and Krystinik,1989). The criteria used in the identification of tempestite deposits usually include bedform morphology, physical and biogenic sedimentary structures and sediment texture (Pemberton *et al.*, 1992). Mineralogical characteristics appear to have little affect on the formation of storm deposits as illustrated by Galli (1989), Haines (1988) Jacobs (1986), Grossnickle (1985), and Goldhammer (1984)

3.2 Hydrodynamic Processes

Walker (1984) stresses that there is a significant difference between the oceanographer's viewpoint of the processes operating on the shelf and those employed by the geologist in accounting for the preservation of sediments Walker attributes this difference to the oceanographer being concerned with those processes that operate more or less continuously while the geologist takes the longer view ("thousand year event") Swift and Niedoroda (1985) *disagree and suggest that there is no real difference* between the dynamic processes of the modern storm-dominated shelf and those responsible for the deposits of ancient storm-dominated shelves. Duke (1985b) suggests that the only storms that significantly affect the shelf bed are hurricanes and severe winter storms In general, three main hydrodynamic processes appear to operate on these storm-dominated shelves 1) wind-forced currents, 2) relaxation (storm-surge ebb) currents and 3) turbidity currents (Walker, 1984)

Wind-forced currents are generated as the wind blows across the water surface, gradually disturbing deeper and deeper ocean layers until the water column is able to move sediment on the seabed. Measurements of flow velocities in the Gulf of Mexico taken by Morton (1981) show that 50 km offshore, in 21 m of water, currents up to 2m/s along shore and 0 5-0 75m/s offshore are generated by wind-forced processes associated with intense storm activity In fine to very fine sand these flow velocities are capable of producing ripples, megaripples and upper plane bed bedforms.

The preservation potential of these bedforms is situation specific and depends on 1) the rate of biogenic reworking, 2) the frequency of the episodic depositional event, 3) the magnitude of the depositional event, and 4) the nature of the infaunal, burrowing organisms (Pemberton *et al.*, 1992, Wheatcroft 1990)

Relaxation (storm-surge ebb) currents are believed to be generated by storm surges which are unusually high due to landward-directed storm winds piling water onshore. As coastal water levels rise, there is a bottom return flow which moves seaward or can be deflected along shore. This current type has been employed as a mechanism for considerable sediment transport (Dott, 1988, Hayes 1967) and has also been shown to be responsible for rip channel deposits (Seilacher, 1982). These channel deposits are often associated with storm sheet sands.

Morton (1981) determined that the graded beds resulting from hurricane Carla were not the result of storm surge ebb (Hayes, 1967), but rather from wind-driven flow parallel to the shoreline, suggesting that relaxation currents are minor components in sediment transport. Walker (1984) suggests that in major wave setups, such as those produced by hurricanes, flows are capable of offshore transport of sand which is introduced directly in quiet water conditions.

Walker (1984) suggests that storm-generated turbidity currents, driven downslope by gravity is a common process operating on the shelf. Despite the low gradient of the shelf, Walker (1984) postulates that turbidity currents can be generated and flow downslope citing the flow of material on the abyssal plain (extremely low gradient) as evidence for this suggestion. Walker (1984) proposes that high velocity turbidity currents are driven by a feedback process called autosuspension. However, this process requires the achievement of a critical velocity to reach "ignition". Once ignition has been reached, a flow can travel great distances, entraining sediment within itself. Since the slopes on the shelf are small, Swift and Niedoroda (1985) argue that ignition cannot be achieved, and flow will not take place.

Swift and Niedoroda (1985) suggest that another density-driven sediment transport mechanism may exist. Loading sediment on the bottom boundary layer by storm waves may add an additional driving force, capable of significantly affecting the velocity of storm-generated geostrophic flows and causing them to veer offshore. This process will not achieve ignition, but will decelerate offshore, depositing sediment out of suspension. Walker (1984) makes no reference to ignition or autosuspension in his model making comparison of the two models difficult.

3.3 Facies and Bedforms

One rather confusing characteristic regarding storm-dominated shelves is that the deposits of the modern day are not well reflected in ancient examples, and conversely, the bedform most common to ancient storm-dominated shelf deposits appears to be underepresented on modern shelves. Three scales of sand bodies are presently observed on the modern shelf: 1) shoal retreat massifs, 2) linear sand ridges and 3) ripple/megaripple/ sandwave bedforms. In contrast to these features, the most characteristic features found on ancient storm dominated shelves are hummocky cross-stratified (HCS) and associated swaley cross-stratified (SCS) sandstones, which are poorly represented on modern shelves. The bedforms and bedform complexes found on modern shelves do not appear to be a common phenomenon in ancient shelves interpreted as storm dominated. Walker (1984) suggests that this difference is a result of the continuous processes and associated bedforms (which may have a low preservation potential) and the geologically significant processes and associated bedforms ("thousand year event")

Hummocky cross-stratification is a bedform which has a controversial origin. It is typically made up of fine to very fine sand, although coarse sand, gravels and even conglomerates may be hummocky cross-stratified (DeCelles, 1987). Figure 9 illustrates the features by which HCS is recognized, and is discussed by Pemberton *et al.*, 1992:

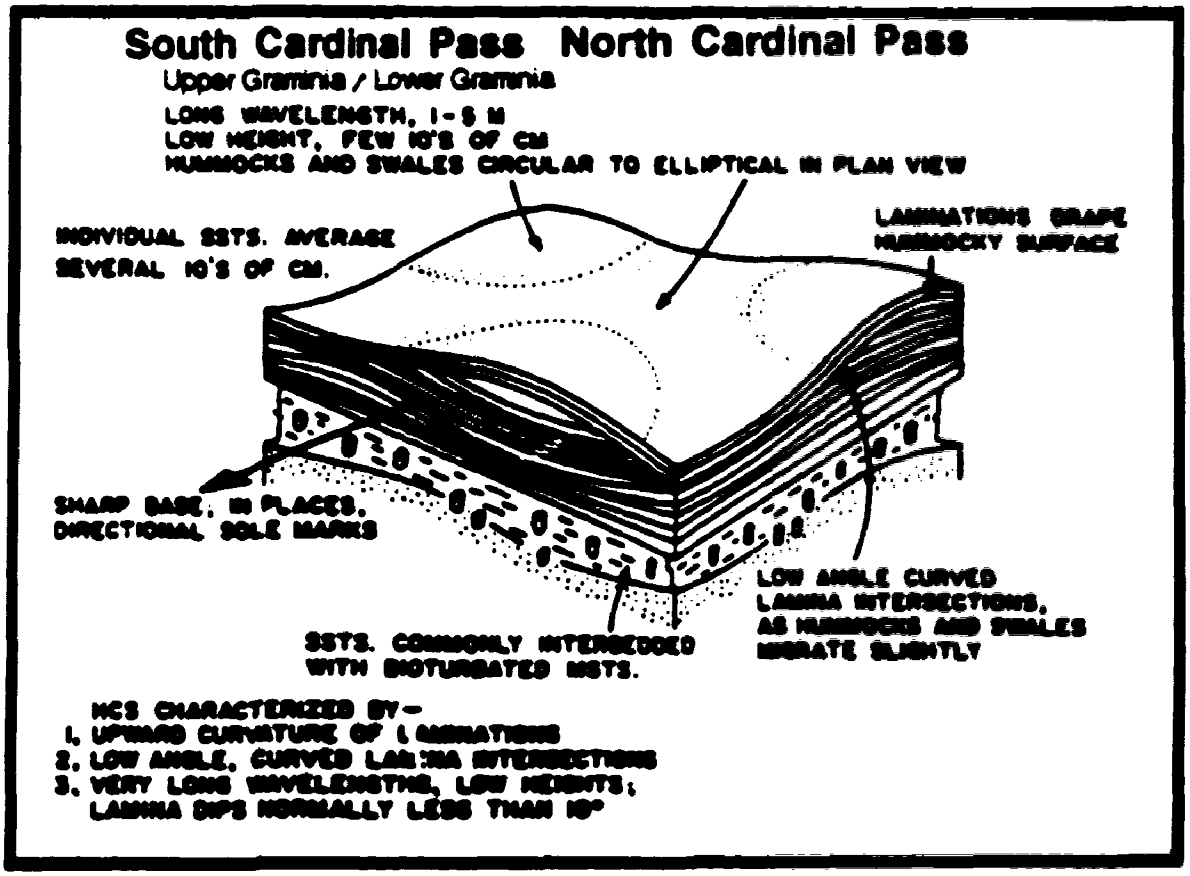


Figure 9. Schematic block diagram illustrating the structures and salient features of hummocky cross stratification and hummocky bedding. (modified after Walker, 1984)

Duke 1991, Frey, 1990, Vossler and Pemberton, 1989 1988, Dyson, 1987 Duke, 1985b,c, Swift, 1984 and Dott and Bourgeois, 1982) The origin of HCS remains uncertain, but most workers attribute it to some storm-induced process

Hummocky cross-stratified sandstones are typically sharp based and interbedded with highly burrowed marine mudstones and siltstones The upper portion of the HCS may also show evidence of burrowing. These observations indicate that HCS was developed in a quiet water environment during periodic high energy states, such as storms Dott and Bourgeois (1982) also suggest that HCS is formed by the redeposition of fine sand delivered offshore by a variety of possible processes below fair weather wave base Deposition is from suspension fallout and lateral tractive flow due to oscillatory flow at the sediment water interface Under intense oscillatory flow, falling grains encounter intense oscillatory sheet flow which drapes sand over an irregularly scoured surface and also moulds the sand into roughly circular, unoriented hummocks and swales The overall flow is thought to correspond to upper plane bed conditions of unidirectional flow defined by Dott and Bourgeois (1982)

Duke (1985b,c) suggests that the most efficient storms capable of producing HCS were hurricanes, due to the flow conditions present at the surface of the bed. Hurricanes appear to disturb the water column more effectively in terms of multidirectional flow than severe winter storms, the only other storm variant believed capable of significantly modifying the shelf bed If unidirectional flow is created at the expense of oscillatory or multidirectional flow (as in the case of severe winter storms) flow conditions at the bed will not be conducive to the formation of hummocks or swales. Thus, the inferred mechanism for the origin of HCS, according to Duke, (1985b,c) is oscillatory- or multidirectional-dominant flow

Arguments by Swift *et al.* (1983) seem to contradict the idea of a multidirectional flow origin for the formation of HCS. Swift *et al.* (1983) suggest that the presence of a significant unidirectional component associated with winter storms is required to generate HCS. Several studies have been completed on HCS (Duke *et al.*, 1991; Duke, 1990; Leckie and Krystinik, 1989; Galli, 1989; Dyson, 1987; Bose, 1987; Duke, 1985a,b; and Swift, 1984) with suggestions made for the specific flow conditions which produce it. The storm activity postulated to be responsible for the formation of HCS does not lend itself to active study and hence, the debate on the specifics of formation of HCS remains open.

Several structures are commonly associated with HCS beds and are correspondingly attributed to storm activity. Swaley cross-stratified sands (SCS) have been formally defined by Leckie and Walker (1982) and shown to form at least a genetic link with HCS sands. SCS is defined as consisting of "a series of superimposed concave-upward scours about 0.5 m to 2 m wide and a few centimetres deep" (Leckie and Walker, 1982). SCS and trough cross-bedding are similar, but differ in that SCS is generally wider and shallower and is not normally associated with angle-of-repose-cross-strata (*i.e.* 35°). Leckie and Walker (1982) also state that in prograding sequences, if SCS is present, it always overlies the HCS beds and may in fact be overlain itself by beach sediments (Wright and Walker, 1981).

The formation of SCS beds is postulated by Leckie and Walker (1982) to be the result of storm activity of decreased intensity in the region at, or slightly above, fair weather wave base. The formation of the scours of SCS may occur frequently enough (*i.e.* frequent storm activity) to rework and remove structures and sediments deposited during fair weather conditions.

Seilacher (1982) suggests that thin channel fill deposits are often associated with sheet sands of a tempestite deposit. Morphologically these channel deposits are similar to nearby tidal channels, however Reineck and Singh (1980) suggest that their size (larger than tidal channels) and the lack of longitudinal cross bedding distinguishes them from the tidal deposits. During a major storm event water is continually piled up onshore and must eventually return to its normal level. Unidirectional currents are generated as this water retreats oceanward and ultimately creates channels as the currents entrain the previously deposited sediment. Normal shelf sedimentation (including storms) will continue following the formation of the rip channels and ultimately fill the scour with sediment.

The surface of HCS bedforms is often observed to be ripple laminated. Oscillation ripple laminae are most common, however current ripples and herringbone cross-statification have also been documented and are suggested to represent a transition from storm dominated to tidally dominated environments (Leckie and Walker, 1982). Flame structures, soft sediment deformation and similar structures generally considered to represent dewatering phenomenon are also common on the surface of HCS units and are suggested to be the result of rapid sedimentation during the formation of the HCS beds.

Biogenic sedimentary structures are a commonly observed phenomenon on the surface of HCS beds. Deposition of high energy sediments (sands) on the shelf in the form of HCS beds will normally be followed by a period of transition as sedimentation on the shelf returns to quiet water deposition. It is during this period of transition that "opportunistic" organisms will inhabit and burrow the previously muddy substrate (Pemberton *et al.*, 1992; Ekdale, Bromley and Pemberton, 1984). It is these opportunistic organisms that are responsible for the destruction of a large portion of the surface structures formed on the HCS beds and which subsequently make their identification difficult. However, the increased diversity of ichnofossils at the upper contact of a storm deposit may allow the geologist to postulate the frequency at which the storm events occurred, and the relative severity of a particular storm event. Depth of burrowing as well as thickness of unburrowed strata give indications of frequency and severity of major storms which will ultimately contribute to the development of an overall depositional model for a particular shelfal environment

The mechanisms of sediment supply to the shelf remains an important consideration with regard to shelf depositional systems. Several processes have been suggested to account for the distribution of sand to the shelf. Sediment transport seaward by shelf processes (storms or tides) and stranding of sediment by transgression/shoreface retreat are the most significant mechanisms of offshore sediment supply. Offshore transport of sediment through tidal deltas or river mouths are also possible mechanisms of sediment supply to the shelf. These processes are generally regarded as minor in comparison to the previously discussed cyclical marine processes. The important consideration in terms of this discussion is that sediment is available on the shelf to be reworked into the above mentioned storm deposits.

3.4 Depositional Model

The modelling of a storm-dominated shelf is somewhat problematic. The vast majority of the depositional features observed on modern shelves are rarely seen in ancient storm-dominated deposits. Conversely, those storm deposits most abundant in the ancient record are not well understood nor adequately documented from modern shelf settings.

An idealised facies association for a storm dominated shelf (modern or ancient) includes: 1) storm erosion with an undulatory basal erosion surface, with sole marks, and intraclasts of pebbles shells or mudstone, 2) main storm deposition with hummocky or swaley cross-stratification and associated horizontal or parallel lamination, 3) waning storm deposition with combined flow or wave rippled sand layers indicating a progressive return to lower flow regime oscillatory conditions, and 4) post-storm / fairweather mud deposition reflecting the final suspension fall-out of storm-derived sediment or return to normal background sedimentation (Pemberton *et al.*, 1992).

3.5 Conclusions

The shelf in a shallow marine system is a poorly understood depositional environment in terms of sedimentary processes and depositional facies. One of the major problems in developing a specific depositional model for a storm-dominated environment, is that few direct modern environmental analogs to the ancient systems exist. Processes observed on modern shelves may simply be serving as sediment distribution systems.

Bedform morphology for storm deposits has recently been accepted to include a series of gently undulating hummocks and swales (HCS and SCS). The combination of these bedforms with interbedded bioturbated mudstone and rippled bed tops has allowed the formulation of a set of general facies associations for ancient tempestite systems. However, with little or no data on modern storm deposits to be used in conjunction with ancient studies, the storm-dominated shallow marine system will remain a well studied and relatively poorly understood environment of sediment accumulation.

4.0 ICHNOLOGY

4.1 *Introduction to Ichnology*

Ichnology is the study of the preservable evidence of structures produced in rocks, sediments, and grains by the life processes of organisms. (Pemberton *et al.*, 1992, Bromley, 1990; Ekdale *et al.* 1984, Haentzschel, 1975) Trace fossil or ichnofossil, refers to the fossilised equivalents of these structures. (Pemberton *et al.*, 1992; Bromley, 1990) Traces, and resultant trace fossils include tracks, trackways, trails, burrows, borings, and miscellaneous bioerosional structures such as drill holes, bite marks, and rasping traces. Also often included as biogenic sedimentary structures, are coprolites, faecal pellets, roots and pseudofaeces (Pemberton *et al.*, 1992; Ekdale *et al.* 1984). Structures such as algal stromatolites, biogenic graded bedding, and biogenic mottling are generally not considered trace fossils, although these are still considered biogenic sedimentary structures. (Pemberton and Frey, 1982; Ekdale *et al.*, 1984) Egg shells, agglutinated foram tests, worm tubes, moulds, casts, and death marks are also not considered trace fossils since they do not reflect a behavioural function. (Pemberton *et al.*, 1992; Ekdale *et al.* 1984).

Recognition of trace fossils and the differentiation of biogenic sedimentary structures from physical sedimentary structures can be difficult. Intangibles which may ultimately affect the identification of biogenic and non-biogenic structures may include personal experience and prejudice in addition to the objective evidence established. (Ekdale *et al.*, 1984). Some of the criteria used for the recognition of biogenic structures are: 1) a resemblance to an anatomical feature of a potential trace maker; 2) uniform dimensions and/or continuity of structures; 3) uniform size in multiple structures; 4) lack of current alignment; 5) regular and complex patterns; 6) linings and distinct walls; 7) spreiten; 8) meniscate infill; 9) pellets; 10) organic residue; 11) very delicate features; 12) preservation in full relief; and 13) association with body fossils. (Ekdale *et al.*, 1984)

The application of ichnology to the study of stratigraphy is often met with serious reservations. Trace fossils are typically poor index fossils. Traces observed in ancient and modern sediments are often the result of a particular organism performing certain life activities under specific ecologic conditions. The resulting traces are then considered facies restricted. Secondly, trace fossils reflect animal behaviour, and as a result, will typically have long time ranges since basic animal behaviour patterns have changed little through time (*i.e.* feeding, resting etc.).

The importance of trace fossils to the study of sedimentology, stratigraphy, and paleontology stems from characteristics common to all trace fossils: 1) long temporal range, 2) narrow facies range, 3) no secondary displacement, 4) occurrence in otherwise unfossiliferous rocks, and 5) creation by non-preservable soft-bodied biota. These characteristics are common to all trace fossils and are useful in the reconstruction of individual palaeoecological, sedimentological, and palaeogeographical scenarios (Pemberton *et al.*, 1992; Ekdale *et al.*, 1984).

Trace fossils have several applications in the study of stratigraphy. One of the most important uses of trace fossils is in the reconstruction of palaeoenvironments as indicators of specific environmental conditions in conjunction with physical sedimentary structures. (Ekdale *et al.*, 1984). Animal behaviour is a direct response to environmental stimuli. (Gould, 1982), and the resultant traces are often indicative of a certain set of physical and ecological conditions. (Ekdale *et al.*, 1984). Traces may also be used to indirectly study the general behaviour of the trace making organisms. These methods are most useful in the study of organisms which, because of morphology or ecology, are commonly not preserved in the fossil record. (Ekdale *et al.*, 1984).

4.2 Investigative Methods

All of the Upper Devonian sections measured measured in this study yielded at least some indirect evidence of biological activity. (Appendices 1 and 2) Ichnological data were collected at each outcrop section along with sedimentary and stratigraphic data. Visible trace fossils were photographed *in situ* where possible. Samples were not collected according to any particular pattern, however, accessibility of the outcrop sections, and specimen availability were important considerations. Detailed description, identification, and photography of the collected trace fossil samples was carried out in the laboratory upon completion of the field work.

4.3 SYSTEMATIC ICHNOLOGY

Ichnotaxa are presented alphabetically by ichnogenus and ichnospecies (where applicable). Stratigraphic ranges are given and each ichnogenera is discussed with respect to morphology, the most probable trace-making organisms, preservation, ethology, and ecology. Plates 54-62 and figures 11-17 illustrate each of the trace fossils discussed. *Figure 10 is a summary of the representative trace fossil suite* of the Upper Devonian Grammnia Formation.

4.3 a) Ichnogenus *Arenicolites* Salter, 1857

Type species

Arenicola carbonaria Binney, 1852, subsequent designation by Richter, 1924

Diagnosis

Simple U-tubes without spreite, perpendicular to bedding planes. Exterior walls are generally smooth with no ornamentation. Limbs of the U-tubes may be somewhat variable in symmetry and configuration, although size is not diagnostic (Howard and Frey, 1983; Haentzschel, 1975) (Figure 11A, Plate 54)

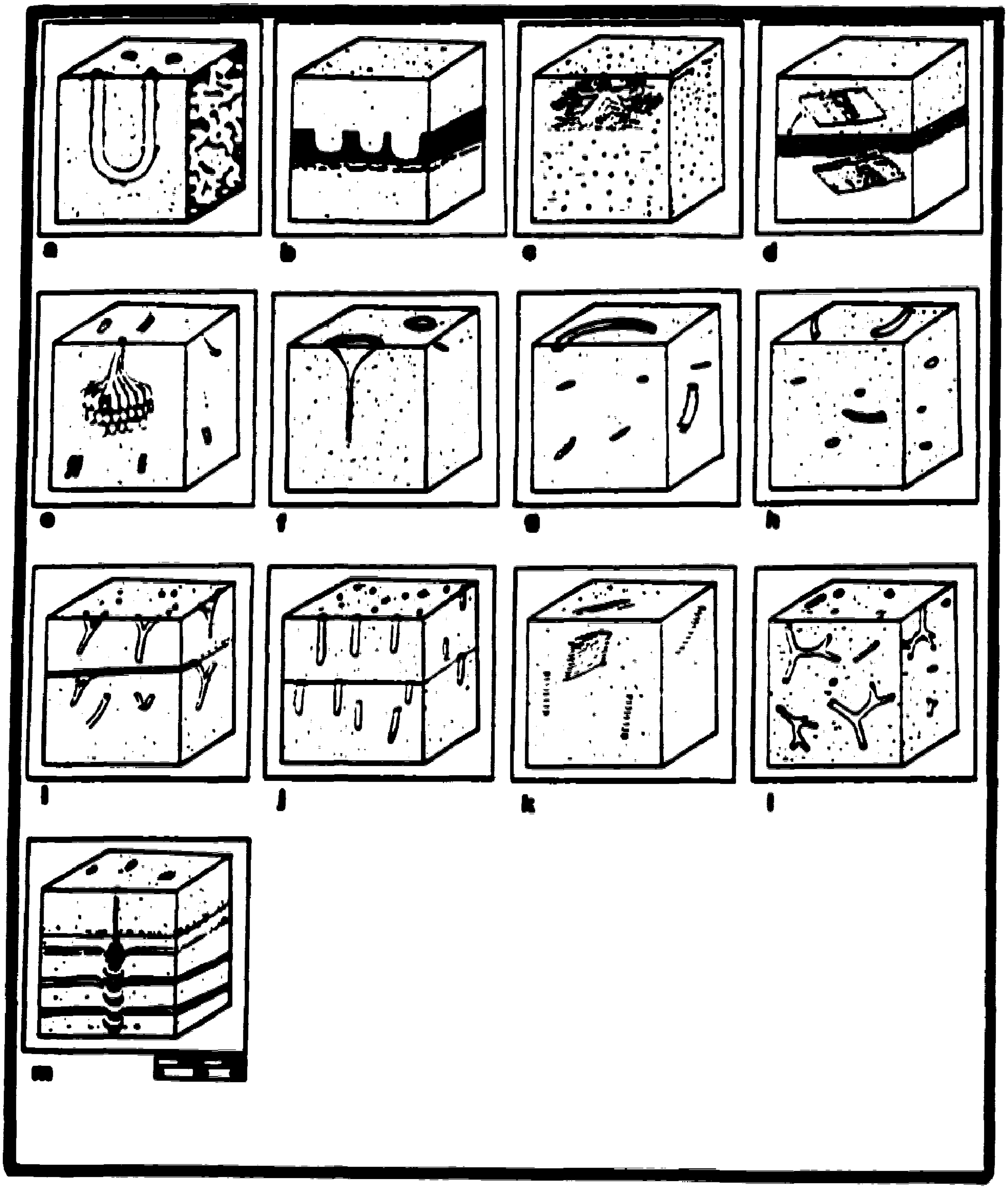


Figure 10. Representative trace fossil suite of the Upper Devonian Graminia Formation, Mountain Park, Alberta. a) *Arenicolites*, b) *Bergaueria*, c) *Chondrites*, d) *Cruziana*, e) *Dactyloidites*, f) *Monocraterion*, g) *Palaeophycus*, h) *Planolites*, i) *Polykladichnus*, j) *Skolithos*, k) *Teichichnus*, l) *Thalassinoides*, m) escape trace and *Lockeia*.

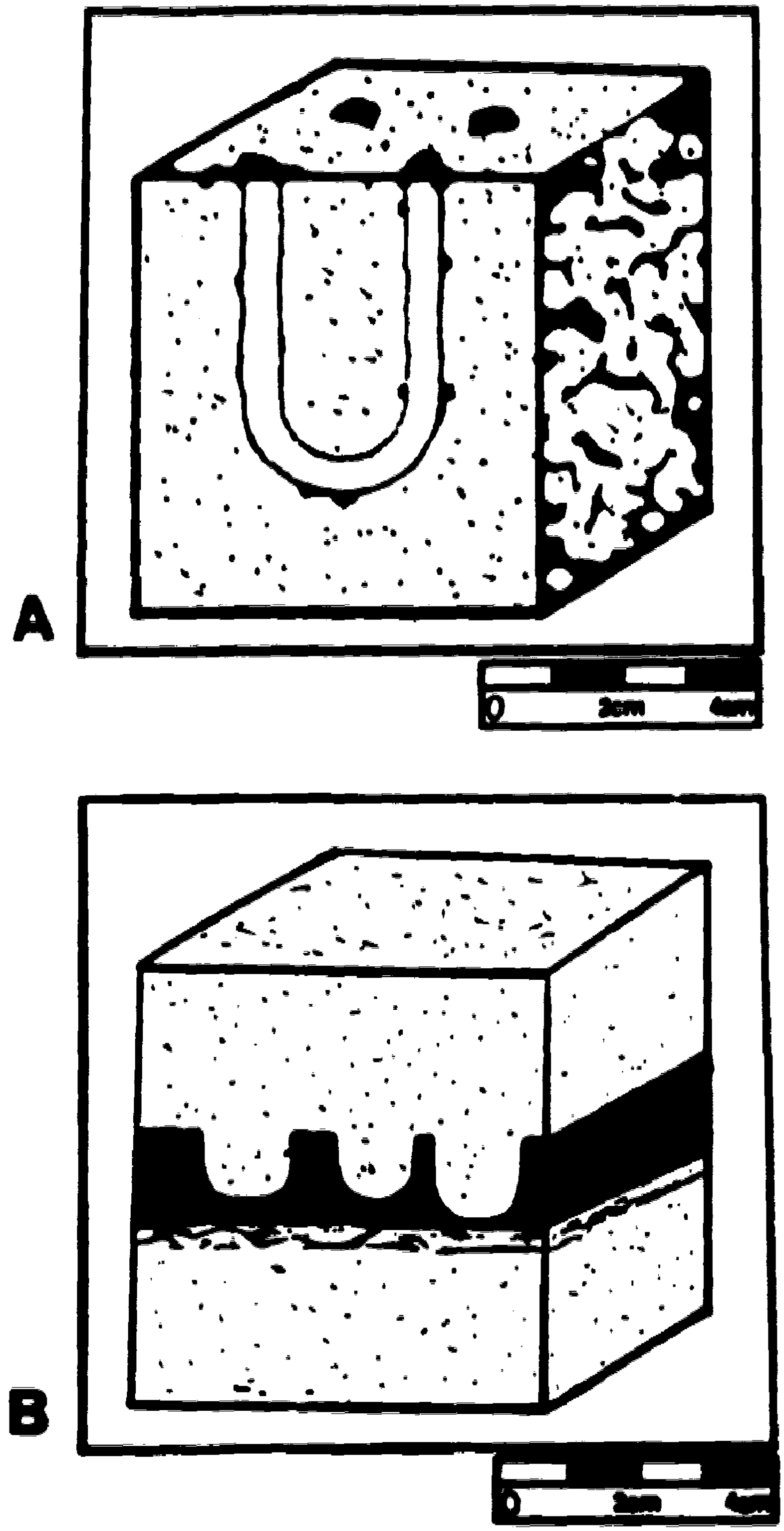


Figure 11. Schematic block diagram. A) *Arenicolites* and intensely bioturbated sediment. B) *Bergaueria* preserved as sand filled casts in a muddy substrate.

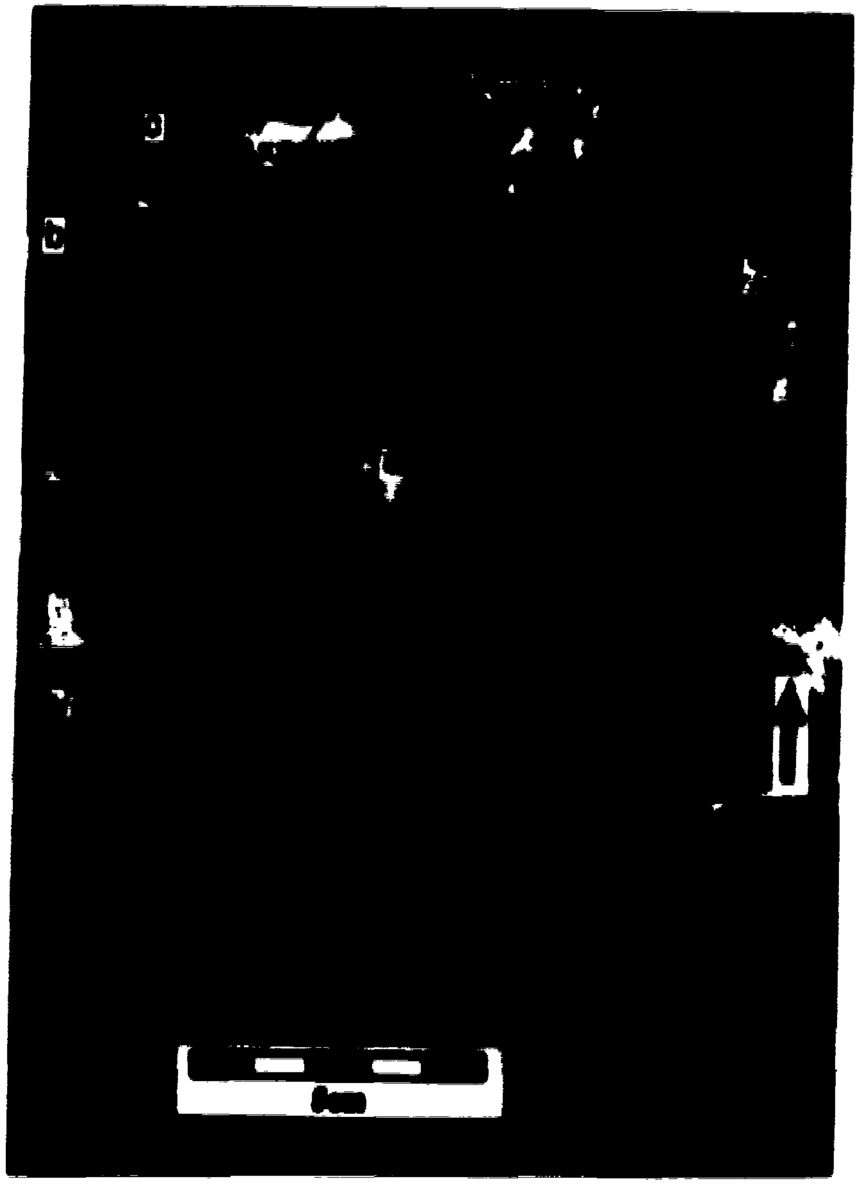


Plate 54. Finely laminated Upper Gramminia Member siltstone. Section MM-2.
Note a) scour surface. b) *Arenicolites*. c) *Skolithos*

Description

Generally small (2mm-4mm), vertical tubes often perpendicular to bedding, but may also be oblique to bedding planes. The infill is markedly different from the surrounding sediments and is most often coarser grained in nature. Bending or "j-ing" is visible at the bottom end of the tubes where the tubes have weathered up from the sample. Bedding plane expressions are in the form of weathered up circular to elliptical structures with relief of up to 5mm. Possible pairing of these structures is visible on bedding plane surfaces.

Stratigraphic Range

Arenicolites is known from sedimentary successions ranging from the Precambrian to the Recent (Chamberlain, 1977)

Discussion

Arenicolites is distinguished from other U-shaped tubes by the lack of any branching or spreiten. (Haentzschel, 1975) They are interpreted to be the infilled remains of open, U-shaped burrows that were open to the surface at both ends. (Osgood, 1970)

The lack of spreite in an *Arenicolites* burrow suggests that the trace making organism was not able to control the burrow depth or that the exact burrow depth was not important to the life activities of the organism. Burrow depth, and the presence or lack, of a burrow lining may have been dependent on substrate stability (Goodwin and Anderson, 1974). However, the anatomy of the trace making organisms and their ability to successfully utilize the surrounding water column for food gathering, are also important considerations in burrow morphology.

Several modern, surface deposit-feeding and filter feeding invertebrates utilize U-shaped burrows for dwelling and feeding. Most commonly, these include polychaetes, insects, and crustaceans (Chamberlain, 1977). Surface deposit-feeders utilizing such a burrow system require periodic, repetitious high energy, and quiet water conditions to allow influx and subsequent settling out of organic debris. Repetition of these processes will allow regular reforaging of a small area around the burrow opening. Filter-feeders utilising such a burrow system must utilize specialized body parts or a mucus trap to capture food particles suspended in the water moving through the burrow.

Arenicolites is found in sedimentary deposits attributed to: a) shallow marine environments, (Fillion and Pickerill, 1984), b) fresh water environments, (Bromley and Asgaard, 1979), c) tidal flat environments, (Crimes *et al.*, 1977), and d) deep marine environments, (Crimes *et al.*, 1977). *Arenicolites* is most commonly observed in shallow marine environments, (Fillion and Pickerill, 1984). Plate 54 illustrates *Arenicolites* burrows from the storm - dominated Upper Gramínia Member in the area of Mount Mackenzie (Section MM-2).

A recent discussion by Bromley and Asgaard (1991) introduced the *Arenicolites* ichnofacies to account for opportunistic occurrences of trace fossils in settings such as storm deposits. Pemberton *et al.* (1992) suggest that this designation is confusing and cannot be separated from the *Skolithos* ichnofacies already present. As a result, Pemberton *et al.* (1992) suggest that the present array of ichnofacies is sufficient to adequately define such occurrences.

4.3 b) Ichnogenus *Bergaueria* Prantl, 1946

Type Species

Bergaueria perata Prantl, 1945.

Diagnosis

Cylindrical to hemispherical, vertical to subvertical burrows with smooth, unornamented, rarely lined walls. Shape, in cross-section, is circular to elliptical. The base is essentially flat and may have radial ridges, a central depression, or concentric impressions. Infill is structureless. (Pemberton *et al.* 1990, Pemberton *et al.*, 1988, Haentzschel, 1975) (Figure 11B, Plate 55.B)

Description

Relatively shallow (15mm), vertical to sub vertical burrow up to 12mm in diameter. Observed in the Upper Graminia Member laminated muds and silts beneath an overlying sand. The overlying sand appears to infill the rounded to sub-rounded impression in the underlying mud. The sand is essentially structureless within the burrow.

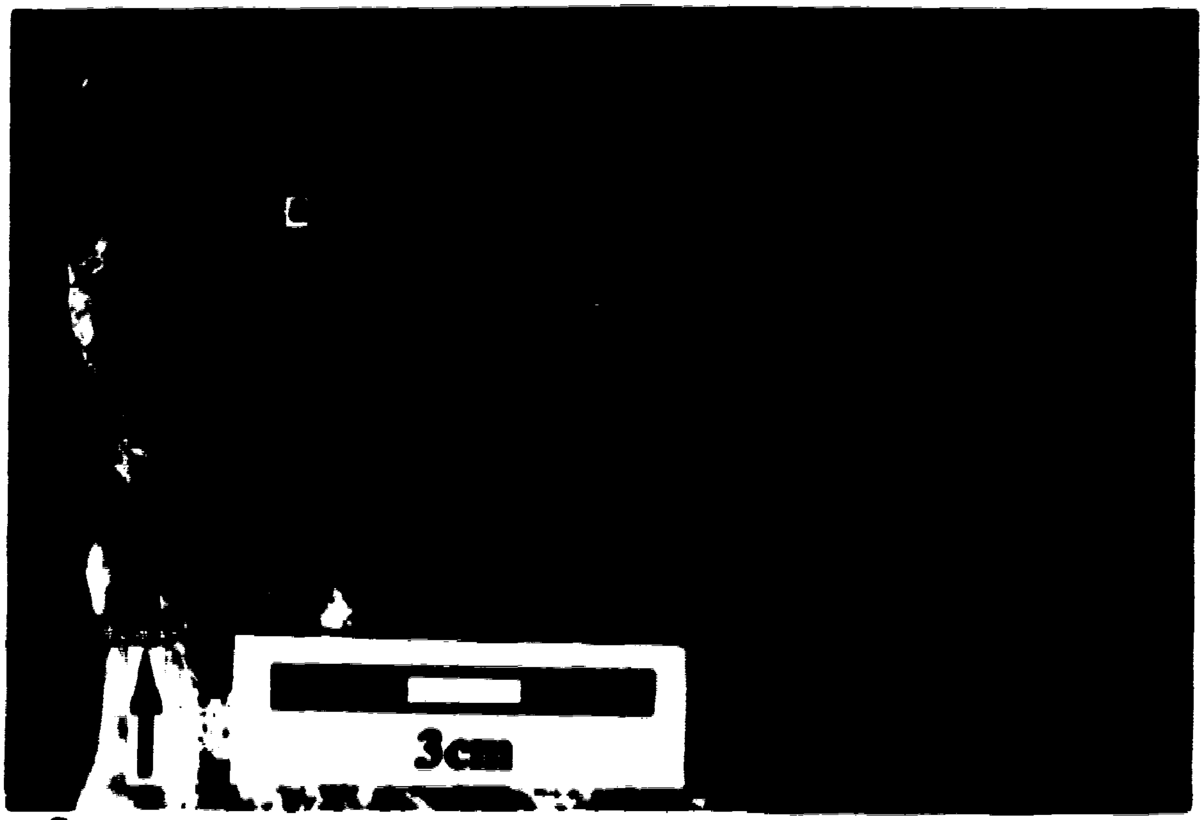
Stratigraphic Range

Bergaueria is known from sediments of the Precambrian to the Pleistocene and are most common in the lower Palaeozoic. (Pemberton *et al.* ,1990, Pemberton *et al.* ,1988)

Discussion

Bergaueria represents a cast of the permanent or semi-permanent dwelling burrow of a soft-bodied organism. (Alpert, 1973). It can occur as a single trace fossil, or in large clusters with no intersecting individuals. (Pemberton *et al.* 1990. Pemberton *et al.* 1988) *Bergaueria* is most often found at the surface between a mud and an overlying sand.

Preservation is thought to have occurred when a sudden influx of sand onto a normally quiet muddy substrate, in which the trace-maker lived, caused death and burial (Pemberton *et al.* ,1990, Alpert, 1973). Subsequent *in situ* decomposition of the organism allowed slumping of the overlying sand into the remaining depression. Slump structures in the burrow and overlying sand beds, (Alpert, 1973) support this hypothesis.



A

B

Plate [illegible]. A) Finely laminated sand infilling *Bergaueria* in massive carbonate mud. Upper Gramina Member Section MM-2.

B) Mold of a *Bergaueria* trace illustrated by disrupted sand beds. Upper Gramina Member, section NCP-1.

Bergaueria most likely represents the dwelling burrow of actinarian sea anemones. (Alpert, 1973) Anemones are known to utilize both filter-feeding and carnivorous feeding strategies. Food is scavenged from the surrounding sediment surface and filtered from the water column. (Barnes, 1980) As a result of being able to scavenge, the actinarians responsible for *Bergaueria* did not specifically require periodic agitation of the water column to suspend food particles.

Pemberton *et al.* (1990) and Pemberton *et al.* (1988) report that *Bergaueria* are rarely found in vertical succession, and evidence that the trace maker was able to anchor itself within the burrow is lacking. As a result, the trace makers appear to have had difficulty in adjusting themselves within a particular burrow, or digging new burrows as adults. Therefore, *Bergaueria* appears to be representative of areas where sedimentation rate and substrate shift remained consistently low for extended periods of time. Plates 55 A,B illustrate *Bergaueria* from the storm - dominated Upper Grammia (sections MM-2 and NCP-1).

4.3 c) Ichnogenus *Chondrites* von Sternberg, 1833

Type Species

Fucoides antiquus Brogniart, 1882, by subsequent designation of Andrews, 1955

Diagnosis

A system of tunnels consisting of one or more vertical to near vertical main tubes which bifurcate into tunnels more parallel to bedding. The tunnels are unlined with well defined walls and remain nearly consistent in diameter over the length of a tunnel system. Interpenetration of the tunnel systems is rare. (after Kotake, 1991; Vossler and Pemberton, 1989; Chamberlain, 1977; Haentzschel, 1975; Osgood, 1970) (Figure 12A, Plate 56 A,B)

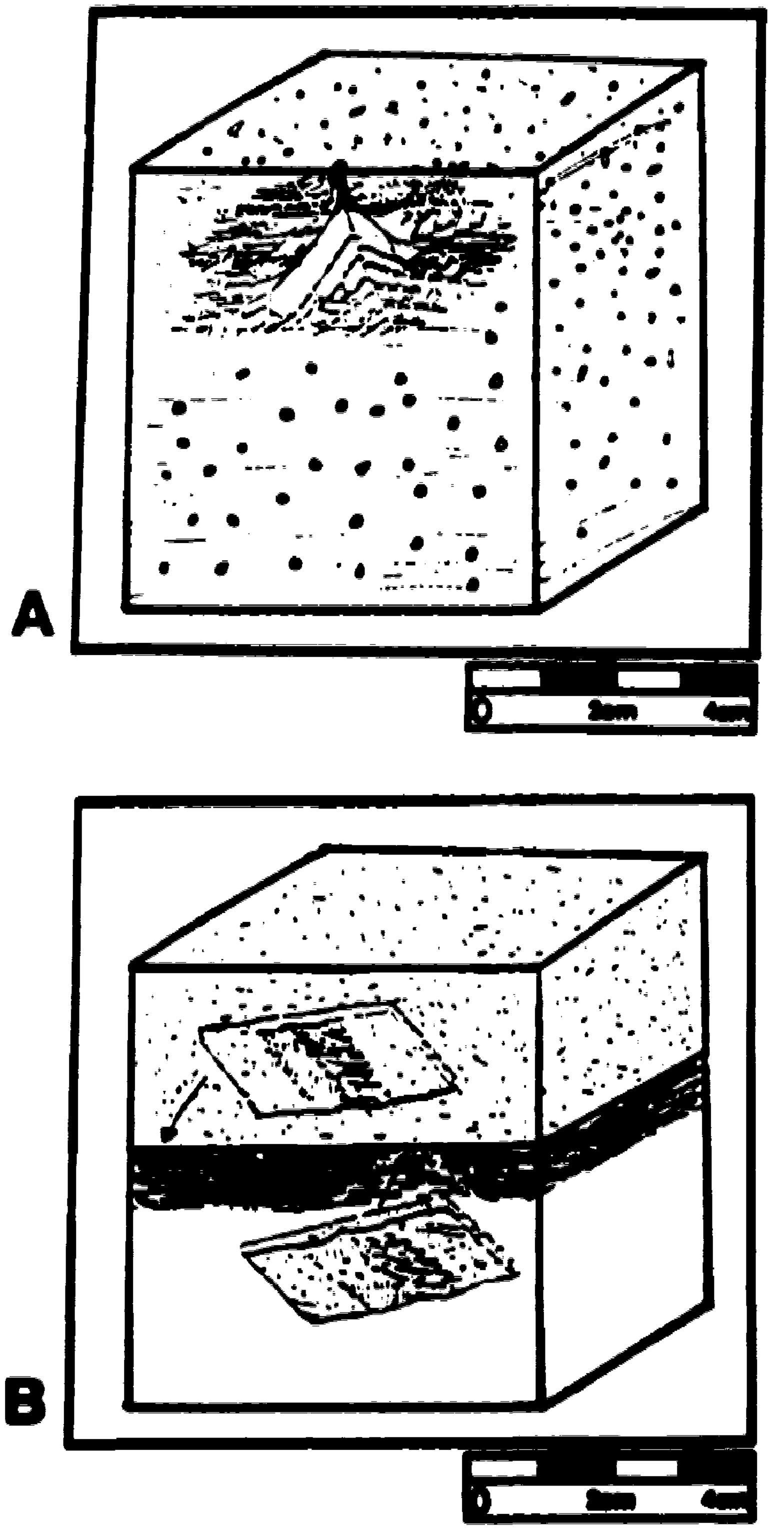
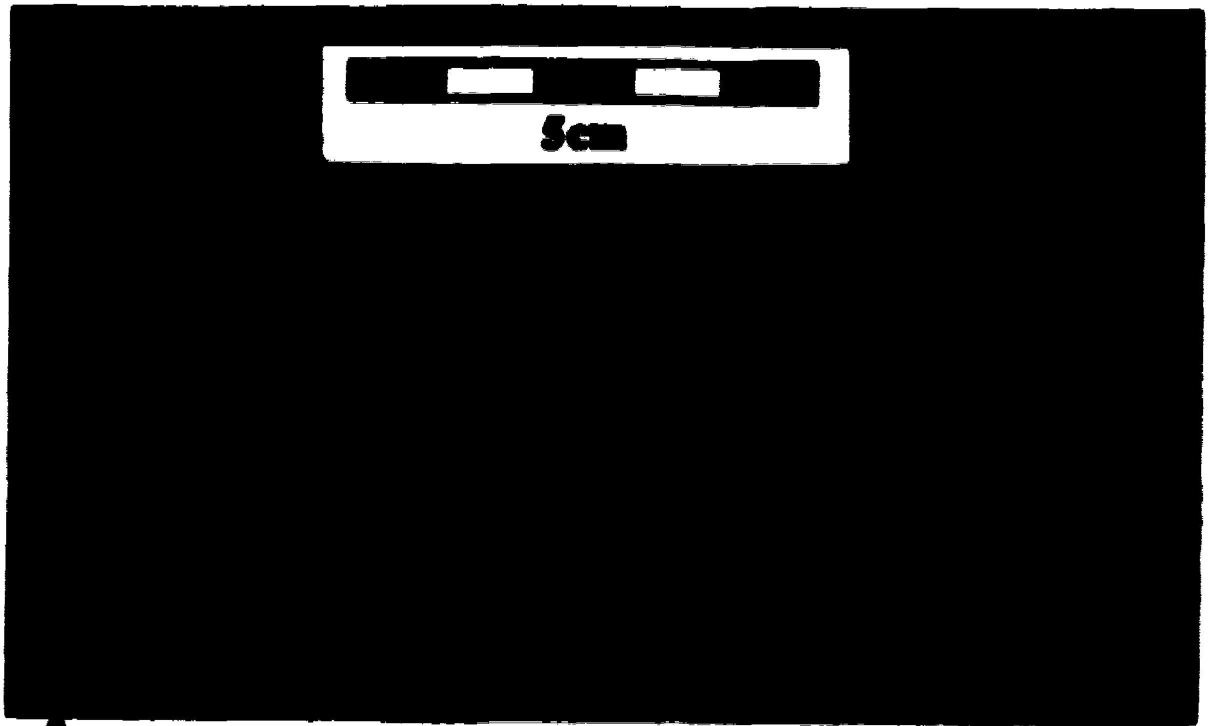
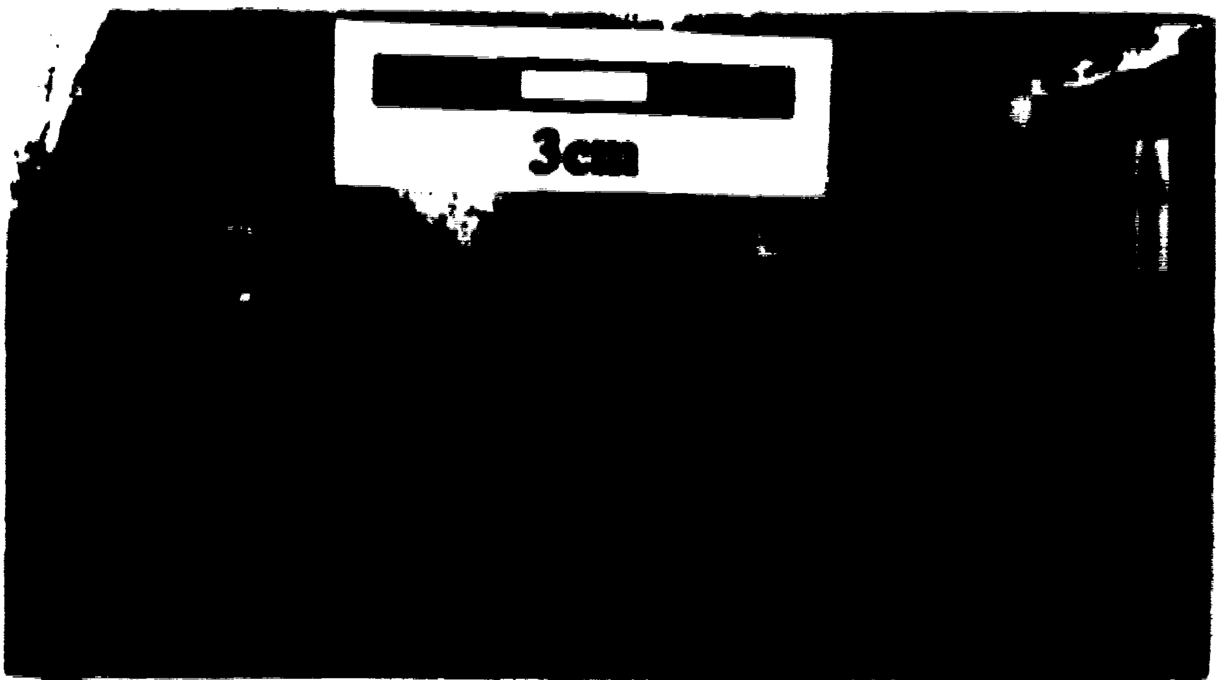


Figure 12. Schematic block diagram. A) *Chondrites* in an organic rich sand. Dark streaks represent organic material being scavenged by the trace maker. B) *Cruziana* preserved at the basal contact of a sandy unit overlying a mudstone. Preserved as sand filled casts.



A



B

Plate 86 A) *Chondrites* preserved on the upper bedding surface of an Upper Grаminia Member siltstone. Section MM-2.
B) *Chondrites* viewed perpendicular to bedding planes in a slightly more argillaceous sediment wedge. Upper Graminia section MM-2.

Description

Small irregularly straight to curving, unlined horizontal burrows up to 3mm in diameter Burrows exhibit up to two orders of branching with individual branches 2 mm - 25 mm in length Burrow frequency is generally high and tunnels appear to branch vertically and horizontally (Plate 56A)

Stratigraphic Range

Chondrites is known from sediments in the Cambrian to the Recent, (Osgood, 1970, Haentzschel, 1975)

Discussion

Traces are preserved in convex hyporelief on bedding plane surfaces at or near basal bedding surfaces of sandstone or siltstone beds The main structure of the *Chondrites* trace consists of a central vertical to near vertical shaft that branches and curves toward the horizontal Several orders of branching within an individual trace are common Branching traces generally remain constant in tunnel diameter Individual tunnels are unlined but have very distinct walls that are clearly distinguishable from the host rock Infill is generally structureless and slightly different in lithology to the surrounding host rock (after Kotake, 1991, Osgood, 1970) (Plate 56 A,B)

Chondrites are fossilised tunnel systems which had free connection to the sediment - water interface and were left open upon abandonment (Kotake, 1991, Osgood, 1970) It is interpreted to be a feeding structure produced by infaunal deposit-feeders (Kotake, 1991, Osgood, 1970) The trace making organism is thought to have remained in the central shaft at or near the surface and extended a proboscis into the surrounding sediment (Osgood, 1970) Despite the lack of a burrow lining the original traces are thought to have been thinly lined with mucous This lining would have allowed the organism to move freely within the burrow system and prevent sediment collapse after abandonment by the trace maker The tunnel systems were then passively infilled by overlying sediments (Osgood, 1970)

Possible trace makers for *Chondrites* include sipunculids, enteropneusts, and annelids (Osgood, 1970). Each of these organisms is capable of extending a proboscis from a fixed point near the sediment - water interface. The extended body part would have probed the surrounding sediment in a deposit feeding behaviour. This behaviour is adapted to systematically exploit buried organic rich layers while keeping the organism in communication with the oxygenated overlying water column. This enabled the trace maker to tolerate dysaerobic conditions not favourable to competitive trace makers and ultimately be the first to scavenge a particular buried deposit (Vossler and Pemberton, 1988).

Chondrites is not indicative of any particular environment. It is found in all substrates, but is indicative of firm to stiff sediments (Ekdale *et al.*, 1984). Several authors have documented *Chondrites* from a wide range of environments: 1) shallow shelf seas (Vossler and Pemberton, 1988), 2) shallow subtidal (Fillion and Pickerill, 1984), 3) marginal marine (Hakes, 1985), 4) abyssal deposit (Bromley and Ekdale, 1984), and 5) tidal flats (Ekdale *et al.*, 1984). Plate 56 A,B illustrates *Chondrites* from the Upper Gramminia platform margin region at Mount Mackenzie (Section MM-2).

4.3 d) Ichnogenus *Cruziana* d'Orbigny, 1842

Type Species

Cruziana rugosa d'Orbigny, 1842, subsequent designation by Miller, 1889

Diagnosis

Elongate furrows bisected by a median groove. The furrow may be bounded by an outer lobe and/or thin marginal ridges which occur along the outer edge of the trace. The surfaces of the lobes are covered by striations at an angle to the length of the furrow.

(Magwood and Ekdale, 1993. Haentzschel, 1975. Crimes, 1970) (Figure 12B, Plate 56A)

Description

Small, (2-3mm), bedding plane traces that appear to be somewhat bi-lobed in plan view. Sediment fill is lithologically similar to surrounding material, however the traces have weathered up suggesting at least minor mineralogical differences. *Cruziana* is closely associated with *Chondrites* and is illustrated inFigure 12B

Stratigraphic Range

Cruziana is known from sediments in the Cambrian to the Jurassic with the most widely known specimens in the Cambrian and Devonian, (Magwood and Ekdale, 1993; Bromley and Asgaard, 1979; Haentzschel, 1975. Crimes, 1970).

Discussion

Cruziana is most commonly preserved as a positive relief structure on the basal bedding surface of a sandstone or a siltstone overlying a shale, (Magwood and Ekdale, 1993. Goldring, 1985, Crimes, 1970;). It is interpreted to be the result of trilobites or arthropods foraging, or moving along the surface of the sediment, (Crimes, 1975). It has also been illustrated to represent foraging or locomotion within the sediment along a discontinuity surface, (Goldring, 1985). In each case the resulting trace is a continuous trough in the sediment. Infilling is accomplished either by the overlying sediment collapsing into the trough, in the case of intrastratal formation, or by sediment deposition at a later time in the case of surface formation. The trace fossil is then formed when sediment infills the trough and the resultant cast is preserved

If the sediment were to have slumped into a newly created trough, as in the case of intrastratal burrowing, evidence in the overlying sediments would be visible, (Baldwin, 1977). Siltstones observed containing *Cruziana* traces in this study appear as small, structureless sand bodies with no internal or external evidence to support an intrastratal formation. Therefore, it is likely that *Cruziana* observed in this study are representative of surface activities of an arthropod. However, evidence for the precise origin of *Cruziana* is somewhat inadequate. The poor preservation of the trace fossils does not allow for a complete and detailed study of individual specimens.

Direct evidence to support the assumption that *Cruziana* is formed by the activities of trilobites appears to be somewhat vague. The best examples of *Cruziana* are most often found in high energy, siliciclastic settings where supporting data such as body fossils are rare, (Seilacher, 1985). There is, however, some direct evidence, and an abundance of circumstantial evidence to support trilobites as the trace maker for *Cruziana*, (Seilacher, 1985). Ekdale *et al.*, (1984) and Seilacher (1985) discuss the similarities between the abundance, diversity, and size of trilobites and *Cruziana* and are able to show a close association.

Caution must be observed when emphatically implying that a singular species is responsible for a particular trace fossil. However, the data presented by several authors over the last several years (Seilacher, 1985, Goldring, 1985, Ekdale *et al.*, 1984), appear to strongly point to a trilobite, or at least an arthropod origin for most forms of *Cruziana*.

The large number of arthropods that are thought to be responsible for *Cruziana* creates many problems when the environment of formation is considered. The trace fossil *Cruziana* is most often associated with the *Cruziana* ichnofacies, (Pemberton *et al.*, 1992, Frey and Pemberton, 1984; Fillion and Pickerill, 1984; Crimes *et al.*, 1977, Crimes, 1970). This ichnofacies is most common in poorly sorted unconsolidated substrates where energy levels fluctuate and range from moderate to low (Pemberton *et al.*, 1992; Frey and Pemberton, 1984). In low to moderate fluctuating energy settings, such as a storm dominated continental shelf, it is typically found beneath fair-weather wave base, but above storm wave base. Sedimentation rates are variable, but are normally rapid (Pemberton *et al.*, 1992; Frey and Pemberton, 1984).

The trace fossil association characteristic of the Cruziana ichnofacies includes *Astericites, Cruziana, Rhizocorallium, Aulichnites, Thalassinoides, Chondrites, Teichichnus, Asterosoma, Rosselia, and Planolites*. This ichnofacies is typically found in estuaries, bays, lagoons, tidal flats, and continental shelves. (Pemberton *et al.*, 1992; Frey and Pemberton, 1984). Within these depositional settings sediment type can vary from well sorted sands and silts to interbedded sands and muds. (Frey and Pemberton, 1984). The best environment for the preservation of these trace fossils appears to be interbedded sands and muds. (Crimes *et al.*, 1977). Muds deposited at low energy are foraged and subsequently burrowed. Sands deposited during the higher energy episodic events would then fill in the surface structures and be cast as trace fossils.

Low energy deposition of muds, punctuated by episodic high energy influxes of sand would allow transportation of organic debris into the environment to be foraged by the surface feeding *Cruziana* trace makers. Predatory forms of the *Cruziana* trace maker would also flourish in such an environment, feeding on the abundant opportunistic infauna able to populate the environment between episodic events. Plate 56A) illustrates the *Cruziana* trace fossils identified from the storm-dominated Upper Grammia Member shelf in the area of Mount Mackenzie (Section MM-2).

4.3 e) Ichnogenus *Dactyloidites* Hall, 1886

Type Species

Dactyloidites asteroides Fitch, 1850.

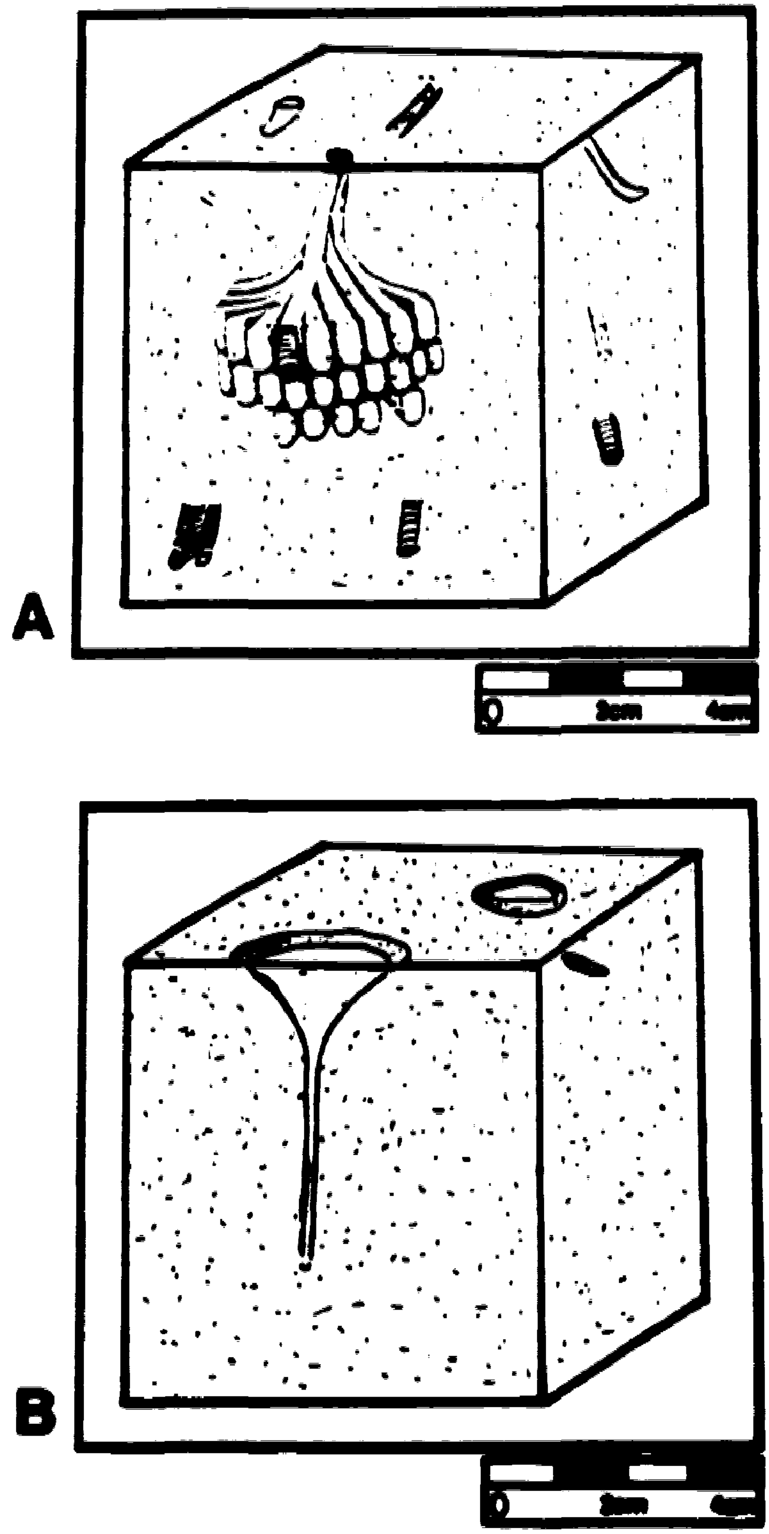


Figure 13. Schematic block diagram. A) *Dactyloidites* preserved in a sandy substrate. B) *Monocraterion* preserved in a sandy to muddy substrate.

Diagnosis

Star-like trails with an elevated central shaft that has an oblique to near vertical orientation. Elongate elements radiate from the central shaft and fan out over slightly more than half of a circle (Pickerill *et al.* 1993, Fursich and Bromley, 1985, Haentzschel 1975) (Figure 13A, Plate 57A)

Description

Small bedding plane traces with a sub-vertical central tube from which sub-horizontal tubes radiate. Vertical dimension is up to 3mm in height with the horizontal radial patterns up to 10 mm in length. Traces are weathered up from the surrounding material and appear to be composed of a coarser grained sediment (Plate 57A)

Stratigraphic Range

Dactyloidites is known from sediments of the Devonian to Pliocene (Pickerill *et al.*, 1993)

Discussion

Dactyloidites is most commonly preserved in full relief on a weathered upper surface of a bedding plane in siltstone to medium sandstone. (Pickerill *et al.*, 1993, Fursich and Bromley, 1985). The *Dactyloidites* traces observed in this study are not of excellent quality. However, using the observed traces from the samples collected and the diagrammatic representations given by Fursich and Bromley (1985), a rough, overall burrow morphology is presented in Plate 57A)

Dactyloidites is the result of a deposit feeding organism mining the sediment in a radial pattern from a central shaft while shifting the causative burrow downward. (Pickerill *et al.*, 1993, Fursich and Bromley (1985). Figure 13A) illustrates the internal structure of individual burrows and the stacked lamellae resulting from the shifting of the burrow in a

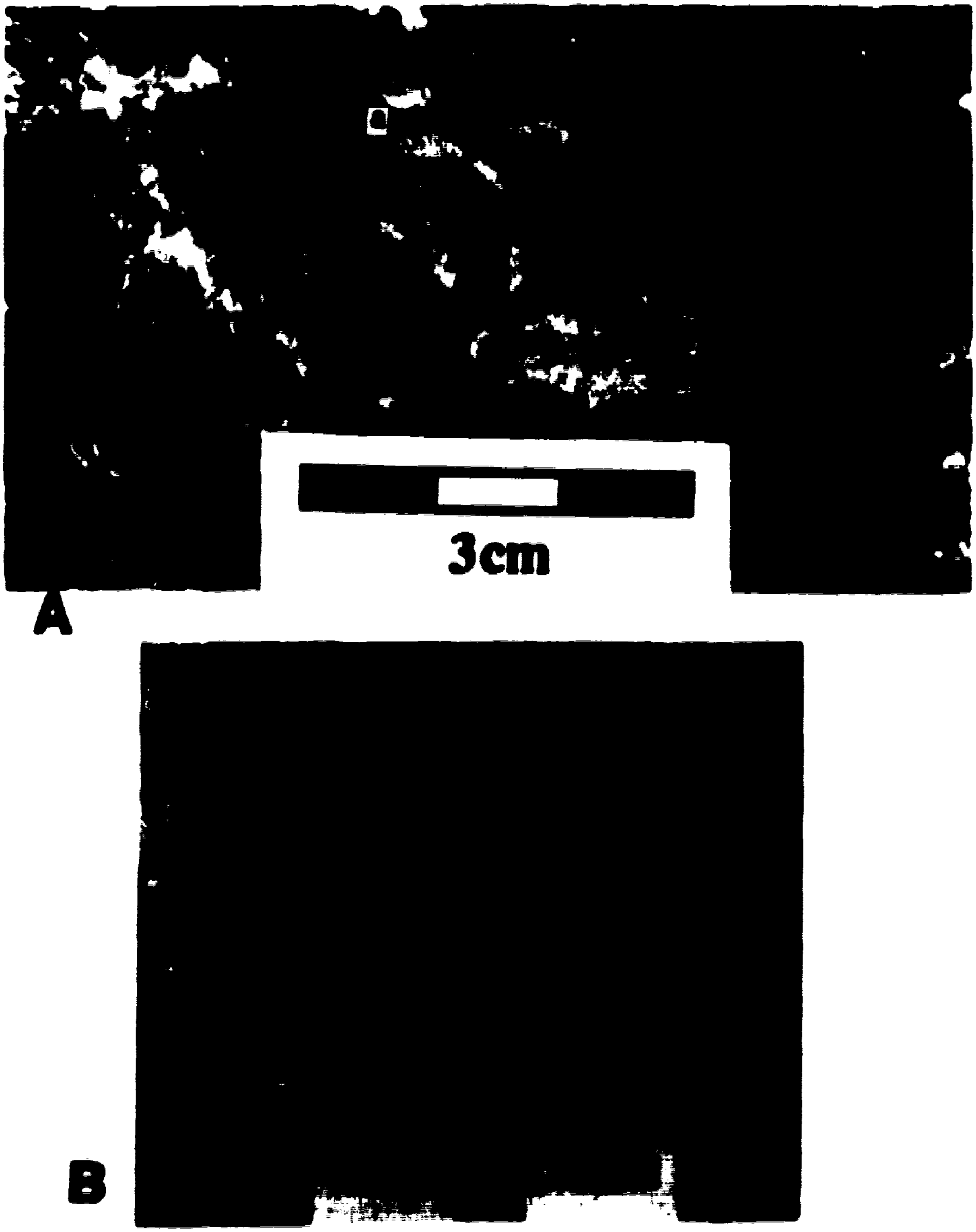


Plate 57. A) *Dactyloidites* preserved on an upper bedding plane of an Upper Graminia Member siltstone. Section MM-2.
B) *Monocraterion* within a pelleted carbonate mudstone. Blue Ridge Member section TC-1

downward direction

Systematic foraging of the sediments surrounding the central shaft was completed from 180^0-270^0 of a circle. (Fursich and Bromley, 1985). Upon completion of a fan-shaped set of spreite at one level within the sediment, the organism would withdraw into the central shaft and begin a new set of spreite at a different level. (Fursich and Bromley, 1985).

The organism responsible for the production of *Dactyloidites* was most likely a worm-like organism possessing a proboscis with which the sediment was reworked. (Fursich and Bromley, 1985). The uniform length of each group of stacked spreite may suggest that the organism maintained at least a portion of its body within the central shaft from which it extended parts of its body adapted for foraging.

Environment of formation is unknown,but sedimentological data in combination with the complexity of this trace and the apparent feeding strategy of its producer suggests that *Dactyloidites* was produced in a quiet water environment that may have undergone periodic influxes of sediment with associated organic detritus. The trace-maker's ability to survive these influxes of sediment is unknown.

Fursich and Bromley (1985) suggest that in the case of specimens from Greenland the trace may be lined with a thin layer of concentrated feldspar grains and plant debris. This suggests that organisms were able to survive slight substrate shifts. No evidence of a lining was visible in any of the specimens observed in this study. However, survival of the trace making organisms during the major catastrophic events interpreted to have dominated this section at the time of deposition seems unlikely. Colonisation of the substrate after the major events appears to be more plausible. Plate 57A) illustrates the *Dactyloidites* samples collected from the area of Mount Mackenzie. (Section MM-2).

4.3 f) Ichnogenus *Lockeia* James, 1879

Type Species

Lockeia siliquaria (Haentzschel, 1975)

Diagnosis

Almond shaped, pod-like structures that are generally pointed at both ends. Size is variable and infill is generally similar to surrounding sediments (Maples and West, 1989, Pickerill, 1977; Haentzschel, 1975). Figure 17 and Plate 62A) illustrate *Lockeia* in cross-section, closely associated with an escape structure.

Description

Shallow, concave upward structure observed perpendicular to bedding in cross-section in a silt to fine grained sand. Depth is approximately 3-5mm. Width is approximately 3-5mm. No internal structure is visible and sediment infill is similar to surrounding silts and fine grained sands. *Lockeia* is closely associated with an interpreted escape trace observed in the underlying laminae (Plate 62A)).

Stratigraphic Range

Lockeia is known from the Ordovician to the Recent (Haentzschel, 1975).

Discussion

The ichnofossil name *Lockeia* is herein used instead of *Pelecypodichnus*, (after Maples and West, 1989). *Lockeia* is most commonly preserved as convex hyporelief structures, (Bjerstedt, 1987). The *Lockeia* in this study are also visible in cross-section as concave upward structures within thinly bedded siltstones and fine grained sandstones. A single ichnofossil is also preserved at the stratigraphic top of an escape structure within the storm-dominated Upper Grammia Formation (Plate 62A)).

Lockeia is generally interpreted to be the resting trace of a Pelecypod, with each ichnofossil representing the foot impression of its producer. (Haentzschel, 1975, Osgood, 1970) However, similar traces have been reported to be formed by ostracodes and conchostracans by Maples and West (1989) Any organism exhibiting periodic resting behaviour, (cubichnia), and having similar morphological characteristics to a bivalve would be capable of producing this trace

Bromley, (1990), reports that resting traces are made by vagile benthos digging down into the sediment for a period and then departing by the same route It is also suggested that few trace-makers actually "rest", and that the production of cubichnia more often represents concealment or stationary feeding strategies. Life activities of most bivalves must include interaction with the overlying normal marine water column. This interaction can be accomplished through positioning of the organism at the sediment-water interface In the case of burrowing trace makers this interaction is accomplished by the extension of a specialized body part up through the sediment into the water column

Lockeia is generally considered to be a poor indicator of environment, (Wright and Benton, 1987) However, sedimentological data suggest that the environment of formation for the *Lockeia* traces observed was in a storm dominated shallow shelf The close association of these traces with escape structures also suggests catastrophic events forced the trace making organisms to periodically alter life activities to compensate for the sudden influx of large amounts of sediment. The presence of *Lockeia* traces at the top of escape structures suggests fair-weather life activities were interrupted and the trace-maker forced to reposition itself with respect to the sediment water interface Following repositioning, normal fair-weather activities were resumed.

4.3 g) Ichnogenus *Monocraterion* Torrel, 1870

Type Species

Monocraterion tentaculatum Torrel, 1870

Diagnosis

Vertical to sub-vertical unbranched funnel shaped structures with a curved to straight interior. (after Marintsch and Finks, 1982) (Figure 13B), Plate 57B))

Description

Relatively shallow structures that have a wide opening at the bedding plane surface, (1-2cm), tapering downward into the sediment in the form of a single, slightly curving shaft. Vertical and sub-vertical structures are perpendicular and oblique to structural tops and appear to be most common in the slightly silty carbonates of the Blue Ridge Member at Toma Creek Section 2.

Stratigraphic Range

Monocraterion is known from sediments of the Cambrian to the Jurassic (Haentzschel, 1975)

Discussion

Monocraterion is most often preserved as passively infilled funnel shaped structures perpendicular to bedding. Downwarping of the surrounding sediments and raised rims are also commonly observed features (Plate 57B)). Sediment fill is generally of similar lithology to the surrounding host sediment. (Eagar *et al.*, 1985). In this study, *Monocraterion* is visible as a surface feature which is observed in the silty carbonates of the Blue Ridge Member (Plate 57B)). This specimen appears to have undergone removal of the infilling sediment, possibly through erosion following uplift and exposure

Several authors have discussed the association between *Monocraterion* and *Skolithos*. (Eager *et al*., 1985, Pienkowski, 1985, Barwis, 1985, Pemberton and Frey, 1985, Hallam and Swett, 1966). The close association between these two ichnofossils and the gradational change from one into the other, (Pienkowski, 1985, Hallam and Swett, 1966), has lead most authors to conclude that the two traces are created by a single organism. Haentzschel (1975) has attributed this dwelling burrow to gregarious, suspension-feeding ,worm-like organisms. Marintsch and Finks, (1982) have suggested that the trace maker was a worm-like organism that occupied a vertical tube and created the funnel-like structure in the upper portion of the trace by extending its food-gathering apparatus into the overlying water column. Barwis, (1985), suggests that the modern polychaete *Diopatra cuprea* may be an analogue for the *Monocraterion* trace-maker.

Monocraterion has been shown to be produced under conditions of relatively rapid sedimentation, whereas *Skolithos* is a similar burrow structure produced under conditions of slow sedimentation, (Hallam and Swett, 1966, Pienkowski, 1985). Sedimentological data from the study area suggest that episodic events introduced medium to coarse grained siliciclastics into an otherwise carbonate dominated depositional environment. The occurrence of *Monocraterion* within the silty carbonates of the Toma Creek Section may represent the trace-makers response to this rapid influx of sediment into the quiet water depositional system.

4.3 h) Ichnogenus *Palaeophycus* Hall, 1847

Type Species

Palaeophycus tubularis Hall, 1847, subsequent designation by Bassler, 1915.

Diagnosis

Branched or unbranched, smooth or ornamented, lined, cylindrical, predominantly horizontal burrows of variable diameter. fill is structureless and is generally the same lithology as the host rock. (Pemberton and Frey, 1982) (Figure 14A), Plate 58A))

Description

Small, (2-4 mm), bedding plane traces which are indicated by the presence of a tube lining, end and cross section of the tubes is round to somewhat elliptical, generally associated with the more abundant ichnofossil *Planolites* (Plate 58A)

Stratigraphic Range

Palaeophycus has been reported from sediments of Cambrian to Holocene age. (Haentzschel, 1975)

Discussion

Palaeophycus is most often preserved as conspicuously lined traces, horizontally oriented or slightly inclined to bedding with short, vertical segments. Vertically compressed burrows and collapse structures are also common. Fill is essentially structureless and is of similar lithology to the host sediment with which the burrow is in contact with at some point (Pemberton and Frey, 1982).

Palaeophycus are thought to represent the remains of open burrows that were passively infilled after abandonment by the trace-maker. (Pemberton and Frey, 1982) Pemberton and Frey, (1982), also suggest that *Palaeophycus* is the result of the activities of sessile infaunal suspension-feeders, or mobile, predaceous animals similar to modern polychaetes. The burrows may have been maintained as permanent or semi-permanent which were left as open tubes after passage of the trace-maker. (Pemberton and Frey, 1982)

Palaeophycus occurs in a wide range of marine environments (Fillion and Pickerill,

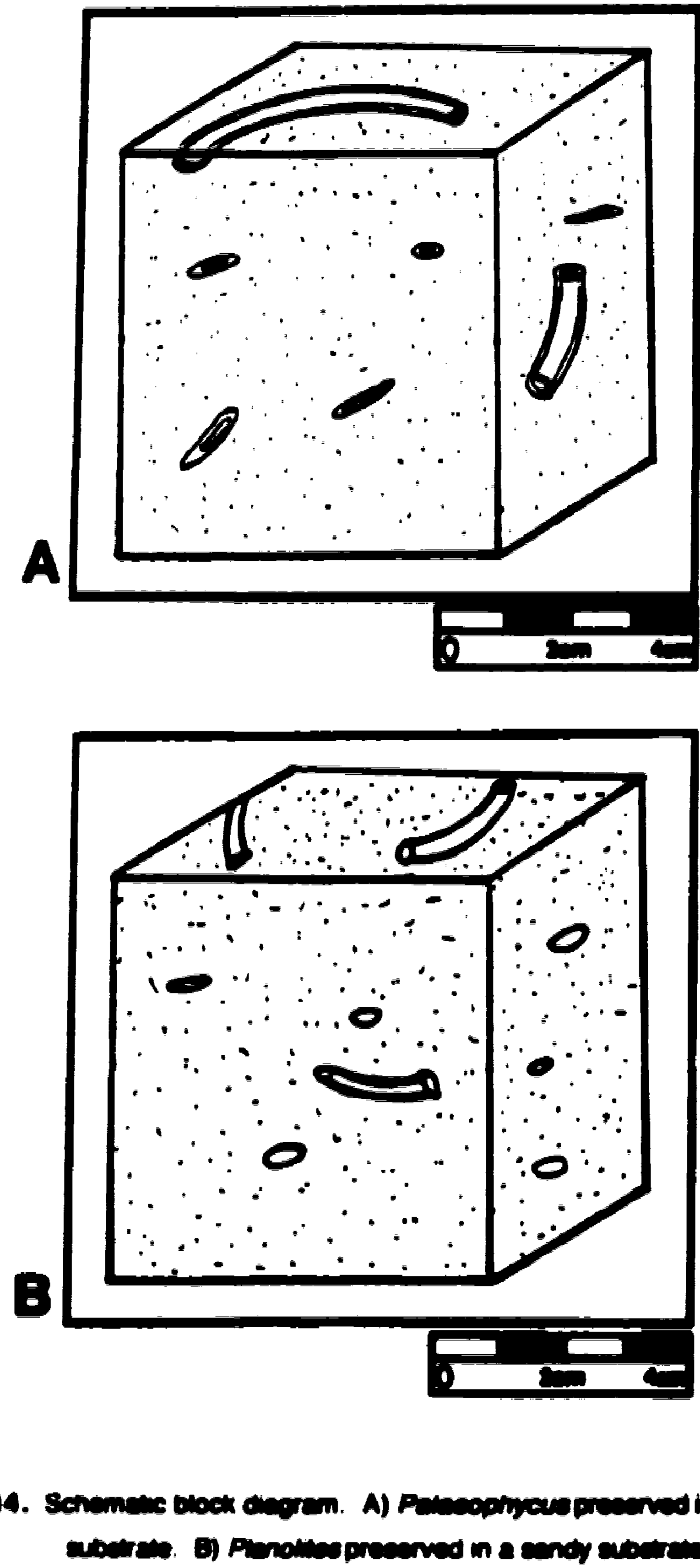
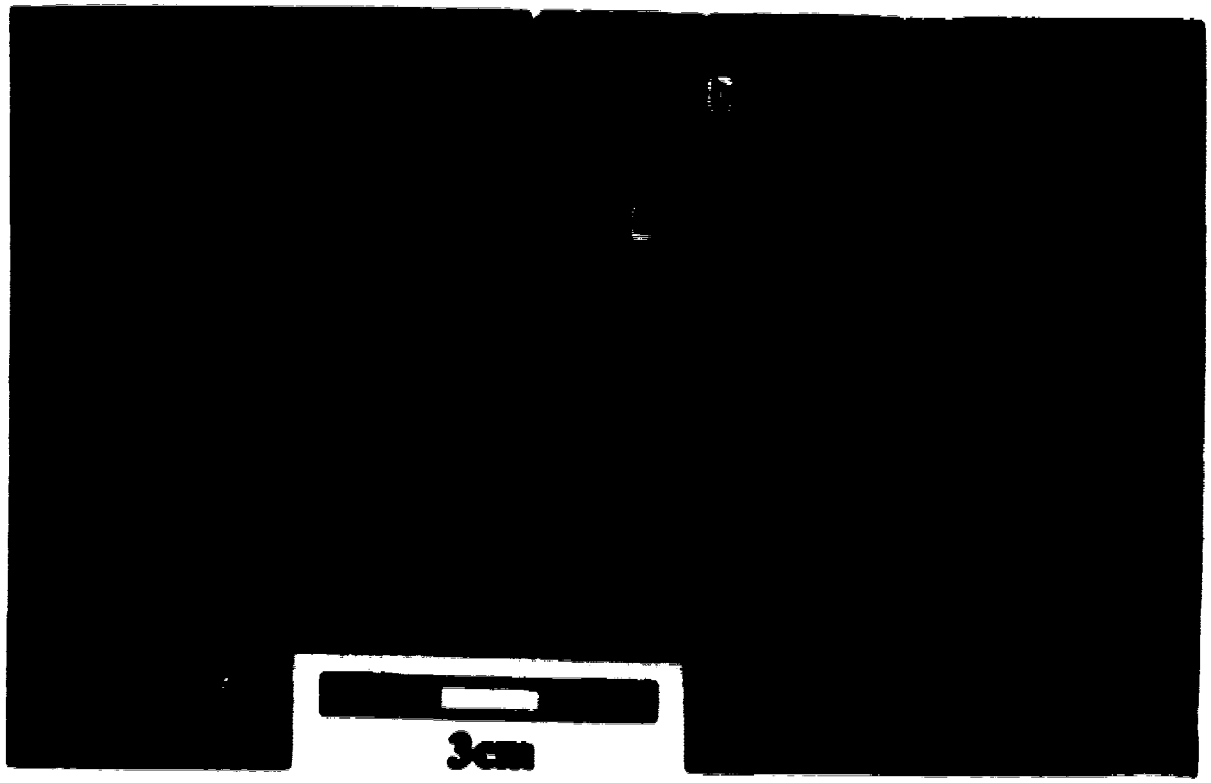


Figure 14. Schematic block diagram. A) *Palaeophycus* preserved in a sandy substrate. B) *Planolites* preserved in a sandy substrate.



A

B

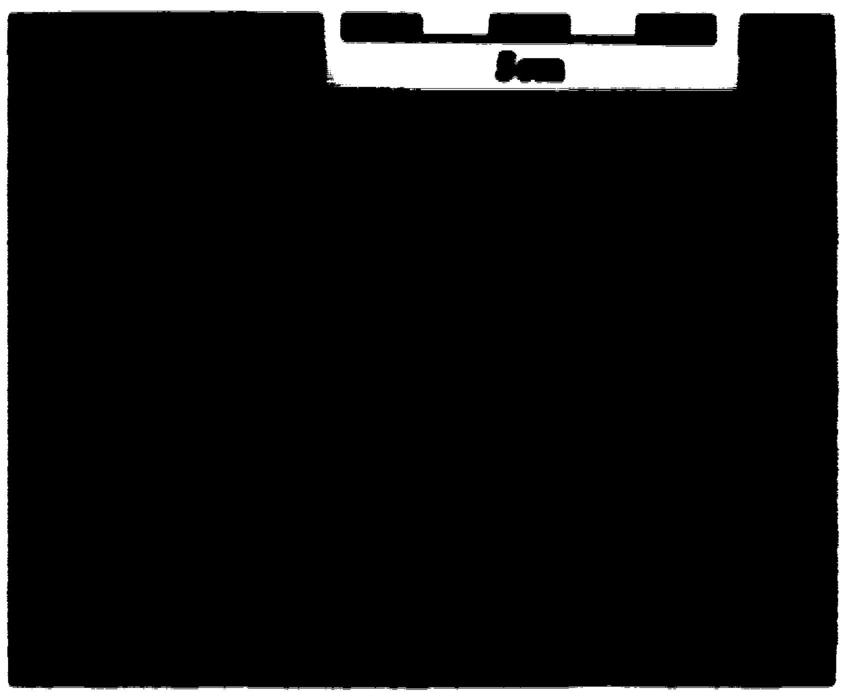


Plate 98. A) Intensely burrowed Lower Gramina Member siltstone. Section SCP. a) *Planolites*, b) *Palaeophycus*.

B) Intensely burrowed silty storm bed of the Lower Gramina Member. Section SCP. a) *Thalassinoides*, b) *Planolites*.

1984), as a result, reconstruction of an environment of formation for the trace must include sedimentological criteria. *Palaeophycus* specimens observed in the storm dominated Upper Graminia Member appear to be relatively simple and thin-walled. The lack of robust linings for these burrows suggests that the dwelling organisms were less involved in burrow construction and more involved in food gathering in the periods between major storm events. Complete destruction of the burrow systems was accomplished during each storm event. Population of the newly deposited substrate was completed after each storm event and included the *Palaeophycus* trace-makers.

4.3 i) Ichnogenus *Planolites* Nicholson, 1873

Type Species

Planolites vulgaris Nicholson and Hinde, 1875 = *Palaeophycus beverleyensis* Billings, 1862, subsequent designation by Alpert, (1975)

Diagnosis

Unlined, rarely branched, straight to tortuous, smooth to irregularly walled or annulated burrows that are circular to elliptical in cross-section and of variable dimensions and configurations. Fill is generally structureless and differs from the host sediment. (Pemberton and Frey, 1982) (Figure 14B), Plate 58A,B))

Description

Small, (2-3mm), relatively abundant bedding plane structures that have been weathered up from the surrounding sediment indicating lithological differences in sediment fill. End and cross-sections of the trace illustrate the elliptical nature of the individual tubes, no lining of the walls is evident in any observed specimen and the tubes generally run across bedding surface in no particular pattern.

Stratigraphic Range

Planolites is known from strata of the Precambrian to the Quaternary. (Haentzschel, 1975)

Discussion

Planolites is commonly preserved as unlined cylindrical to subcylindrical burrows with varying degrees of tortuosity. Higher degrees of tortuosity are common as burrow density increases. Crossing and interpenetration of burrows becomes more frequent as population density increases (Pemberton and Frey, 1982). The burrow fill is structureless and differs from the host sediment (Pemberton and Frey, 1982).

Planolites is interpreted to be the actively backfilled burrow of mobile, deposit-feeders (Pemberton and Frey, 1982). The sediment is processed within the acidic gut of the trace-maker as it moves through the sediment. Processing of the sediment may include the consumption of organic components, alteration of clay fractions, reduction of grain size in carbonate material, and the general mixing of the sediments (Pemberton and Frey, 1982). These processes result in an altered sediment being excreted from the organism and are partly responsible for the contrasting lithologies of the burrow and the host rock.

Selective deposit-feeding and simple passage of sediment around an organisms body as it moves may also create an alteration of the sedimentary grains within a system. The ultimate result would be a burrow lithology different from the surrounding host rock as is seen in *Planolites* burrow systems (Pemberton and Frey, 1982).

Planolites has a wide bathymetric range and has been documented over an extensive geologic time period. (Pemberton and Frey, 1982, Haentzschel 1975). However, several authors have illustrated specific environmental conditions that may be common to its formation *Planolites* is indicative of brackish to near normal salinity, (Pienkowski, 1985) soupy substrates, (Ekdale *et al*., 1984), and oxygenated conditions within the sediment as no connection with the water column is maintained. (Bromley and Ekdale, 1984) The extensive geologic time range, variable bathymetric range and relatively simple structure of *Planolites* suggests that several biotaxa may be responsible for its production. (Pemberton and Frey, 1982)

4.3 j) *Planolites montanus* Richter, 1937

Diagnosis

Relatively small, curved to irregularly contorted burrows, that are visible within any vertical or horizontal plane within a given sediment system. Burrow fill is structureless and is lithologically different from the host sediment. (Pemberton and Frey, 1982)

Description

Small, (2-4mm), straight to highly tortuous, horizontal to vertical structures that show little width variability over the length of a single tube. Structures have been weathered up from the surrounding sediment and show a slight lithological contrast between burrow and host sediment. The tubes are elliptical in cross-section with single tubes crisscrossing the bedding plane surface and occasionally interpenetrating.

Discussion

A lack of annulations, consistently smaller size, and more tortuous nature distinguish *P. montanus* from other species of this ichnogenus. Branching of the individual segments is rare, but crossovers, interpenetrations and reburrowed segments can be abundant. Burrow fill is consistently cleaner and better sorted than the surrounding matrix. (Pemberton and Frey, 1982)

P. montanus is found within the storm dominated beds of the Upper Gramminia Member at Mount Mackenzie and South Cardinal Pass. Specimens have also been observed in the stratigraphically equivalent basinal sections at Cardinal Headwaters Sections 1 and 2. At these locations, silty to muddy intervals are burrowed and show contrast between host rock and burrowed sediment infill.

4.3 k) Ichnogenus *Polykladichnus* Fursich, 1981

Type Species

Polykladichnus irregularis Fursich, 1981

Diagnosis

Vertical tubes with y-shaped bifurcations usually connected to the bedding surface. The number of bifurcations is variable (usually between 1 and 4). (Pemberton and Jones, 1988; Fursich, 1981) (Figure 15A), Plate 59)

Description

Vertical to sub-vertical tubes with y-shaped bifurcations branching upwards close to a bedding surface. Burrow size is generally less than 3mm in diameter and 10-15mm in height. The burrow fill is somewhat different from the surrounding laminae and consists of slightly coarser grained sands which allows the tubes to weather up from the surrounding sediment. Internal structure is massive and no lining is visible in any of the specimens, nor is swelling observed at the point of bifurcation. The shape and relative size of the bedding surface opening is not discernible due to a lack of highly weathered bedding surfaces.

Stratigraphic Range

Polykladichnus is previously known only from the Upper Jurassic to the Pleistocene. (Pemberton and Jones, 1988; Fursich, 1981). Description of

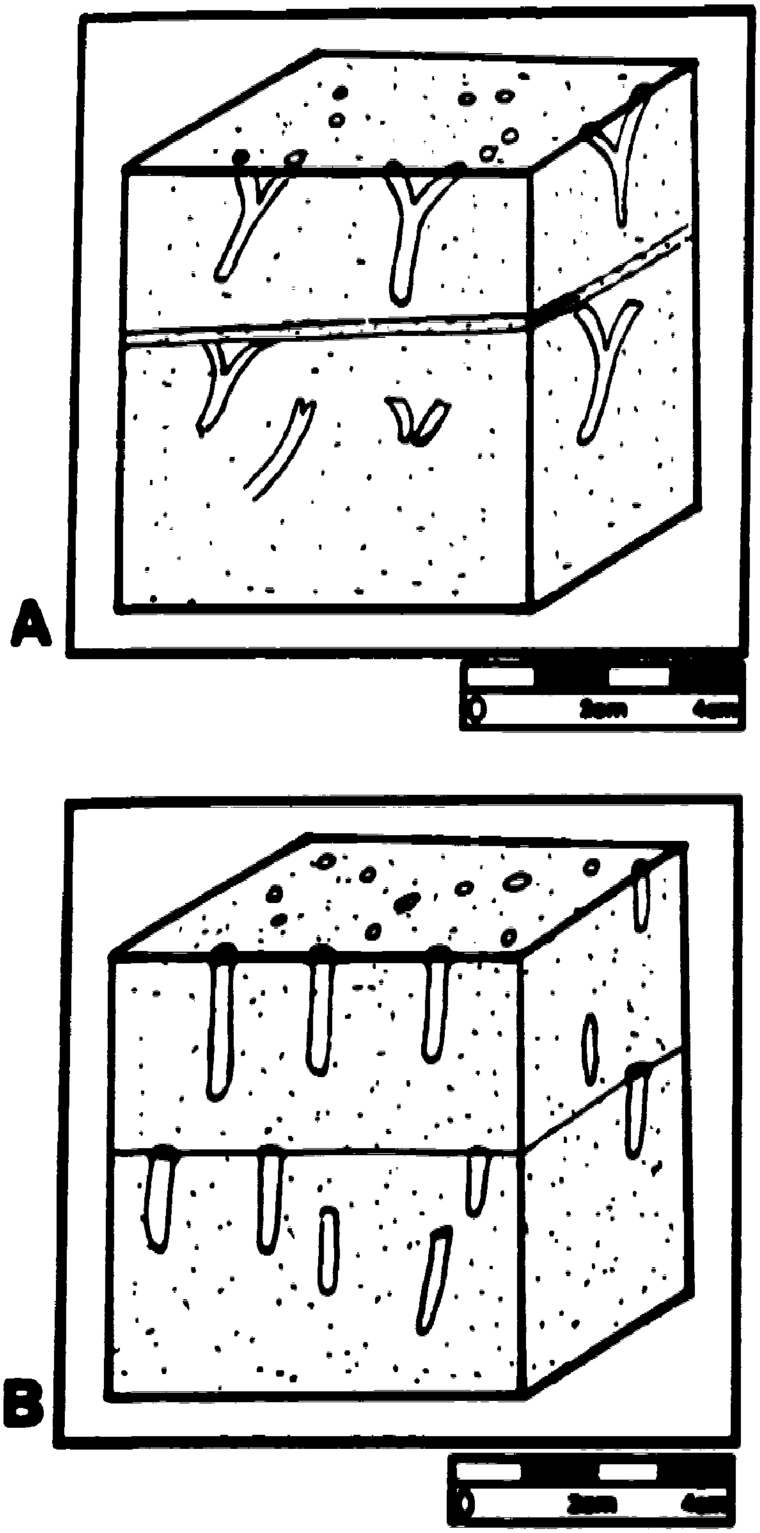


Figure 15. Schematic block diagram. A) *Polykladichnus* - a vertically oriented trace bifurcating near the sediment - water interface of a sandy substrate. B) *Skolithos* preserved in a sandy substrate.

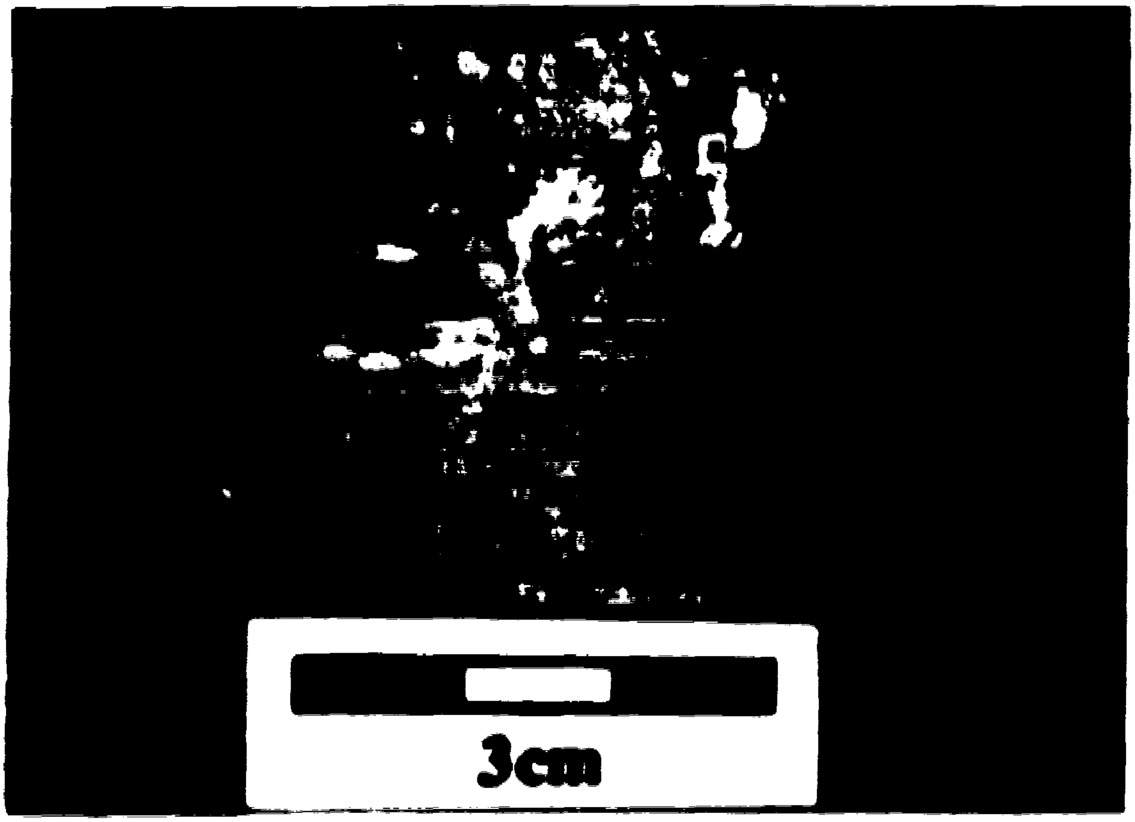


Plate 59. Finely laminated Upper Grammia Member siltstone a) *Polykladichnus*

Polykladichnus in this study, is the first known occurrence from Upper Devonian aged beds.

Discussion

Polykladichnus is preserved in full relief within the finely laminated muddy siltstones of the Lower Grammia Member at South Cardinal Pass Section 1. The distinctive Y-shaped burrow is visible as the slightly cleaner, coarser grained burrow fill weathers up from the surrounding laminated silts (Plate 59).

Polykladichnus has been interpreted to be the passively infilled dwelling burrow of a suspension-feeding polychaete worm or a cerianthid anemone, (Pemberton and Jones, 1988, Fursich, 1981). The size and cross-cutting nature of the burrows with respect to sediment laminae indicates that the burrow opening at the sediment-water interface remained open, and that the burrow represents a dwelling trace. The oblique angle of the Y-shaped branches to the main shaft, (Fursich, 1981), and the lack of swelling at the point of bifurcation suggests that the junctions did not serve as turning points for the trace-maker. The funnel shaped apertures and burrow lining reflect a low degree of substrate stability as sediment continually falls into the open burrow and is pressed against the outer walls, (Fursich, 1981).

The samples collected from South Cardinal Pass all occurred at the top of a series of finely laminated undulatory bed sets overlying a more massive, coarser grained sandstone. This series of laminated and massive sands appears to correspond to sediments from a storm dominated depositional environment. *Polykladichnus* in this case may represent the activities of an organism involved in the repopulation of recently deposited storm beds. Plate 59 illustrates the *Polykladichnus* burrows, and the storm dominated nature of the samples in which they were observed.

4.3 l) Ichnogenus *Skolithos* Haldeman, 1840

Type Species

Fucoides linearis Haldeman, 1840

Diagnosis

Simple, vertical to slightly oblique, non-branching, cylindrical to sub-cylindrical, non-branching tubes. The burrow walls may be distinct or indistinct and can be smooth to slightly rough or annulated. Burrow diameter can vary slightly over the length of a single tube with the burrow being structureless. (Vossler and Pemberton, 1989, Alpert, 1974) (Figure 15B), Plate 60A))

Description

Simple, singular, vertical to sub-vertical shafts where sediment infill is markedly different from the host sediments. The bedding plane expression may be represented by a single weathered - up circular to elliptical structure. Burrow length is generally less than 2 cm and width is less than 5mm. The linings of individual burrows were difficult to ascertain due to the small specimen size (Plate 60A)

Stratigraphic Range

Skolithos is known from strata of the Precambrian to the Quaternary. (Crimes, 1987)

Discussion

Skolithos is generally preserved as straight, cylindrical to subcylindrical, vertical burrows that are unbranched and may show dark burrow wall linings. Burrow size varies from 1-30 mm in width and up to 1 metre or more in length. (Haentzschel, 1975) Burrow fill is generally structureless, but may show concave upward, passive infill structures.

Skolithos is interpreted to be the passively infilled dwelling burrows of suspension-feeding organisms, possibly phoronids or annelids. (Alpert, 1974). Many worm-like animals including modern deposit-feeding maldanid polychaetes also produce similar vertical burrows. (Miller and Knox, 1985)

Burrow morphology may offer several clues as to the environment of formation for the *Skolithos* burrows observed in this study. Most *Skolithos* observed were relatively small in size with a maximum length of 2 cm. This indicates that the conditions within the water column were sufficiently stable to allow the trace-maker to live within the upper few centimetres of the substrate. If the salinity and temperature within the water column vary widely, the organisms may be forced to burrow deeper to utilize the buffering effects of the sediment. (Ekdale *et al.*, 1984). The storm dominated nature of the sediments where the *Skolithos* are observed suggests that there would have been prolonged periods of low energy conditions punctuated by periodic influxes of organic debris. This scenario serves as an ideal environment for the deposit feeding *Skolithos* trace maker. The continual reworking and redeposition of the sediments on the shelf through the action of storm events effectively destroys any organisms inhabiting the substrate. Immediately following any storm event there is little or no life within the sediment. This allows several opportunistic trace-makers, including *Skolithos*, to flourish in a predator-free environment.

Sedimentary structures, such as hummocky bedding in addition to the presence of *Skolithos* within the heavily burrowed upper portions of storm beds suggest a storm dominated, shallow shelf environment of formation. Shallow burrow penetrations also indicate a normal marine environment as the trace-making organisms were able to interact freely with the overlying water column.

4.3 m) Ichnogenus *Teichichnus* Seilacher, 1955

Type Species

Teichichnus rectus Seilacher, 1955

Diagnosis

Horizontal spreiten structures resembling U-shaped gutters, stacked vertical to bedding with a prominent upper cylindrical burrow. Burrows are straight to slightly sinuous and may curve upward (Haentzschel, 1975) (Figure 16A), Plate 60B))

Description

Teichichnus consist of a stacked series of concentric lobes 5-10 mm across and up to 6 cm in length. The structures run oblique to bedding surface and are most visible on the weathered surface where concave upward laminae are most visible (Plate 60B)). This trace is also visible on fresh surfaces as a slightly convex ridge directly correlatable with the visible weathered surface structure.

Stratigraphic Range

Teichichnus is known from Cambrian to Tertiary strata (Haentzschel, 1975)

Discussion

Teichichnus is preserved as straight, unlined vertically stacked exichnia within the siltstones and fine grained sandstones of the Lower Gramina Member at South Cardinal Pass Section 1. The burrow fill is slightly cleaner and coarser grained than the surrounding heavily burrowed host sediment at the South Cardinal Pass Section (Plate 18B))

Teichichnus is interpreted to be the product of a fixed position deposit-feeder foraging for food within a single burrow beneath the sediment-water interface (Jordan

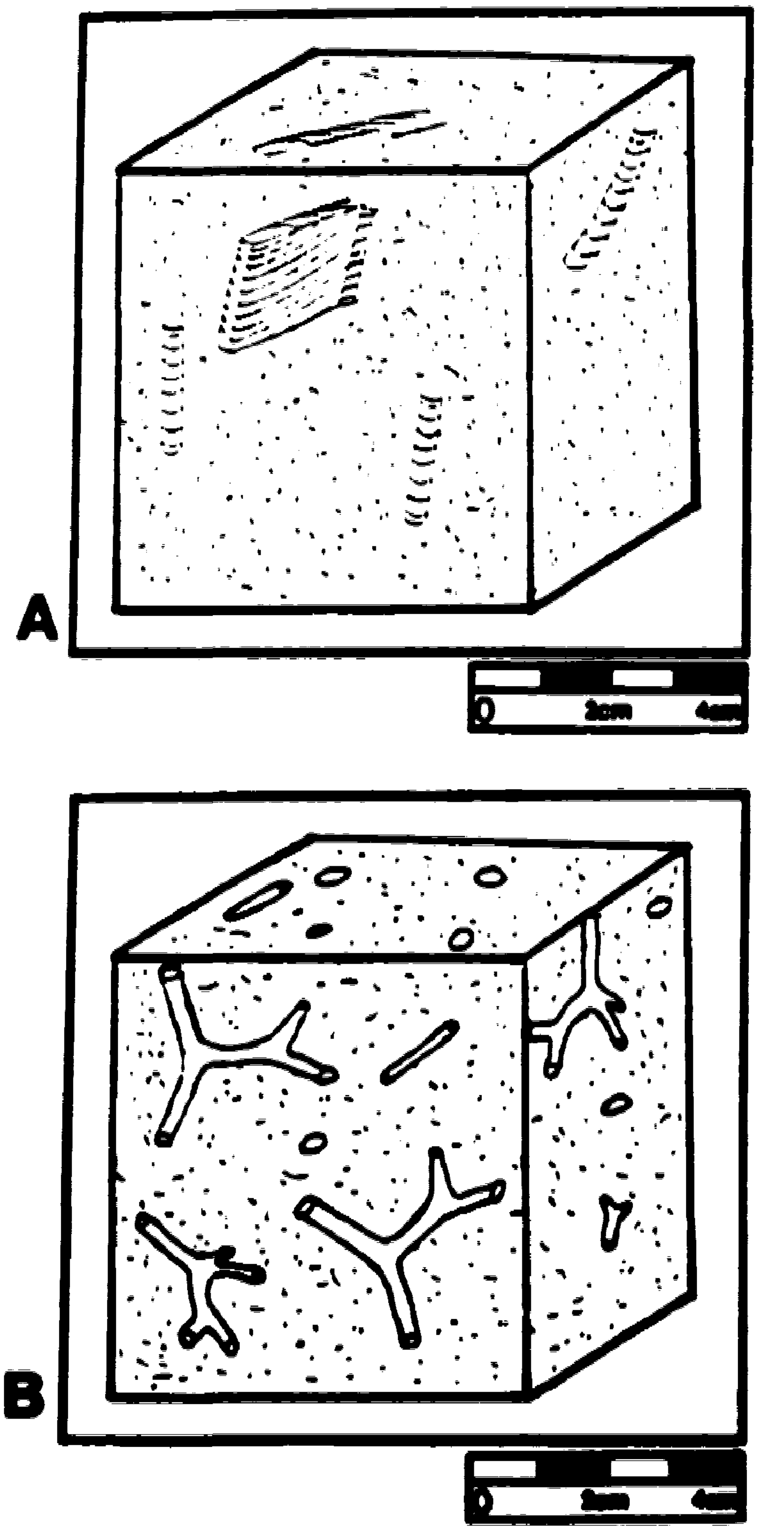
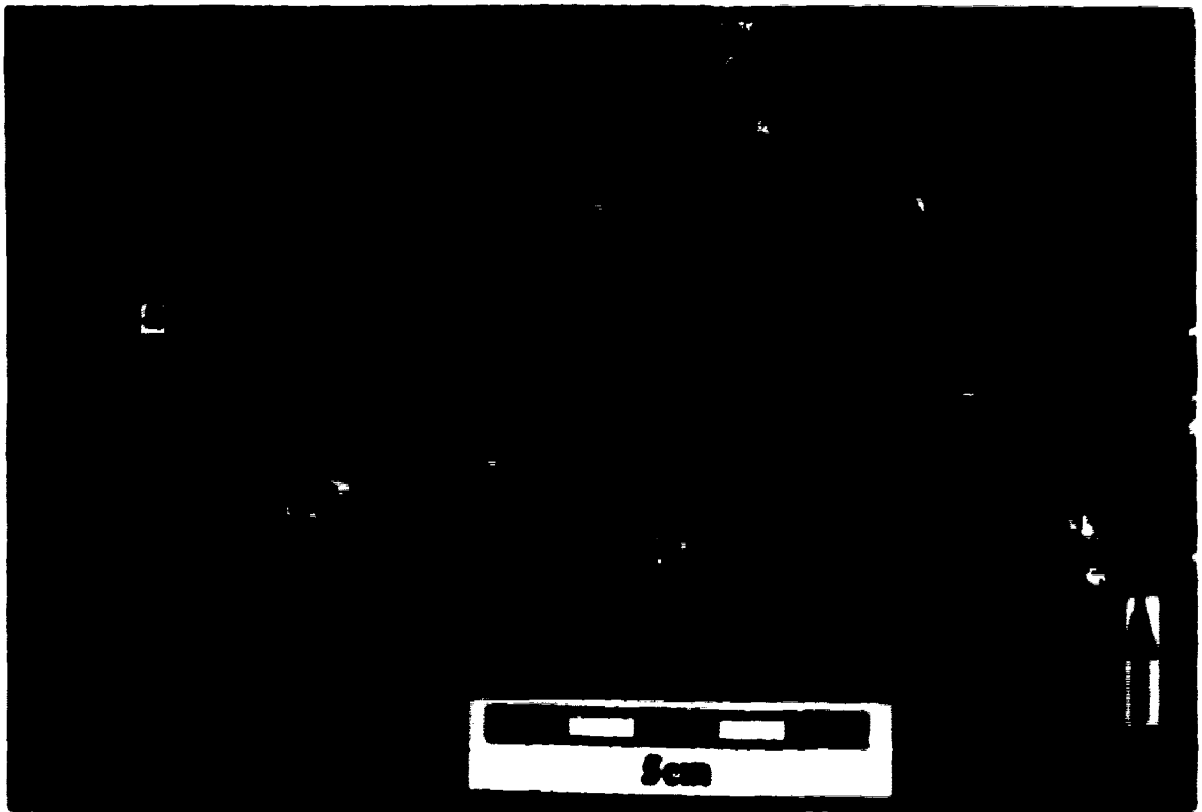


Figure 16. Schematic block diagram. A) *Teichichnus* preserved in a sandy substrate. B) *Thalassinoides* preserved in a sandy substrate.

A



B

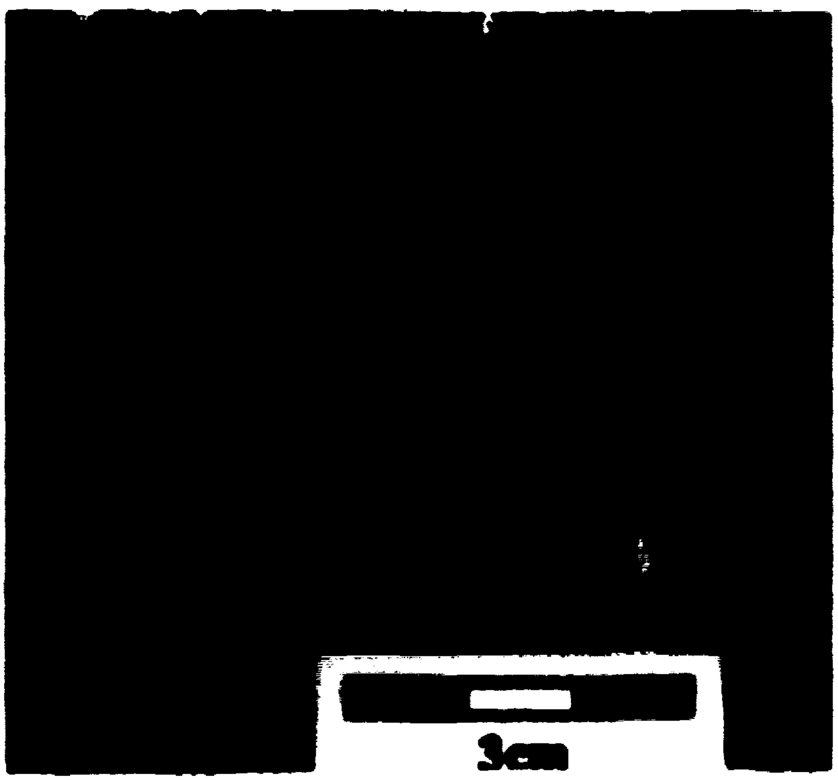


Plate 60. A) Silty carbonate of the Upper Graminia Member. Section MM-2. a) *Skolithos*. b) *Arenicolites*.
B) Intensely burrowed Upper Graminia Member siltstone. Section SCP. a) *Teichichnus*.

1985). Possible trace makers include annelids and arthropods, but *Teichichnus* may also be produced by a slightly larger animal (Fillion and Pickerill, 1984).

Fillion and Pickerill, (1984), suggest that the trace results from the trace-maker scraping material off the top of the burrow and processing the available nutrients before depositing the waste sediment onto the bottom. This behaviour of mining buried organic material appears to be indicative of low energy, fluctuating conditions with periodic influxes of organic debris and subsequent clastic deposition. Deposition of sand and silt beds immediately following the settling out of organic debris buries the newly deposited organic material. This serves to protect it from surface deposit-feeders allowing it to be mined at a slightly later date by the *Teichichnus* trace maker.

Specific environmental associations for *Teichichnus* are extremely difficult to formulate. Several environmentally distinct deposits have been illustrated for the *Teichichnus* trace-maker. These include interbedded black shales (Jordan, 1985), brackish water deposits (Hakes, 1985; Pienkowski, 1985), abyssal deposits (Fillion and Pickerill, 1984) and more commonly, shallow, normal marine intertidal to subtidal deposits (Fillion and Pickerill, 1984). The *Teichichnus* traces observed in this study are present within an apparent shallow shelf, normal marine environment that is dominated by storm processes (*e.g.* Lower Grammia Member).

4.3 n) Ichnogenus *Thalassinoides* Ehrenberg, 1944

Type Species

Thalassinoides callianassae (Haentzschel, 1975).

Diagnosis

Large burrow systems consisting of smooth-walled, essentially cylindrical components. Branches are Y - to T-shaped and are enlarged at the points of bifurcation. Burrow dimensions may vary within a given burrow system and systems can be horizontal or irregularly inclined. (Pemberton and Frey, 1984) (Figure 16B), Plate 61A,B))

Description

Burrows are robust 1-2 cm in diameter, circular to ovate in cross-section, with length varying 1 cm to 10 cm. Traces cut across what appears to be relict bedding surfaces. *Thalassinoides* weathers up out of samples easily and clearly illustrates the Y-shaped junction with the slightly enlarged point of bifurcation. Surface ornamentation is absent. This burrow is associated with the bioturbated storm influenced beds of the Upper and Lower Graminia Members at South Cardinal Pass and North Cardinal Pass Section 1 (Plate 61B))

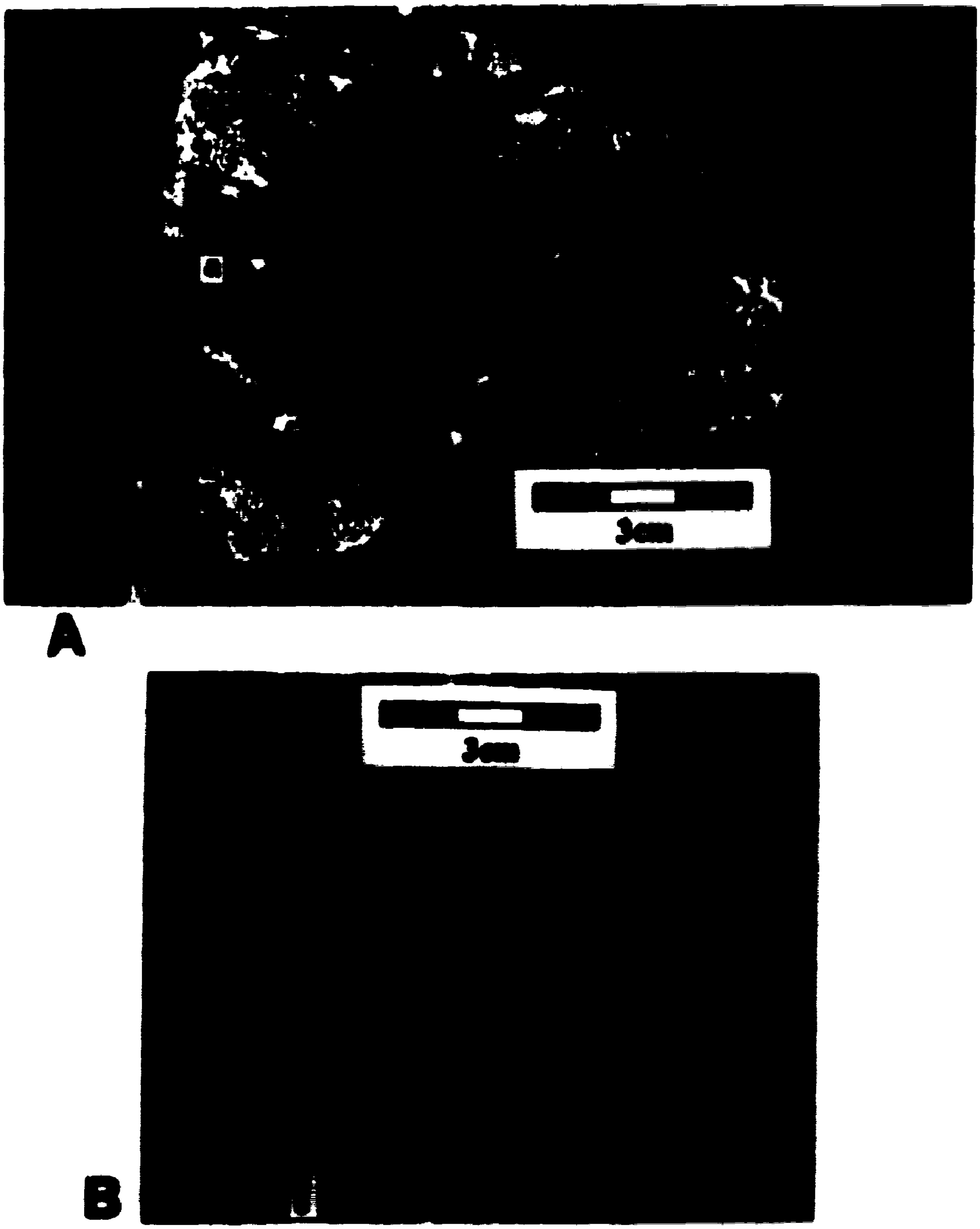
Stratigraphic Range

Thalassinoides is known from Devonian to Quaternary strata (Haentzschel, 1975)

Discussion

Thalassinoides is preserved as domichnion and/or fodichnion in full relief and in convex hyporelief, (Pemberton and Frey, 1984). The most spectacular specimens were preserved as the only visible traces within an otherwise completely churned sediment in the Upper and Lower Graminia silts and sands (Plate 61B)). No burrow lining was visible.

Thalassinoides is generally regarded to be the dwelling and/or feeding burrow of decapod crustaceans, particularly callianassid or thalassinidean shrimp, (Pemberton and Frey, 1984; Bromley and Frey, 1974). These assumptions are based on the morphological characteristics of the trace and on comparisons between recent and ancient examples. Several authors have reported the presence of crustaceans within *Thalassinoides* burrow systems. These include: Fursich, (1974), Bromley and Asgaard, (1972), and Sellwood



A

B

Plate 61. A) Intensely burrowed Upper Graminia Member siltstone. Section SCP. a) *Thalassinoides*.

B) Intensely burrowed Upper Graminia Member siltstone. Section SCP. a) high relief *Thalassinoides* burrow.

(1971). In modern settings, callianassid shrimp create burrows similar to the *Thalassinoides* ichnofossil. (Bromley, 1990; Howard and Frey, 1975)

Individual Y-junctions of the *Thalassinoides* burrow system are enlarged at the point of bifurcation. These swellings correspond to the point within the burrow system where the trace-making organism was able to turn around. (Bottjer, 1985; Haentzschel, 1975)

Burrow morphology of the collected specimens does not unequivocally suggest specific feeding strategies for the *Thalassinoides* trace-makers of this study. However, suspension feeding and deposit feeding are both utilized by modern shrimp, analogous to the *Thalassinoides* trace-maker. (Bottjer, 1985). In the case of suspension feeders the burrow system is utilized for protection and as a dwelling structure from which food gathering apparatus is extended. Deposit feeders separate and ingest organic material from the sediment excavated during burrow construction. (Bottjer, 1985)

When taken in conjunction with sedimentological evidence, the environment of formation for *Thalassinoides*, in this study appears to be within a storm-dominated shallow shelf. Erosional truncation of the bioturbated beds containing *Thalassinoides* burrows also illustrates the catastrophic nature of the depositional system. The size and abundance of ichnofossils suggests a normal marine, well oxygenated sedimentary environment capable of sustaining large numbers of infauna.

4.4 Miscellaneous Ichnofossils

Several biological structures and textures not assigned to an ichnogenus have been identified. These include escape structures, bioturbate texture, heavily concentrated pellet structures and indistinct burrows not readily assigned to a particular ichnogenus.

4.5 Escape Traces

Escape traces (fugichnia) are commonly preserved in the complete form, especially within rapidly aggraded substrates (Figure 17, Plate 62A)). Recognition of a singular escape structure includes several necessary criteria which include: internal laminae either in echelon or as nested funnels or chevrons, internal U-in-U spreite and any structures reflecting the displacement of sediment by an organism as it moves upward or downward with respect to the original substrate surface, down-warped laminae with a uniform dip (Frey and Pemberton, 1984).

Non-biogenic collapse structures are distinguished from fugichnia by an upward decreasing downward dip of adjacent laminae, the association with flame structures, sedimentary dikes and rhizoliths, (Kamola, 1984), and collapse structures are generally filled with laterally adjacent sedimentary material.

Escape structures are ordinarily made by organisms that live at specific depths within the substrate. The organisms must therefore maintain a constant spatial relationship with the sediment surface despite sudden influxes of sediment, sudden erosional events (storms), rapid environmental changes, or abrupt movement of the organism to a hostile environment, (Frey and Pemberton, 1984). In an effort to maintain this spatial relationship with the sediment surface, the organism will create short bursts of locomotion in the desired direction.

Rapidly aggrading storm deposits common to the Upper and Lower Graminia Members at Mount Mackenzie, South Cardinal Pass, and North Cardinal Pass all have indications of escape traces. Plate 62A) illustrates an escape structure gradationally associated with a *Lockeia* trace at Mount Mackenzie within the Upper Graminia Member. In this example the probable producer of the escape trace was a bivalve. However, the majority of the fugichnia observed had no associated traces. The absence of any

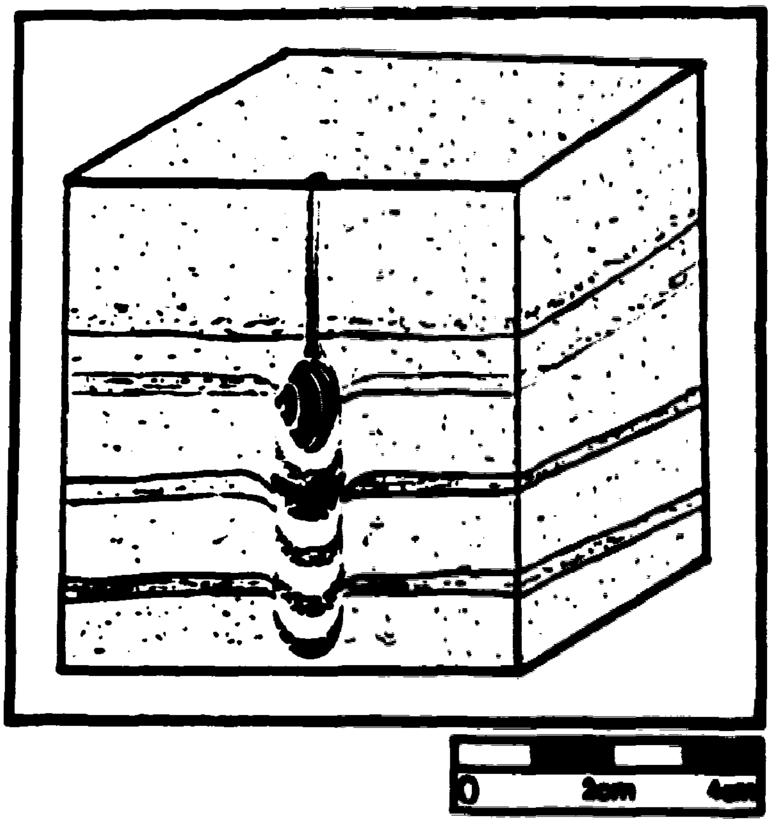


Figure 17. Schematic block diagram of an escape trace preserved in an interbedded sandy and muddy substrate. The resting trace *Lockeia* is present at or near the top of the escape structure.

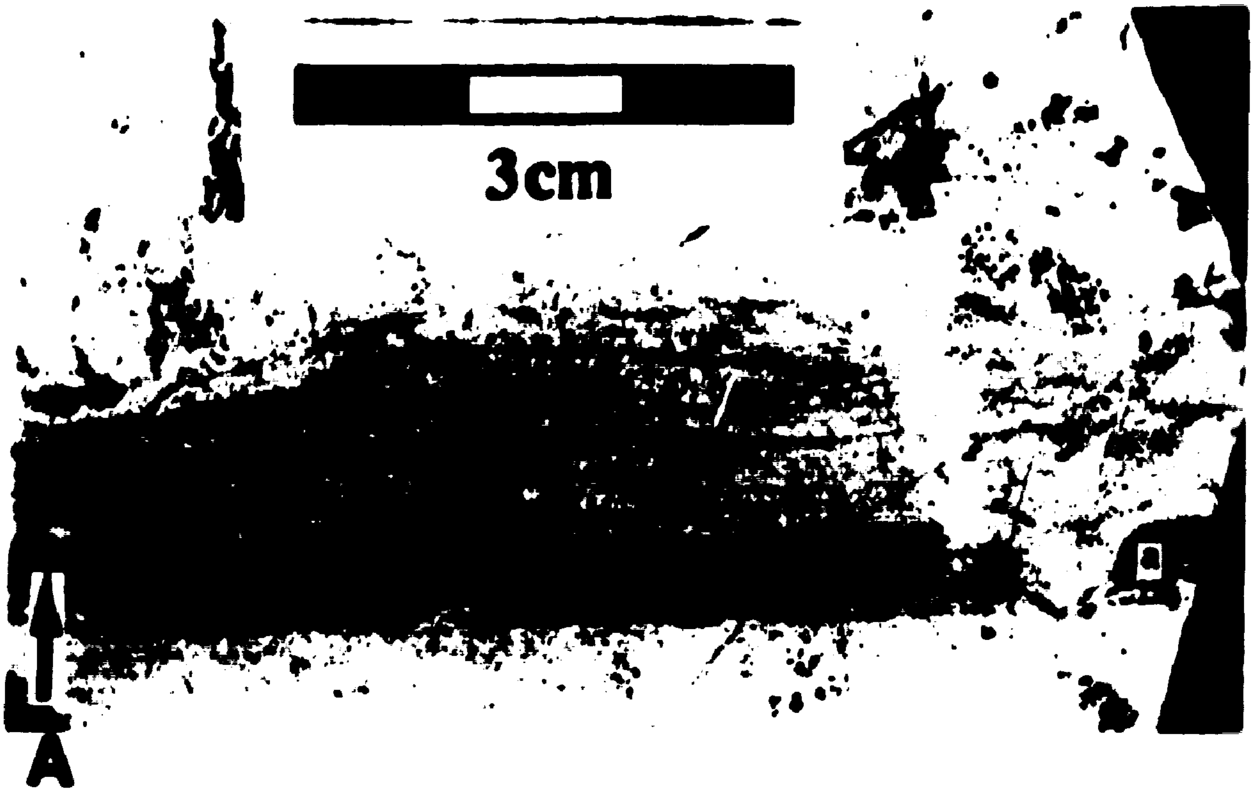


Plate 62. A) Thin Blue Ridge Member silty storm bed within a massive carbonate mud. Section MM-2. a) escape trace and associated *Lockeia*.
B) Intensely burrowed Lower Grammia Member siltstone. Section SCP.

associated ichnofossils may reflect the inability of the escaping organisms to overcome the sediment influxes, ultimately resulting in the organism's demise.

The formation of escape structures within the Grammia Formation appears to have been in response to rapid influxes of sediment during catastrophic events. Life activities in the normal marine shallow shelf environment were disrupted and then re-established following rapid readjustment by the trace-making organism.

4.6 Bioturbate Texture

Complete churning of the sediments through the action of infauna is common within the storm-dominated Upper and Lower Grammia Members. In all instances the upper portions of the storm beds were burrowed and all sedimentological structures obliterated. Preserved ichnofossils were also rare from these intervals. It appears likely that several groups of biota populated each storm bed between major catastrophic events. As a result of the activities of burrowing organisms within relatively thin storm beds, several ichnogenera were imprinted on the sediment. The biological texture resulting from this high degree of infaunal activity is a completely churned sediment with few specific recognisable traces (Plate 62B) (Frey and Pemberton, 1991).

4.7 Pelleted Muds

The Blue Ridge Member of the Grammia Formation is predominantly carbonate mudstone with rare body fossils and a relatively small percentage (<10%) of silt sized clastic material. Within this member, trace fossils were rarely documented. Traces present include *Monocraterion*, *Skolithos*, and *Lockeia*.

Pellets are defined as "ovoid particles of sediment, commonly composed of only calcium carbonate, which range up to 5 mm in diameter..." (Brooks and Whitten, 1975). They are generally considered to represent fossilised faecal material resulting from the excretory process of a wide variety of invertebrate animals. As a representation of this life activity, most pellets are considered trace fossils. (Pemberton *et al.*, 1992; Ekdale *et al.*, 1984; Pemberton and Frey, 1982)

Pellet-like structures were visible throughout the Blue Ridge Member as discreet singular pellets and groups or patches of densely packed pellets up to 30 mm in diameter (Plate 27B)). Individual pellets were generally less than 5mm and averaged approximately 1-2mm in diameter. No specific structures were visible within individual pellets, nor in any of the areas where the concentration of pellets was high. These areas of high pellet concentration may represent areas of high infaunal density. However, this remains problematic due to the lack of any body fossil or ichnofossil evidence.

4.8 Indistinct Structures

Several bedding plane structures were observed that were not readily assignable to any of the previously identified biological or sedimentological features. These structures were generally present within the storm-dominated Upper and Lower Graminia Members. The morphological characteristics of these features very widely and include indistinct, "trough-like " structures up to 5cm in length and 1cm in depth with no apparent repetition. They may represent surface structures as storm induced currents dragged material over a semi-consolidated surface. In this case, these would be classified as tool marks and are not considered trace fossils.

4.9 Summary

The ichnofacies concept involves the grouping of characteristic ichnofossils into recurring ichnofacies. Ichnofacies reflect adaptations of tracemaking organisms to changing environmental factors. Water salinity, food supply, substrate consistency, hydrodynamic energy, water turbidity, temperature, and sedimentation rate develop environmental scenarios to which resident biota must adapt. Nine ichnofacies are recognized and are named for a representative ichnogenus (Pemberton *et al.*, 1992) Recognized ichnofacies include: *Scoyenia*, *Trypanites*, *Teredolites*, *Glossifungites*, *Psilonichnus*, *Skolithos*, *Cruziana*, *Zoophycos*, and *Nereites*

The trace fossil suite within the Grammia Formation of the study area is a storm influenced mixed *Skolithos-Cruziana* ichnocoenose with a resident *Cruziana* ichnocoenose (Pemberton *et al.*, 1992; Frey, 1990; Vossler and Pemberton, 1988) Pemberton *et al.*, (1992) suggest that these two ichnofacies are distributed according to numerous environmental conditions and the representative trace fossils may occur in other environments. Conversely, these two ichnofacies may contain trace fossils not typically found within their environmental niches.

The *Skolithos* ichnofacies develops within slightly muddy to clean, well-sorted, loose or shifting particulate substrates. Formation of the *Skolithos* ichnocoenose represents relatively high levels of wave or current energy. Most trace fossils found within the *Skolithos* ichnofacies are created by suspension feeder and are permanent domiciles (Pemberton *et al.*, 1992). Figure 18 is representative of the *Skolithos* ichnofacies which is characterised by: 1) predominantly vertical, cylindrical, or U-shaped burrows, 2) protrusive and retrusive spreiten in some burrows, which develop in response to sediment aggradation or degradation, 3) few horizontal structures, 4) few structures produced by mobile organisms, 5) low diversity, and 6) mostly dwelling burrows constructed by suspension feeders or passive carnivores (Pemberton *et al.*, 1992)

Subtidal, poorly sorted and unconsolidated substrates characterise the *Cruziana* ichnofacies. Formation of the *Cruziana* ichnocoenose represents moderate energy levels below fair weather wave base but above storm wave base to low energy levels in deeper quieter waters. Both suspension feeders and deposit feeders create the trace fossils found within the *Cruziana* ichnofacies. Figure 19 is representative of the *Cruziana*

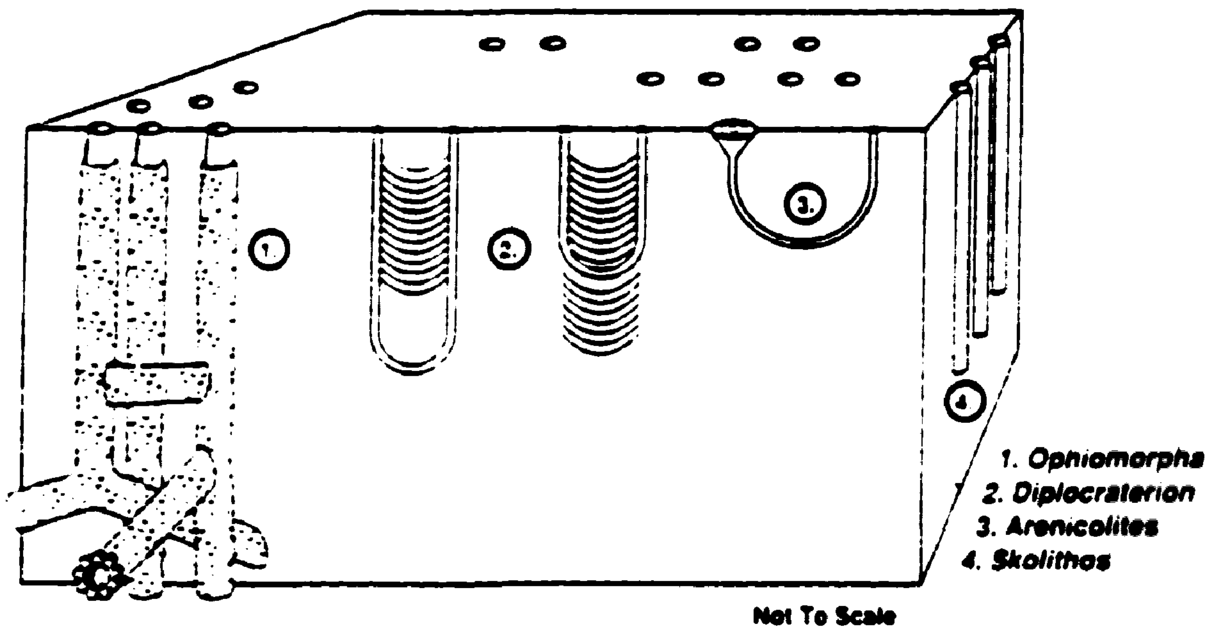


Figure 18. Schematic block diagram illustrating the trace fossil association characteristic of the *Skolithos* ichnofacies (after Pemberton *et al.* 1992)

ichnofacies which is characterised by 1) mixed associations of vertical, inclined and horizontal structures, 2) the presence of structures constructed by mobile organisms, 3) generally high diversity and abundance, and 4) mostly feeding and grazing structures constructed by deposit feeders (Pemberton *et al.*, 1992)

Skolithos, *Arenicolites*, and rare *Polykladichnus* characterise the upper portions of storm deposited siltstones within the Upper and Lower Grammia Members (Plate 54) These trace fossils represent the dwelling burrows of the suspension feeding organisms responsible for recolonisation of the substrate following a storm event (Frey, 1990, Vossler and Pemberton, 1988) Subsequent infestation by resident biota overprints fair weather trace fossils on the opportunistic suite (Plates 60B) and 62B))

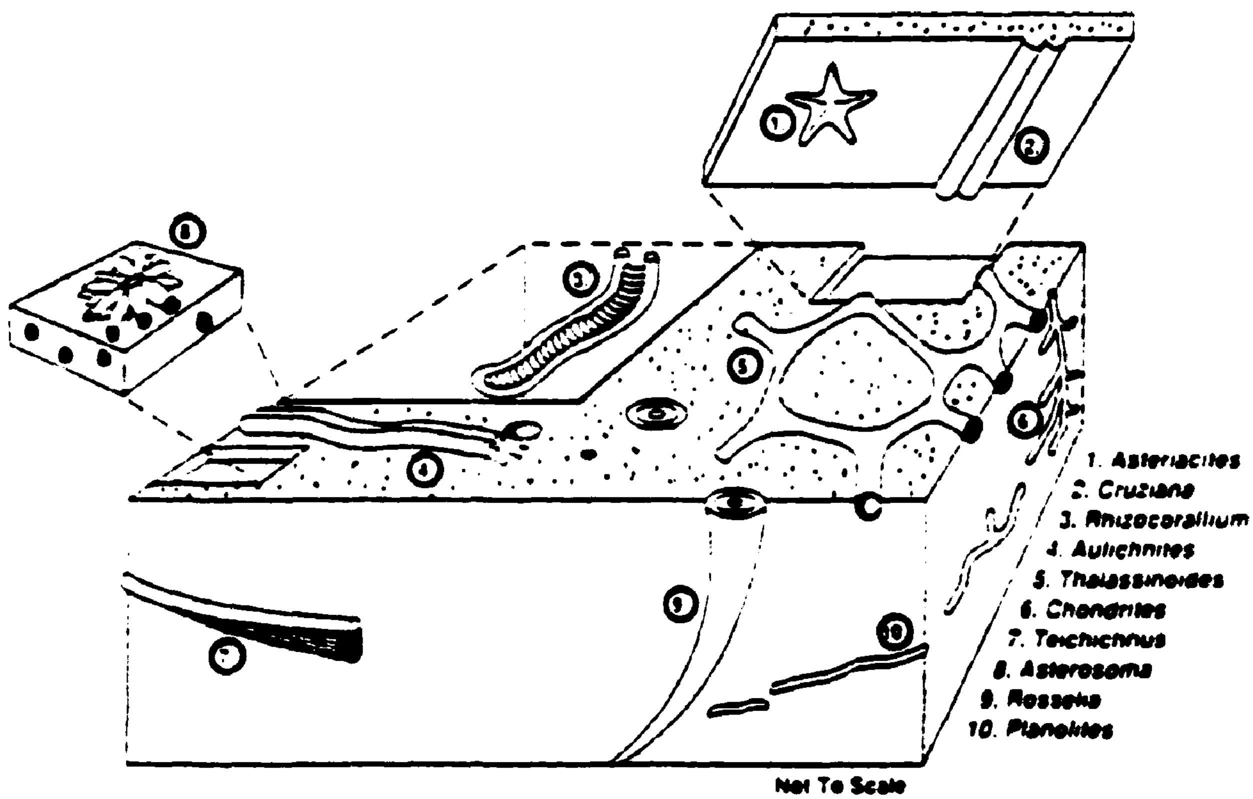


Figure 19. Schematic block diagram illustrating the trace fossil association characteristic of the *Cruziana* ichnofacies (after Pemberton *et al* 1992)

5.0 Conclusions

Figure 8 schematically represents the depositional stages of the Gramimia Formation and associated facies.

1) The Graminia Formation in the Mountain Park region consists of three platform members and their basinal equivalents. These include Platform Lower Graminia Member/Calmar Formation, Blue Ridge Member, and Upper Graminia Member. Basin Lower Graminia Member ("Silt Doublet"), Blue Ridge Basinal Basinal Member, and Upper Graminia Member.

2) Calmar Formation clays contain thin interbeds of cross-stratified siltstone that represent storm deposition on the platform at Lower Graminia Member time. Siliceous silts dominate the siliciclastic portion of the the cross-stratified interbeds with minor amounts (<2%) of feldspar. Cambrian, Ordovician, and Silurian aged beds on the West Alberta Ridge may have supplied the Jasper basin in the study area with siliciclastics. The "Silt Doublet" represents basinal Lower Graminia Member deposition and is correlative with the Calmar Formation.

3) The Lower Graminia Member "Silt Doublet" is a paired set of storm deposits. A preferentially weathered series of interbedded hummocky bedded and bioturbated siltstones characterise basinal Lower Graminia Member deposition in the North Cardinal Pass area. The hummocky bedded units are prominent and represent the visible "Silt Doublet" beds. The bioturbated beds are recessive and represent intense biological activity following storm cessation. Relief and exposure of the Arcs/Grotto platform margin prevented deposition at Lower Graminia Member time.

4) Blue Ridge Member deposition on the platform is carbonate-dominated with periodic inundations of storm-driven siliciclastic material. Carbonate deposition on the platform was not drowned by siliciclastic input and resumed following cessation of storm activity. Siliceous and feldspathic silts dominate the siliciclastic portion of the the storm deposited interbeds. Fossiliferous and pelleted packstones to grainstones dominate carbonate deposition on the platform. Blue Ridge Basinal Member deposition is characterised by calcareous mudstones to wackestones and is correlative with upper Mount Hawk Formation deposition. Blue Ridge Basinal Member deposition includes development of an off-bank carbonate mound that was partially lithified shortly after deposition.

5) Storm-dominated siltstones characterise the Upper Grammia Member which is correlative with the Sassenach Formation. Clastic input onto the platform at Upper Grammia time drowned carbonate deposition. Interbedded hummocky cross-stratified and bioturbated siltstones represent cyclical storm activity affecting the platform and basinal regions of the study area.

6) Trace fossils are common throughout the Grammia Formation and are visibly abundant within the bioturbated interbeds of the Upper and Lower Grammia Members. The resident trace fossil suite within the Grammia Formation of the study area is a storm influenced mixed *Skolithos-Cruziana* ichnocoenose with a resident *Cruziana* ichnocoenose.

7) *Polykladichnus* is described within the Famennian aged Upper Grammia Member which represents the stratigraphically oldest documented occurrence of this trace fossil to date.

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Legend

Ichnofossils

- rootlets
- *Skolithos*
- *Monocraterion*
- *Planolites*
- *Palaeophycus*
- *Polykladichnus*
- Escape Trace
- *Arenicolites*
- *Lockeia*
- *Bergaueria*
- *Dactyloidites*
- *Thalassinoides*
- *Chondrites*
- *Teichichnus*

Physical Structures

- horizontal planar lamination
- low angle planar lamination
- hummocky cross-stratification
- churned or chaotic bedding
- fault

Fossils

- Stromatoporoids
- Brachiopods
- Bryozoans
- Calcispheres
- Corals, colonial
- Corals, solitary
- Gastropods
- Bivalves
- Rudists, undiff

Lithologic Modifiers

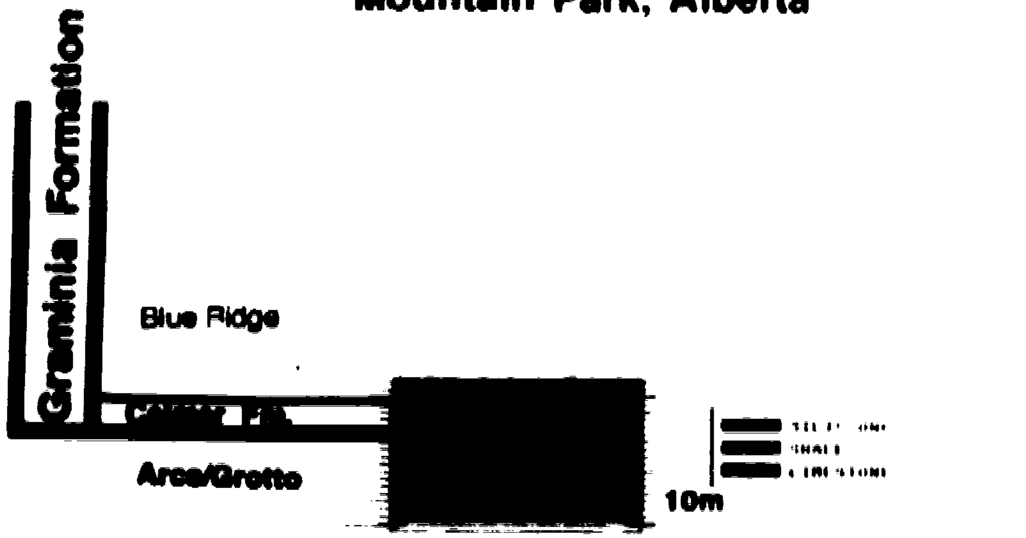
- sand lamina
- silt lamina
- shale lamina
- calcareous
- dolomitic
- smectite
- rip-up clasts
- shell fragments
- oolitic

Appendix 1

Section TC-1

Toma Creek

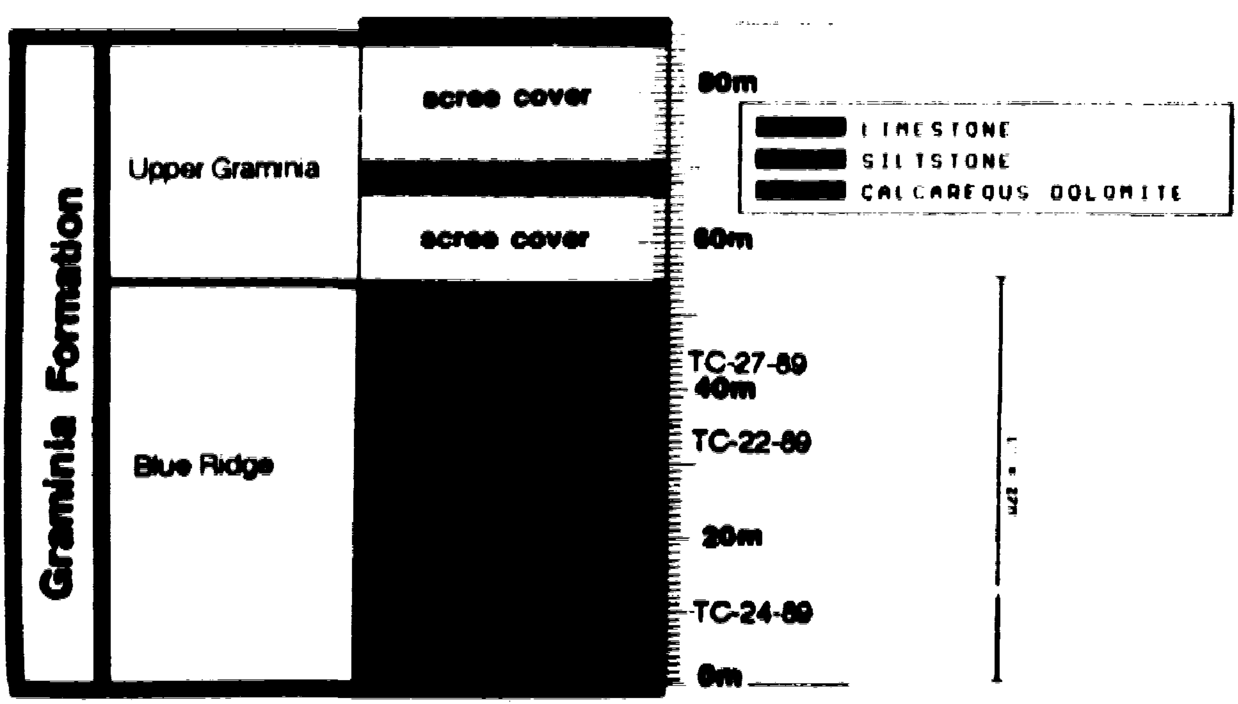
Mountain Park, Alberta



Section TC-2

Toma Creek

Mountain Park, Alberta



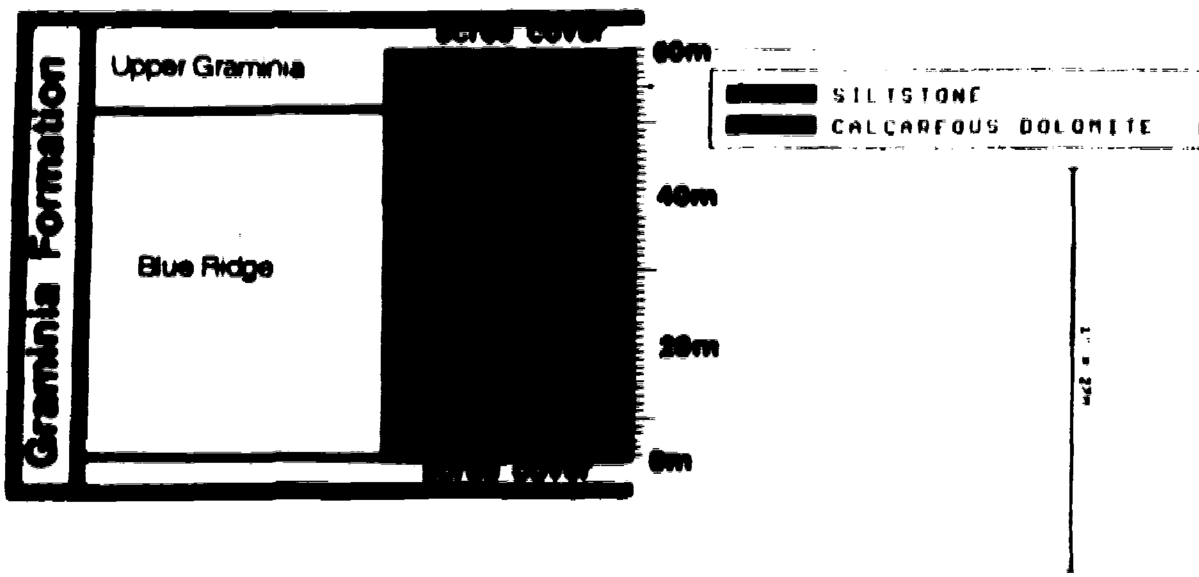
Section MM-1

Mount Mackenzie
Mountain Park, Alberta

Section MM-2

Mount Mackenzie

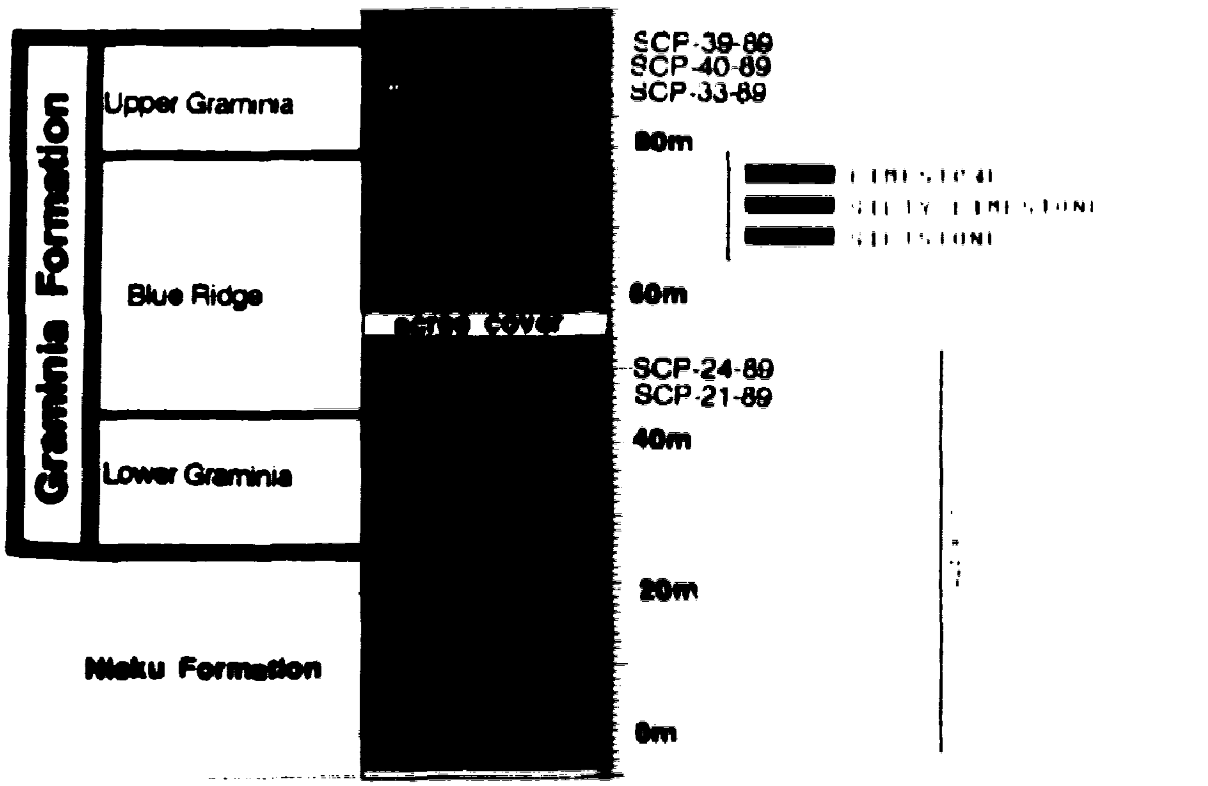
Mountain Park, Alberta



Section SCP

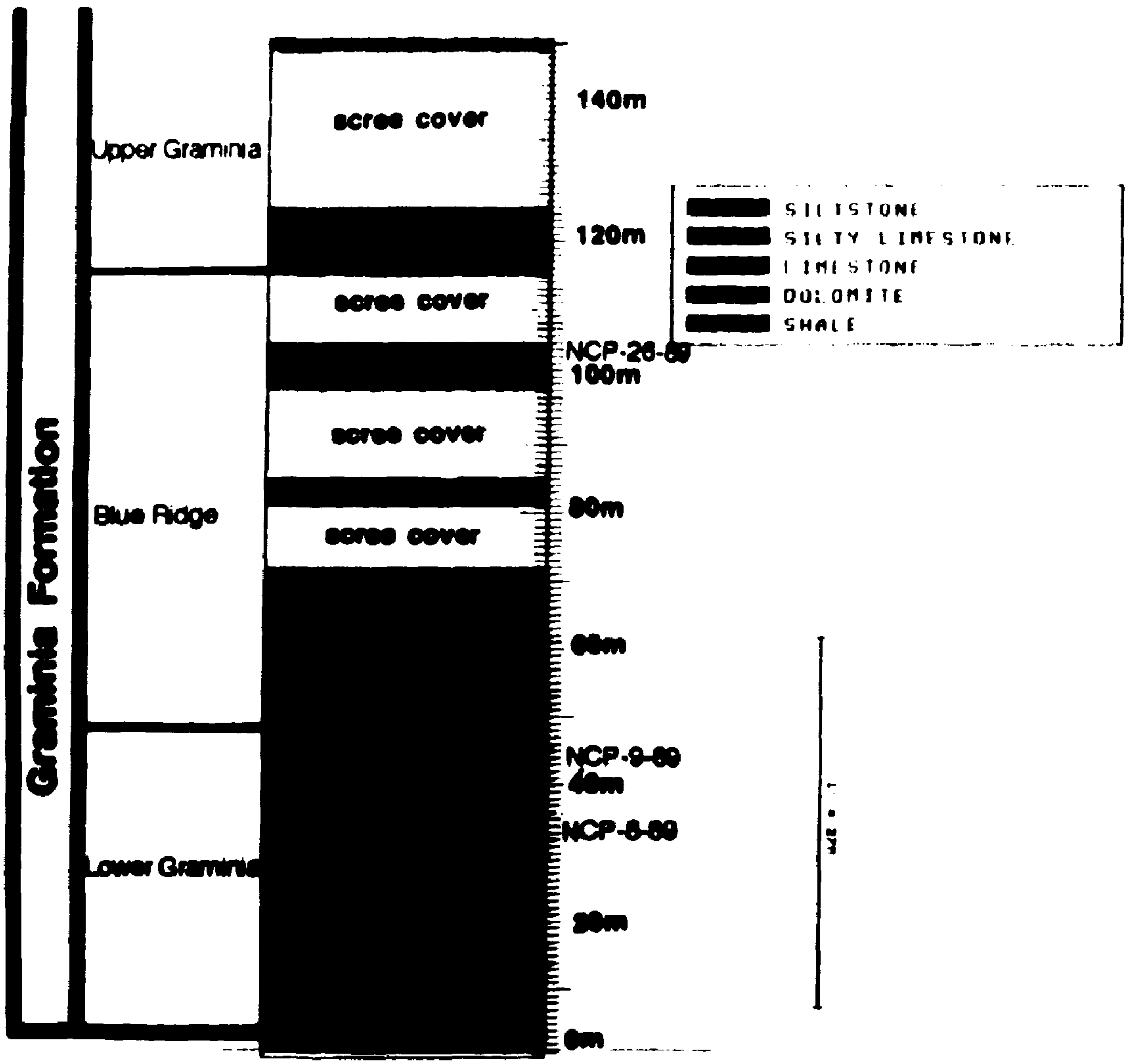
South Cardinal Pass

Mountain Park, Alberta



Section NCP-1

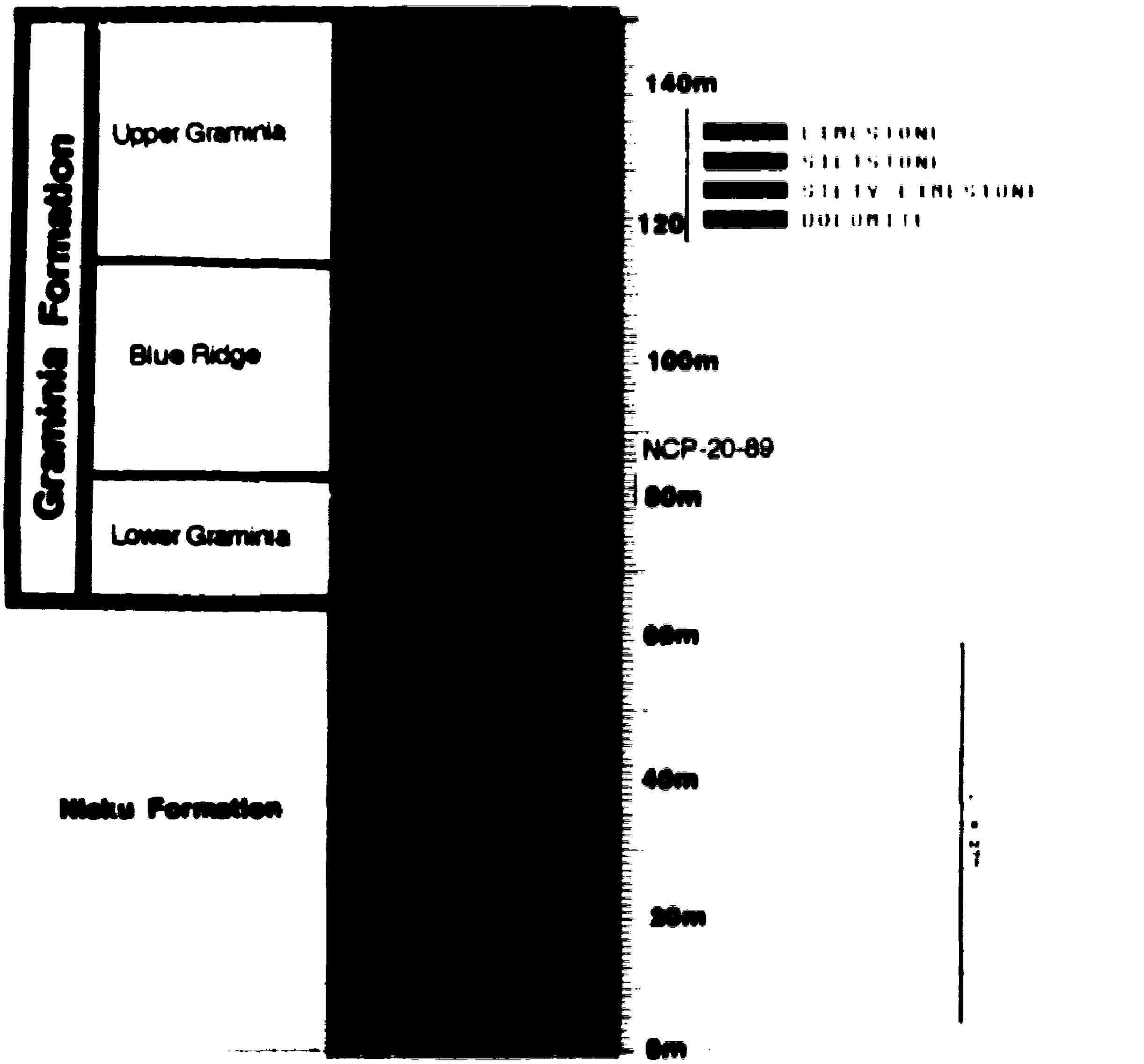
North Cardinal Pass
Mountain Park, Alberta



Section NCP-2

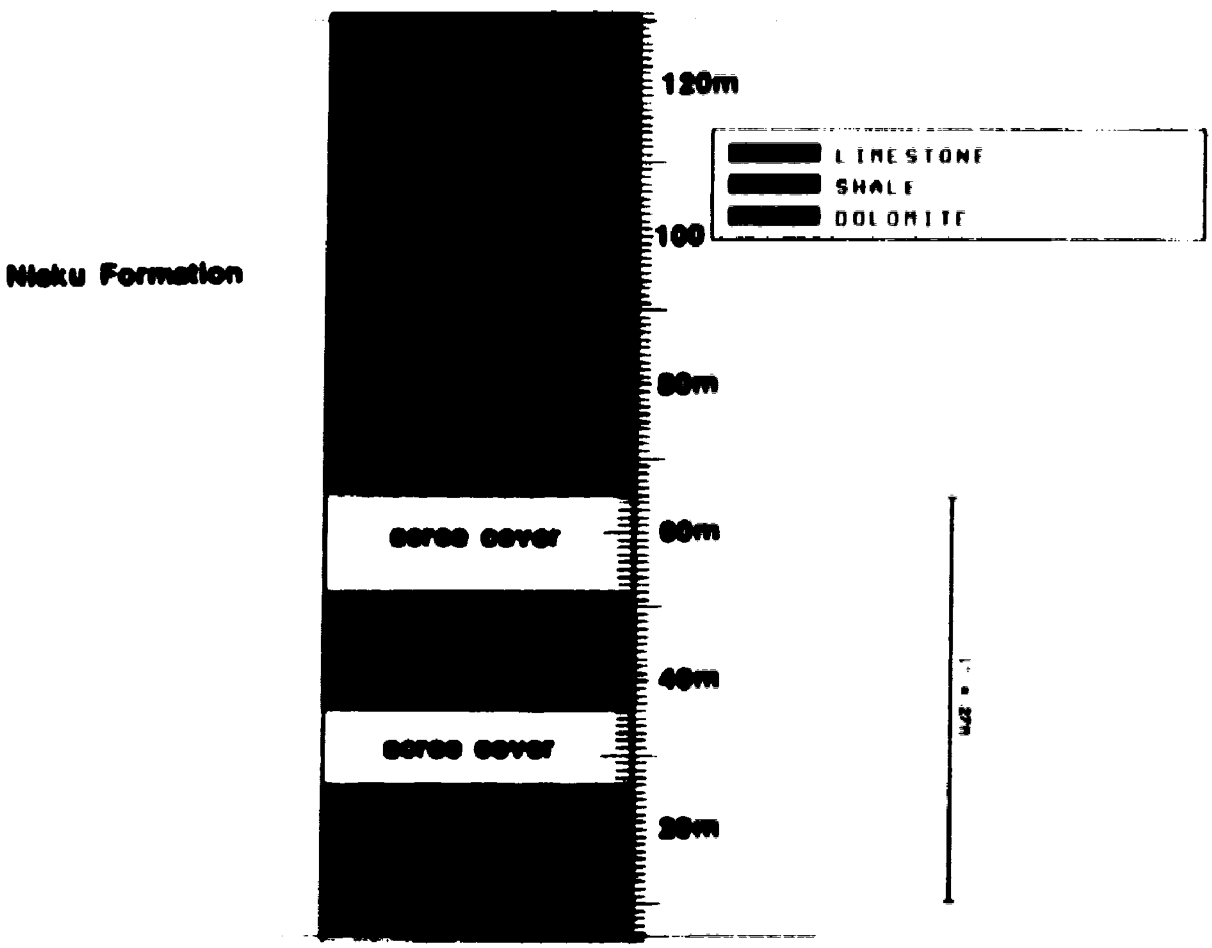
North Cardinal Pass

Mountain Park, Alberta



Section CH-1

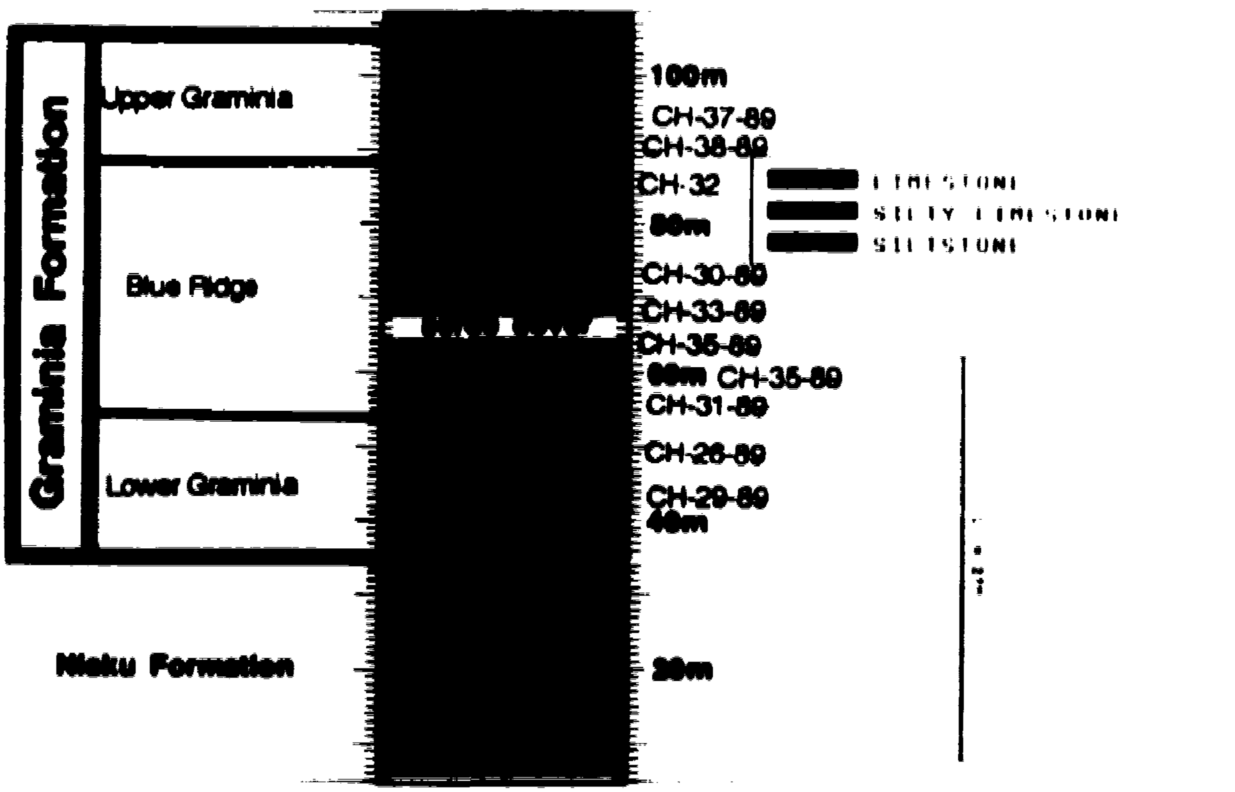
Cardinal Headwaters
Mountain Park, Alberta



Section CH-2

Cardinal Headwaters

Mountain Park, Alberta



Appendix 2

TOMA CREEK SECTION 1 (TC-1)

0 m - 13 m: Cairn Prominent

- dark grey to black, medium to fine crystalline dolomite.
- quarter sized vugs.
- banding at 4.5 m
- stromatoporoid-like material at 7.5-8.5.
- highly fossiliferous 120 m - large % of stromatoporoids.
- sharp upper contact with Peechee member.

13 m - 55 m: Peechee Prominent

- white to light cream dolomite limestone limey dolomite.
- 5-10% large vugs.
- rusty (limonite) at approximately 50 m - 10-15 m basinward.
- interfingers with overlying unit - basinward.
- fairly sharp upper contact.

55 m - 102 m: Prominent

- dark/black weathered rock - brown - cream on fresh limey dolomite.
- large calcite replace fossils (patches).
- 15% vugs near lower contact (up to 30 cm).
- 2-3% vugs up section.
- rusty (limonitic) zones or patches throughout.
- basinward at 50 m - Peechee appears to return as contact wanders
- large patches of crystalline calcite roughly parallel to bedding at 75 m.
- patches of lightly (more coarsely crystalline) colored to rusty throughout (<2%)
- sharp upper contact - 2-4 cm rusty zone - abundant calcite at boundary.

102 m - 151.5 m

- more recessive unit, but still prominent.
- sharp lower contact.
- 5 cm thick brecciated zone at contact.
- highly fossiliferous wackestone/packstone near contact (1-15 m) dolomite

- brachiopods, crinoids, bryozoans, corals, algae?
- matrix of dark mud - dolomite, limestones/limey dolomite.
- vugs 1-2%.
- fossils decrease up section.
- at 104 m - 20 cm zone where vugs are up to 40% of rock.

105 m - 115 m: Scree

- distinct zones where vugs increase to approximately 30% - 5-10 cm thick.
- limonitic staining (<2%).
- fossil percentage decreases to approximately 5% at 120 m - vugs and coarse calcite continue.
- fossil percentage increases at 126 m to 10-15% - vugs decrease to 1-2%.
- 126 m - 134 m - several lighter colored zones without vugs - crosscut bedding.
- resembles Peechee (dolomitic limestone).
- 136 m - return to vuggy darker weathered rock.

151.5 m - 152.5 m: Prominent

- material is brecciated limestone and shows good angularity.
- appears silicified.
- fragments of corals, brachiopods, crinoids, etc.
- breccia fragmented from 1-2 mm - 10-20 mm.
- sharp upper contact.

152.5 m - 168 m: Rel. Prominent

- medium-dark weathering rock, cream on fresh surface - limestone.
- weathers platy.
- slightly silty dolomitic mud.
- fossil percentage 2-3% - large branching corals. Weathered out - brachiopods and pelecypods - infilled with calcite.
- fossil percentage may be higher but difficult to see on surface.
- at 154 m - 156 m - dark fossiliferous mud wackestones.
- patches up to 1 m x 3 m of this material common throughout.

168 m - 169.5 m: Relatively

- prominent.
- light cream colored weathering, lightly silty limey sandstones.
- no fossils.

169.5 m - 170.7 m: Prominent

- cream colored.
- relatively high percentage of silt.
- many small (2-3 mm) vugs.
- limonitic stain (<5%).
- finely laminated (1-2 mm).

170.7 m - 175.5 m: Less Prominent

- slightly silty limey mudstone.
- thin 2-3 cm lenses (beds) of grey limey mudstone.
- mud bands completely destroyed by weathering (very recessive).

175.5 m - 175.9 m: Recessive

- 40 cm band of fine grained silty carbonate mud.
- limey.

175.9 m - 176.3 m: Prominent

- fine grained limey mudstone.
- structures on surface?
- red/pink staining in rock.
- unit "sinks" into lower mud.

176.3 m - 176.5 m

- recessive mud.
- limey.

176.5 m - 179.0 m: Prominent

- fossiliferous lime mudstone.
- rusty surface - from above unit.

179.0 m - ?: More Prominent Unit - overhangs underlying unit.

- approximately 179.5 m - shows staining.
- possibly silicified.
- limey.

TOMA CREEK SECTION 2 (TC-2)

Base Lower Silt Member = 0 m

0 m - 2 m: Scree

- at 0 m (base of Scree) - Arca/Grotto/Members - Sou"heast Formation

2.- m - 3.5 m: Relatively Prominent

- rusty limonite stain on weathered surface.
- cream - brown on fresh surface.
- finely laminated limestone.
- biologically traces (possibly burrows) on bedding surface.
- silt - fine sand.
- minor secondary carbonate.

3.5 m - 4.2 m

- fairly prominent.
- no laminae - dolomitic limestone.
- no visible fossils.
- at 3.5 m - then (1/2 cm) recessive rusty shaly unit.

4.2 m - 6.0 m

- silt/sand as above w/rust.
- grain size of sand changes rhythmically every 10-15 cm.

6.0 m - 6.5 m: Relatively Recessive

- heavily altered mud/siltstone.
- appears heavily biologically altered.

6.5 m - 7.5 m: Relatively Prominent

- laminated silt/sandstone with dolomite interbeds on scale 2-3 cm.

7.5 m - 9.0 m: Relatively Prominent

- laminated silty carbonate mud (2-3.5 m).

9.0 m - 9.4 m: Prominent

- light weathered carbonate unit.
- rough weathered surface.

9.4 m - 9.5 m: Relatively Recessive

- silty/sandy unit approximately 10 cm thick.
- pinches and swells shelfward and basinward.
- no laminae.

9.5 m - 10.0 m: Relatively Recessive

- light weathered carbonate (lime) unit.
- small vugs and sharp weathered up surfaces.
- possible pelletized packestone/grainstone.

10.0 m - 12.5 m: More Recessive

- silt/sand lime mudstone.

12.5 m - 59.5 m: Blueridge Member

- highly prominent unit.
- first 1/2 meter is silty/sandy.
- light weathering material with sharp weathered up material.
- 14.5 m - 15.3 m - unit becomes dense and siliceous looking.
- 15.3 m - 15.7 m- rusty surface weathering (limonite) red, hematitic stain on fresh.
- silty carbonate - bedding increases.
- 15.7 m - 16.2 m - return to sharply weathered material as above.
- 16.2 - 17.5 m - silty carbonate unit returns as 15.3 m - 15.7 m.
- silty unit is very recessive compared to carbonate unit.
- organism at 16.5 m - shows large vertical and smaller horizontal structures.
- 17.5 - 20.5 m prominent.
- light weathered limey carbonate - massive and lacks fossils.
- 20.5 - 21.0 m - silty unit with limonite and hematite stain.

- slightly recessive pinches - swells basinward.
- 21.0 - 23.5 m - massive grey, evenly weathering unit with sandy/grainy beds up to 3.0 cm thick.
- with white/cream colored specks (pellets?).
- grainy/sandy beds recessive.
- areas with relatively high percentage of fossils - corals, brachiopods.
- upper contact of this zone marked by 3 cm silty/sandy beds (continuous up and down strike) - just above fossiliferous zone.
- 23.5 - 29.7 m - light grey - sharply weathering up limey material - prominent.
- 29.0 - 29.4 m - finer grained/dense unit - gradational.
- 29.7 - 34.5 m - light medium grey roughly (sharply) weathered surface - organisms and possible bioturbation shows up on weathered surface.
- slightly less prominent.
- 34.5 - 53.5 m - lighter - slightly more prominent unit.
- visible evidence of biological alteration decreased.
- large *megalodont* and *bivalves* on bedding surface at approximately 37.0 m.
- at approximately 38.5 - 40.0 m, biological structures in zones approximately 10 cm thick alternating with more massive material. Relatively prominent.
- at 46.0 - 48 m - 10-20 cm zones of biologically altered material.
- at 54 m - 54.1 m unit has 10 cm bed of finely laminated silty/sandy material.
- 54.5 - 55.5 - silty unit.
- bedding/laminae - cross-bedding.
- no visible biological activity.
- rusty (limonite) stain on weathered surface.
- 55.5 - 59.5 m - increased biological activity of fossils.
- rare (<5%) thin (2-5 cm) silty bedded material.
- slight increase in biological activity.
- fossils and biological evidence decrease and nearly disappear within 1/2 m on top.
- 10-15 m basinward unit becomes more silty and muddier and decreases in biological activity.

59.5 - 60.0 m

- generally quite recessive and disappears up section into scree.
- brownish limey mud.

- vugs - 5% - stylolites (with rust) (top Blue Ridge Member) or base Sassenach Formation.

60.0 - 66.0 m

- Scree and snow.

66.0 - 69.5 m

- relatively recessive compared to Blue Ridge Member but more prominent than previous scree zone.
- silt/sandstone - only secondary limestone.
- rusty weathering surface.
- minor laminae and/or bedding visible - otherwise generally massive.
- 10-15 cm zones where grain size of large fragments increases at 69.0 m rock becomes fine sand with biological activity.
- good sharp upper contact with Palliser - contact meander.

Palliser at 69.5 m

MT. MACKENZIE SECTION 1 (MM-1)

- *Graminia has been faulted and folded in this area making measurement of a full, true thickness section difficult.*
- The NW shoulder of Mt. MacKenzie was inaccessible to the Blue Ridge Member and lower Graminia silts.
- The section shown here is a rough work of what was present.
- A wedge of sand was mapped for the lower silt member the folded Blue Ridge member along a scree pile was measured; then the Sassenach was measured as several meters of scree just beneath the cliff forming rocks of the Palliser Formation.

0 - 19.5 m

- sharp contact with Arcs = 0 m.
- tan and black mottled carbonate mudstone - dark on fresh.
- up to 5 cm of fine laminae.
- remainder of unit appears massive except for prominent biological activity.
- rare fossils, corals, bryozoanss-ramose.

At approximately 3.0 m

- unit becomes bedded - shown by light and dark material.
- bedding planes not distinct due to biological activity.
- lower silt unit resembles biological altered unit at NCP Section 1 and upper unit resembles silty unit at NCP.
- these 2 units alternate on a scale of 1-2 m of 5-6 m.
- bryozoans in dark rock at approximately 5.5 m
- increase calcite content as move up section - little or none at 1-2 m sample etc.
- quite noticeable at approximately 6.0 m.
- limestone units are prominent as compared to non-limey units which are more recessive.

At 10.5 m

- unit becomes crudely bedded and fossil content increases including corals, bryozoans, bivalves.

At approximately 13 m

- unit begins to resemble silt unit at NCP.

At 16.5 m

- run into fault running approximately parallel to bed.
- upstrike at 16.5 m unit appears biologically altered as shown by fine sand/silt as light material within dark carbonate matrix.

At 23.0 m

- fault ran up right side of section line.
- cliff face veers upward and becomes nearly vertical.
- estimate total thickness to be 28 m to top of cliff face.

Moved downstrike approximately 50-75 m

- base (0.0 m) is Blue Ridge base.
- approximately 10.0 m of silty carbonate mudstone beneath contact (0.0 m).
- Blue Ridge is intensely altered (folded and faulted) here.

0.0 m

- light colored, sharply weathered surface.
- corals.
- several (approximately 6) pan photos of Mt. MacKenzie show structural complexity.

MT. MACKENZIE SECTION 2 (MM-2)

0 m - 52 m: Blue Ridge Member

- highly prominent unit.
- first 1/2 meter is silty/sandy.
- light weathering material with sharp weathered up material.
- 14.5 m - 15.3 m - unit becomes dense and siliceous looking.
- 15.3 m - 15.7 m- rusty surface weathering (limonite) red, hematitic stain on fresh.
- silty carbonate - bedding increases.
- 15.7 m - 16.2 m - return to sharply weathered material as above.
- 16.2 - 17.5 m - silty carbonate unit returns as 15.3 m - 15.7 m.
- silty unit is very recessive compared to carbonate unit.
- organism at 16.5 m - shows large vertical and smaller horizontal structures.
- 17.5 - 20.5 m prominent.
- light weathered limey carbonate - massive and lacks fossils.
- 20.5 - 21.0 m - silty unit with limonite and hematite stain.
- slightly recessive pinches - swells basinward.
- 21.0 - 23.5 m - massive grey, evenly weathering unit with sandy/grainy beds up to 3.0 cm thick.
- with white/cream colored specks (pellets?).
- grainy/sandy beds recessive.
- areas with relatively high percentage of fossils - corals, brachiopods.
- upper contact of this zone marked by 3 cm silty/sandy beds (continuous up and down strike) - just above fossiliferous zone.
- 23.5 - 29.7 m - light grey - sharply weathering up limey material - prominent.
- 29.0 - 29.4 m - finer grained/dense unit - gradational.
- 29.7 - 34.5 m - light medium grey roughly (sharply) weathered surface - organisms and possible bioturbation shows up on weathered surface.
- slightly less prominent.
- 34.5 - 38.2 m - lighter - slightly more prominent unit.
- visible evidence of biological alteration decreased.

- at approximately 38.5 - 40.0 m, biological structures in zones approximately 10 cm thick alternating with more massive material. Relatively prominent.
- at 38.2 - 41.0 m - 10-20 cm zones of biologically altered material.
- at 41.1 m - 43.0 m unit has 10 cm bed of finely laminated silty/sandy material.
- 43.4 m - 44.4 m - silty unit.
- bedding/laminae - cross-bedding.
- no visible biological activity.
- rusty (limonite) stain on weathered surface.
- 44.4. m - 48.3 m - increased biological activity of fossils.
- rare (<5%) thin (2-5 cm) silty bedded material.
- slight increase in biological activity.
- fossils and biological evidence decrease and nearly disappear within 1/2 m on top.
- 10-15 m basinward unit becomes more silty and muddier and decreases in biological activity.

52.0 m - 53.0 m

- generally quite recessive and disappears up section into scree.
- brownish limey mud.
- vugs - 5% - styloliles (with rust) (top Blue Ridge Member) or base Sassenach Formation.

53.0 m - 66.2 m

- Scree and snow.

66.0 - 69.5 m

- relatively recessive compared to Blue Ridge Member but more prominent than previous scree zone.
- silt/sandstone - only secondary limestone.
- rusty weathering surface.
- minor laminae and/or bedding visible - otherwise generally massive.
- 10-15 cm zones where grain size of large fragments increases at 69.0 m rock becomes fine sand with biological activity.

- trace fossils: *Skolithos, Polykladichnus, Palaeophycus, Chondrites, Planolites, Bergaueria, Dactyloidites*
- physical structures - low angle cross-stratification, soft sediment deformation, hummocky cross stratification.

Palliser at 102.3 m

- after approximately 10 m of scree.

SOUTH CARDINAL PASS (SCP)

0 m - 46.5 m: Prominent

- silty zones of bedding (2-3 cm) up to 20 cm thick.
- lighter colored material (silt) in beds 2-5 cm thick.
- medium grey - tan - irregular/blocky weathered surface.
- grey fresh surface.
- siltstone - no fizz, possibly dolomite.
- oblong patches of light colored silt 5-10 cm long, 2-5 cm wide.
- possible biological.

18.0 - 20.0 m

- more massive, increased grain size to sand - detrital.
- content remains similar.

20.0 m - 23 m

- return to finely laminated silt with mud layers interbedded - up to 1 cm thick.
- this section has rare, rusted, weathered up features, not identifiable.
- structures in sand include cross-laminations and trough cross laminations - near top of sandy unit.

23.0 m - 23.4 m

- becomes somewhat finer grained and more muddy.
- more massive due to decrease in grain size.

23.4 m - 23.9 m

- medium grained sandy bed.
- massive - some silt/mud laminae - 4-5 mm.

23.9 m - 36.0 m

- at 24.5 - 28.0 m unit becomes mottled with lighter patches of biological material.
- fine laminated rock returns at 28.0 and sand bed returns at 29.5 m - 36 m.

35.0 m - 36.5 m

- fine dolomitic mudstone with silt layers up to 2 cm.

36.5 m - 38.5 m

- sandy bed.

39.5 m - 42.5 m

- interbedded sand-silt-mud on scale of 5-10 cm.

42.5 m 46.5 m

- mud predominates w/sand beds up to 10 cm.

46.5 m to approximately 73 m: Prominent

- gradational contact into overlying massive sandy/silty dolomite.
- silty dolomite beds in this unit reach up to 10 cm thick.
- rounded clasts and what appear to be stringers.
- sand and silt present as 2-3 cm beds - approximately 10% of total unit.
- clasts of sandbed in overlying massive dolomite bed.
- even weathering pattern - greyish brown on fresh.
- vugs in 10 cm zones - 63-65 m.
- at 65 m - return to finely laminated silty dolomite for 1.0 m.
- 66.0 m - silt/sand decreases, mud percentage increases.
- 67.0 m - recessive muddy limey dolomite for 10 cm.
- alternating beds from sandy/salty beds - muddy dolomitic beds - muddy limey beds.

73 m - 78 m: Scree

78 m - 81 m: Recessive

- black, medium crystalline mottled looking dolomite mudstone.
- patches of weathered up rock, very fine grained material.
- generally massive except for patches.
- at 78.0 m - rock has holes (vugs) and light and dark patches.
- weathered up black material present in distinct zones (beds) as discontinuous patches.

- unit is distinctly bedded with some fissile character - for 2.5 m.
- at 80.5 m - weathered up material becomes tan colored.
- fissile character decreases after 80.5 m.

81.0 m - 89.0 m Sharp Contact

- vuggy, massive tan colored (weathered) material.
- highly fossiliferous limestone - crinoids, byozoans.
- fossils-cream colored - matrix medium to light grey.
- overall massive with zones of high fossil percentage (wackestone) approximately 1/2 m thick, just above contact.
- surface appears highly altered.
- 83.0 m - 89 m - 10-20 cm bed repeated approximately 10 times.
- more recessive beds appear sandy or silty, but are massive and have no laminae.

89.0 m - 93.0 m Scree

93.0 m - 94.5 m

- massive medium-light grey weathered dolomite.
- appears to be similar to recessive material at 83.0 m.
- ie. whole unit is same as recessive unit below.
- small vugs - <1%.
- possibly biological activity.

94.5 m - 102.0 m

- black weathered material.
- this unit has large vugs making up approximately 10-15% of surface - also present - smaller vugs.
- gradational boundary has non-vuggy material in to overlying slightly vuggy material in to overlying very vuggy material.
- occasional brachiopod in very vuggy material.

102 m - 109 m: Prominent

- coarsley broken up weathering pattern.
- possible stromatoporoids and also pelecypods.

- richly fossiliferous zones throughout - up to wackestone, packstones.
- reefal in appearance.
- dolomitic mud with fossils up to packstone/wackestones.

109 m - 118 m: Scree - Recessive

- medium grey weathering silty dolomite mudstone.
- rare vugs.
- mottled appearance in places - dark and light colored.
- fine silt laminae present (<1%).

124.5 m - 127.5 m: Scree - Recessive

- light grey weathering - medium brown on fresh surface - medium crystalline dolomite.
- laminae gives rock cleavage planes (silt) and one unit approximately 20 cm thick shows abundant parting planes (silt?).
- surface is pitted and pocked (small vugs) in zones approximately 30 cm.

130.5 m - 138.5 m: Scree - Recessive

138.5 m - 143.0 m: Recessive

- black richly fossiliferous dolomitic mudstone/packestone.
- fossil zones - packstones.
- fossils - crinoids, bryozoans, corals.
- less fossiliferous rock has large (approximately 15 cm) vugs.
- within this unit there are patches and beds (with no fossils) of medium to coarsley crystalline light grey weathering (brown on fresh).
- light patches have areas where small vugs (1-3 cm) are up to 10% of rock.
- dolomite, with little or no structures visible.
- units appear to interfinger between light and dark fossiliferous material.

143 m - 144.5 m: Scree - Recessive

144.5 m - 161.5 m: Prominent

- gradational boundary.

- light colored reefal looking material limey mudstone.
- fossils <5% - corals and large patches of calcite, vugs approximately 5%.
- also small bands of previous unit 10-20 cm thick.
- *at 145.5 m - bands of previous unit disappear.*
- vugs decrease above break.
- black material is less brittle - possibly more dolomite.
- 149 m - rock becomes somewhat mottled - light and dark patches.

151.5 m - 157.5 m: Scree - Recessive

157.5 m - 160.5 m: Prominent

- light grey weathered limey mudstone.
- pock marked - black on fresh surface.
- sharply weathered up surface.
- fossils 5-10% - fragments of crinoids, corals, brachiopods.

160.5 m - 196 m: Scree - Recessive

196 m - 202 m: Prominent

- medium grey - tan rust on weathered surface - limey mudstone.
- black on fresh.
- altered surface exhibits silty weathering appearance.
- somewhat mottled.
- laminae present and interbedded recessive fissile material and black massive limestone - fossils - crinoids, bryozoans, corals.
- 196-199 m unit becomes bedded with limey mudstone and fissile shaly material.
- 199-202 m return to altered mudstone as below 196 m, same mottled appearance.

202 m - 216 m: Scree

216 m - 217.0 m

- approximately 70 cm more massive mudstone.
- areas approximately 30% of unit where fine laminae predominate.
- small, sharp, weathered up areas.

- silty?

217.0 m - 220 m: Scree

220 m - 222 m: Prominent

- much same unit as before scree.
- 220-220.5 - 1/2 meter weathered smooth with fine laminae - limestone with oblong black structures.
- fossils include - brachiopods, coral debris.
- rocks above this unit (ie. 220.5-222) appear to be the same composition but more disrupted.
- same fossil debris.
- rock appears speckled with white specks on black fresh matrix.

222 m - 223.2 m

- more recessive lighter weathering rock.
- fossil content decreases slightly.
- black on fresh surface.
- fossils, brachiopods, corals - debris.
- end/side view of bedding plane shows oblong nature of sediments.
- unit is more prominent up section.

223.2 m - 272 m

- most prominent with 1.0 m overhang.
- similar overhang to basal contact at Toma Creek.
- 224-224.5 - 1/2 meter massive black/grey mud w/minor fossil debris - limestone.
- distinct smooth weathering surface.
- smoothly weathered massive unit is repeated several times in this unit - generally <20 cm thick.
- interbedded with finely grained mud and finely grained laminae with parting surfaces (silt?).
- silty/muddy units are recessive carbonate. mud is prominent.

234.0 m - 239 m: Prominent

- ridge after approximately 5 m of spotty outcrop and Scree mottled appearance on weathered surface.
- black on fresh with occassional fossils, corals, brachiopods, crinoids.
- unit approximately 30 cm thick at 236 m shows no fossils and is very massive black limey mud.

At approximately 239 m

- unit appears somewhat speckled.
- black weathering up material 2-3 cm maximum.
- black and white material.
- black weathered up material decreases upward but is still present at 259.5 m.

262 m - 264 m

- definite biologically altered zone on weathered surface.
- generally massive limey mudstone.

264 m - 266 m

- sharply weathered up material (as Blue Ridge at Toma Creek).
- contact marked by thin (1/2 cm) sandy silty beds.
- fewer biological structures obvious.
- fossils include corals, brachiopods.

266 m - 272 m

- return to massive unit as 262-264 m

272 m - 273.5 m

- relatively sharp break area 1.5 m between biologically altered lime mud below (266-272) to vuggy, roughly weathered silty material above.
- boundary zone (1.5 m) is vuggy -15% and has silt within carbonate mud matrix.
- silt:carbonate ratio = 1:5

273.5 m - 282. 0m

- definitely silt with carbonate matrix.

- laminae - well developed.
- breaks between laminated silt and biologically altered silty limestone are sharp, but over a thickness of approximately 10 m they alternate with maximum thickness of each unit approximately 1.5 m.

(These two units alternate over this thickness (272-282) maximum thickness of bed 1.5 m.)

At approximately 276.5 m - 279 m unit has weathered up structures in vuggy unit.

282 m - 283 m

- rock returns to pre-silt type rock (ie. Blue Ridge Member).
- bryozoans and mottled appearance.

283 m - 288 m

- fossils and roughly weathered material.
- organisms have weathered up.
- zones of increased biological activity.
- above the silt material (282-283) rock becomes intensely vuggy, roughly weathered material.
- slight differences to unit which was interbedded with laminated silt ie; more and larger vugs.

288 m - 297.5 m

- silty lime mud.
- fossils include crinoids, bryozoans, corals.
- much same as last small unit (282 m- 283 m).

297.5 - 299 m

- silty unit with same mottled appearance with rare weathered out organisms.
- fine grained silty lime mud.
- clasts of lower mottled lime mud in this sandy/silty unit.

299 m - 302 m

- lime mud.

- these units (288-297.5) and (297.5-299) appear to be alternating between the silty material and the lime mud.
- thickness of each unit is approximately 1-2 m which are then overlain by the other unit.
- repeated 2 times.

302 m - 306.5 m

- silt percentage in carbonate mud appears to decrease.
- interbedded units of prominent carbonate (lime) mud and recessive silty carbonate mud.
- 306.7 - small (10 cm) unit where fine silt laminae are present.

306.5 m - 312.5 m

- recessive silty units disappear and light colored lime mud with coral fragments predominates.

312.5 m - 348.0 m

- unit becomes laminated with silt laminae up to 2 cm.
- interbedded with biologically altered lime mud.
- at 314.0 m - cross-bedded finely laminated silt/sand with minor limey mud.
- light background with black biological structures.
- generally massive except where laminae are present.
- zones of biological activity (massive) and zones of laminae alternate over entire unit.
- laminae are absent after approximately 320 m.
- unit retains same mottled appearance.
- vugs at approximately 328 m.
- at 341.5 - unit becomes exaggeratedly mottled - light matrix and dark structures.

348.0 m

- Palliser Formation - good exposure not until 353 m.
- dark matrix with light structures.

NORTH CARDINAL PASS SECTION 1 (NCP-1)

0 m - 2.5 m: Prominent

- dark grey with tan ie; nodular limestone with minor silt interstitial to nodes.
- several recessive 1-2 cm black shale material.
- no fossils visible.

2.5 m - 2.75 m

- black lime mudstone.
- fossils brachiopods, crinoids, corals.
- rusty fragments.
- sharp upper and lower contact.

2.75 m - 11.0 m: Prominent

- dark grey with tan/rust weathering surface.
- silty.
- several 2-4 cm shaly beds - black and fissile at 3.8 m.
- minor secondary calcite.
- shale beds increase in width upwards.
- at 5.5 m - 6.25 m unit appears to have a decrease in biological activity.
- same weathering color.
- minor fossil percentage.
- 6.25 m - top - massive.
- with 2 cm shale bed at 6.6 m.
- heavy biological activity.
- black shale unit 30 cm at 8.1 m.

11.0 m - 13.5 m: Recessive

- much same unit as 2.75 - 11.0 m - appears to have increased mud and different organisms?
- gradational contact.
- same shale beds and same color.
- gradationally less silt upwards.

13.5 m - 17.5 m - Recessive

- muddy, fissile, light grey shale/mud.

17.5 m - 21.5 m: Prominent

- sharp lower contact.
- muddy silt.
- several organism types and possible biological activity.
- several 2-3 cm sandy beds - up to maximum 15 cm - at 19.0 m
- clean sand.
- same rusty tan color as 2.75 - 11.0 m.
- sharp upper contact.

21.5 m - 30.0 m

- limestone - medium grey mudstone.
- fossils brachiopods crinoids, corals - generally articulated.
- fine grained massive dense mud.
- fine layers of silt in groups up to 5 cm thick.
- minor secondary calcite.

30.0 m - 43.0 m

- medium grey lime mudstone - smooth weathering surface.
- several types but minor in numbers, macrofossils - fragments.
- rugose corals, brachiopods.
- at 30 - 30.5 m - light cream colored silt - very fine sand.
- has oblate fragments/clasts - photo with quarter.
- no organisms or biological activity.
- possible mud clasts draped by sand/silt?

43.0 m - 46.0 m: Recessive

- return to lime mud - medium grey with light grey weathering.
- rare fossils.

46.0 - 50 m: Prominent

- transitional boundary.
- weathering pattern changes back from silty below to massive/smooth above (46-50).
- this massive unit has more visible biological activity-appears to have silty surface on end section.
- definite increase in biological activity on bedding surfaces.
- relatively sharp upper contact.

50 m - 52 m

- silty lime mudstone.
- sharp contacts.
- breakage perpendicular and parallel to bedding.

52 m - 56.0 m

- massive lime mustone.
- corals, biological activity, rare brachiopod.
- 55.8 m - silt/fine sand layers.
- 20 cm thick - continuous up and down strike.
- more prominent than massive mud.
- crossbeds in sand/silt.
- possible calcareous matrix with sand/silt grains.
- at 56.0 m - sharp contact.
- contact appears erosional after sandbed.
- irregular and overlying unit "sinks" down into unit.

56 m - 61.5 m

- massive lime mudstone.
- no sand or silt.
- possibly lighter in color on weathered surface.
- upper 2-3 m more silty.
- measure through 3-4 m scree.

61.5 - 64 m: Prominent

- lighter color on weathered.

- "pock" marked.
- grainy beds - up to wackestone/packstone - 20-30 cm thick at 61.8.
- sharply weathered material.
- areas where? something? has weathered up.
- <2% brachiopods and corals.
- large vugs and calcite replaced blobs - 5% - scattered throughout at 61.8 - 62 m - distinct fossil unit - brachiopods, corals, crinoids.
- fragments in dense lime mud.

64 m - 74.5 m: Generally Recessive

- most of unit is somewhat recessive but the more massive units are more prominent.
- massive and heckled units interbedded on scale of 1-3 m.
- several (2-3) fossil units 10-20 cm throughout at 61.8-62.
- base of this unit has clasts of light colored pock-marked unit.
- fossils include articulated crinoids.
- good biological structure at 66 m - *Thalassinoides* at 67.5 m - 5-10 cm bed where burrows and crinoids make up to 25% of rock - matrix lime mudstone.
- at 74-79.5 more prominent unit and is more massive.
- less biological activity and no visible macrofossils.

74.5 m - 83 m: Scree

83 m - 86 m: Prominent

- light colored limestones - several "ridges" on weathered surface.
- possible increase in grain percentage - wackestone.

86 m - 90 m: Scree

90 m - 104.8 m

- medium grey silty dolomite mud.
- few fossils.
- light grey on weathered surface.

104 m - 106.0 m

- highly fossiliferous lime mud.
- corals, brachiopods, bryozoans, corals.

106 m - 117.5 m: Scree

117.5 m - 126.5 m

- medium brown wackestone.
- pocked, light colored on weathered surface.
- silt content appears to increase and fossil percentage decreases slightly.
- bryozoans, brachiopods, crinoids, corals.
- two beds approximately 40 cm thick of black massive lime mud - at 119 and 123 m.
- large scale structures (weathering) 1/2 cm long - 6 cm across.
- fairly uniform over entire thickness except for 40 cm beds.

126.5 m - 143.5 m: Scree

143.5 m - 146.0 m: Recessive

- fissile, light weathering silt/sand.
- shows minor (<5%) 1-2 cm mud laminae.
- little or no cross-bedding.
- possible hummocky cross stratification.

NORTH CARDINAL PASS SECTION 2 (NCP-2)

0 m - 9.0 m: Grotto Equivalent

- undulatory bedding seen in cross-section.
- medium to dark grey.
- generally massive with thin (1-2 cm) bedded areas where breakage has occurred (silt?).
- black fissile material also present <10%.
- area appears to have been extensively folded and then weathered to show older units to be younger.
- at 9.0 - nose of fold is visible and bedding resumes typical dip for the area.

9.0 m - 0.0 m

0.0 m - 41. 0 m: Becoming more recessive

- interbedded massive lime mud and black fissile shale.
- same units as 0-9 m below but now rhythmically bedded.
- scale: approximately 20 cm for massive bed; approximately 10 cm for fissile unit.
- brachiopod fragments in massive unit.
- black fissile unit shows rare pyritized and/or rusted burros (*Skolithos*).
- at 12.0 m unit begins to have increased thickness of massive unit at the expense of the shaly unit.
- massive unit is up to 2.0 m thick with small beds of fissile shale.
- fossil content in massive unit increases as well as pyritized burrows.
- massive unit is more prominent than shale unit and begins to show up more as go up in section.
- shale unit becomes slightly more frequent yet thinner.
- at 27.5 m unit becomes more prominent and more massive.
- lose all but rare black fissile bed.
- rare articulated corals.
- interbedded material continues.

41.0 m - 57.5 m: Arce/Grotto Equivalent, Prominent

- more thickly bedded - thinly bedded in areas.
- lighter colored material.
- at 48.0 m - large bedding plane shows rough/sharply weathered and "pocked" surface.
- at 50 m - get change to thinner bedded darker material with shale interbeds (3-4 cm) common.
- possible increase in silt percentage.
- at 54.0 m unit becomes bulbous (nodular) on weathering surface.
- at 56.0 m small interbeds of white, silty shale.
- rare fossils, rugose corals.

57.5 m - 62.0 m - Prominent Lower Graminia Silt/Sand Member

- unit becomes rusty colored on surface and is bedded (5-10 cm) with laminated silty units and massive lime mud units.
- rare pyritized and/or rusted structures on bedding plane.
- recessive at approximately 61.0 m where recessive shale predominates - approximately 1.0 m.

62 m - 71.0 m: Recessive

- fissile shale/mud.
- at 63.0 m - 1.5 m bed of shale with small (4-5 cm) massive units.
- at 66 m - 69 m - 4-5 cm massive units disappear.
- no bedding plane biological structures on black fissile material.

71 m - 74.5 m: Prominent

- 3.5 m bed of massive rusty colored material - as before (57.5 - 62.0) with small shale interbeds.
- upper contact marked by 10 cm thick massive carbonate lime mud which is in turn capped by 3 cm fissile bed.
- with in rusty unit there are elongated blobs of light grey carbonate lime mud - approximately 15% (oncolites).

- above is light-medium grey nodular lime mud - which forms 10-20 cliff. Blue Ridge moved up silt - over Blue Ridge - found base of Sassenach Sandstone and used this base as 0.0 m for Sassenach - Palliser.

0.0 m - Sassenach

0.0 m - 3.0 m: Upper Graminia Member/Sassenach Formation

- rusty weathered silty.
- generally massive with crude bedding shown by darker patches.
- sharp contact with lower nodular unit.
- upper 2 m shows biological structures?
- structures on bedding planes inc. *Arenicolites, Cruziana*.

3.0 m - 60.0 m

- dark colored limey silty/sandy mud.
- blobs of dark colored material - light cream interstitial.
- generally massive or thickly bedded.
- small (5-10 cm) recessive shale beds.
- dark patches appear to be oncolite structures - with light matrix.
- appears to be thickly bedded (5-7 m) interbedded with nodular unit and sandy biological churned unit.
- repeated several times.
- matrix is always somewhat silty/sandy.
- at 29.9 m - nodular unit 1.5 m thick, also broken up.
- 31.4 m - 33.0 m return to massive sandy unit.
- at 33.0 m biological structures decrease leaving thickly bedded massive unit.
- rare 10 cm shale beds at approximately 37.0 m - 40.0 m capped by 3-4 cm finely laminated silt beds.
- 44-60 m - massive silt and carbonate unit.
- laminated silt and churned appearance returns giving weathered rock a broken up appearance.
- distinct boundary between laminated and churned unit and massive unit.
- small, random 10 cm shaly units throughout.
- at 51.0 m - ground flattens and continues for approximately 9.0 m.

At 60.0 m large prominent ridge - Palliser Formation.

- black matrix with light colored patches.

CARDINAL HEADWATERS SECTION 1 (CH-1)

0 m - 13.0 m: Prominent

- dark grey and tan weathering rocks.
- several 1-2 cm black-grey shale beds are present given bedding appearance to the rock.
- beneath 0.0 m recessive rock which is extremely fissile, tan colored shale - no carbonate with pyrite.
- beds of black fissile shale are maximum 20 cm thick interbedded with cross laminated silt/sand and massive silty carbonate mud.
- at 6.0 m sand percentage increases.
- 7.3 m - unit becomes cleaner carbonate mud with a decrease in sand and silt.
- sand percentage increases and decreases in 10-20 cm beds over the next 3 m of section.
- move up strike approximately 100 m - use marker shale beds to establish total thickness at approximately 13.0 m.

13.0 m - 15 m: Recessive

- sharp contact.
- at 13.0 m - rock becomes less coarsley bedded and is replaced by finely laminated silty carbonate.
- light grey weathering finely laminated silty carbonate mud.
- laminations show silt.

15.0 m - 19.0 m: Recessive

- sharp contact.
- dark laminated silty carbonate mudstone with minor (2-3 cm) black shale beds.
- at 15.0 m - 1-2 cm sandy bed.
- unit has beds (5-10 cm) of less laminated and lighter colored material (silty mud) which are generally more massive.

19 m - 30 m: Scree

30.0 m - 31.5 m

- basinal Grotto Formation equivalent.
- fissile sand-silt and mud.
- heavy rust color.
- layers of more purple material with crawling traces on top of bedding surface - *Cruziana*.
- medium colored sand with bands of lighter colored sand throughout.
- trough shaped structures in lower part of unit - *Cruziana*.
- no structures in sand except for purplish bedding planes.
- at 30.8 - 31.1 m - abrupt change from finely laminated sand with crawling traces to highly burrowed sandy rock with indistinct burrowing returns to massive and laminated sand.
- sharp upper contact - marked by purplish shale beds.

31.5 m - 40.2 m

- much same unit as 1.5 m unit (ie. purplish shale and tan shale) only not nearly as fissile.
- generally massive with rare, small (4-5 cm) shale beds.
- laminae present weather up from rock and are wavy and discontinuous - possible algal.
- shelfward - purple shale decrease.
- three zones, approximately 1 m thick where sand increases and wavy material decreases.
- return to finely laminated rock after zones.
- 39.0 - 39.3 m grey fissile shale.
- 39.3 m - return to wavy material in rock.
- wavy material ends at 40.2 m.

40.2 m - 47.5 m

- generally massive carbonate mudstone (dolomite) for 1/2 m then at 40.7 m 20 cm of upper fine grained laminated mud for shale then return to massive carbonate dolomite mudstone.
- minor/rare fossils (brachiopods).
- 43.5-47.5 slight change in color to light grey and generally massive rock.

47.5 m - 60.0 m

- sharp contact marked by 20 cm shaly zone where underlying carbonate mud has been altered.
- overlying unit is roughly weathered (possible increase in biological activity).
- small scale "bulbous" structures on weathered surface.
- biological structures more visible in sandy/silty bed.
- sandy/silty beds roughly 20% of unit - up to 20 cm.
- at 55.0 m unit becomes somewhat laminated with overall increase in silt content.
- generally same carbonate mud.

60.0 m - 63.0 m

- change in color from light grey weathering to dark grey weathering.
- silt content increases dramatically showing blocky weathering and fine laminations.

63 m - 66 m

- return to light grey weathering lime mud.
- little or no silt.

66 m - 69.0 m: Recessive

- sandy/silty carbonate mud.
- visible only in small outcrop several meters downstrike.

69 m - 72.0 m: Recessive

- sandy/silty carbonate mudstone.
- clasts of mud in unit.
- somewhat fissile along silty layers.

72 m - 81.0 m: Recessive

- dense fine grained finely laminated carbonate mud.
- shows silty weathering pattern and is tan/grey on weathered surface - grey on fresh.
- silty/sandy zones up to 10 cm.
- at 78 m - thin fissile unit showing good parting
- capped by bed approximately 30 cm with holes (vugs).

81 m - 83.5 m: Recessive

- sharp contact.
- vuggy, mottled.
- base of this unit is marked by the upper bedding surface of a 20 cm recessive silt with biological structures.
- medium grey weathering surface.

83.5 m - 101.5 m: Prominent

- sharp contact.
- black carbonate mudstone wackestone.
- abundant corals.
- other fossils indicated by roughly weathering surface.
- zones where corals predominate and zones where stromatoporoids predominate.
- also 10-15 cm fissile shaly beds.
- maximum thickness of alternating zones and shale approximately 40 cm.
- also zones where rock is black and generally free of fossils and/or structures.

101.5 m - 106 m: Recessive

- sharp contact.
- unit is less bedded, light grey on weathered surface.
- biological activity and fossils appear abundant.
- large areas of weathered out material.
- reefal looking?
- at 101.5 - 1 m thick unit of finely grained dense lime mud with little or no structure.

106 m - 112 m: Recessive

- contact under scree.
- dark grey carbonate mud with abundant secondary calcite stringers.
- possible fossils.
- 108.5 - 110.5 m same unit but weathering has created vugs up to 4 cm across.
- same black carbonate mud with abundant secondary calcite.
- appear to be bioturbated shown by mottled and churned weathered surface.

- 110.5 - 112.0 fossil content increases dramatically including byozoans, corals, crinoids.

112 m - 124.0 m: Predominant

- Nisku Formation Buildup.
- sharp contact.
- light colored carbonate mud - somewhat mottled in appearance.
- vugs over 5 cm common - generally vuggy surface.

CARDINAL HEADWATERS SECTION 2 (CH-2)

0 m - 124 m from day 1 - move approximately 300-400 m south of buildup Section 1.

0 m - 32 m: Scree - Recessive

- upper Mount Hawk Member/Lower Graminia Basinal Equivalent

32.0 m - 60.0 m: Recessive

- massive black carbonate mud with numerous 4-5 cm beds of silt (light colored fissiles).
- fossils - rare corals.
- cyclical repetition of massive mud and bedded silt on scale of 10-20 cm.
- up section bedded silt predominates with base massive mud.
- 46.5 m - tan weathering somewhat nodular.
- overall unit appears to alternate between nodular unit and fissile darker shale on scale of 1-2 m maximum.
- shale is recessive and nodular material more prominent.
- sharp brecks between shale and nodular material.
- 53.5 m - shale beds decrease and disappear showing prominent ridge of nodular tan weathering material.
- continues upward with minor (3-4 cm) shale beds scattered throughout.
- rare secondary calcite stringers.

63 m - 72.0 m: Scree

72.0 m

- return to previous black carbonate mud (nodular).
- also have rare fissile shale units at approximately 72-74 m.
- brachiopods present <2% above shale.
- unit becomes speckled due to presence of 2-5% fossil debris, crinoids, brachiopods, at 79.5 m - unit becomes increasingly silty and lighter in color.

80.0 - 119.0 m

- interbedded as well as more massive units described below - scale of 3-4 m.

80.0 m - 84.5 m: Prominent

- sharp contact (Lower Graminia Member basinal equivalent).
- rusty, weathered massive material.
- crudely bedded within 30 cm of contact.
- silty.
- first 30 cm have rough weathered surface bioturbated.
- contact has rusty nodular surface.
- rust at contact is common along strike.
- darkened "blobs" present up to 5%.
- relatively homogeneous except for dark patches.

84.5 m - 87.0 m: Blue Ridge Basinal Equivalent

- sharp contact.
- dark grey to black carbonate mud.
- fossils <5% include brachiopods, pelecypods, corals - fragments.
- mainly calcite replaced.
- rare bands (4-5 cm) of black fissile material.
- silt and carbonate units alternate over a thickness of approximately 40 m.
- silt units are prominent and form steep ridges whereas carbonate units form recessive areas.
- there are approximately 7 silt beds including very lowest bed and approximately 6 carbonate beds.
- all units of each lithology are very similar with minor variations in thickness.
- silt bed at approximately 92.0 m has wispy black material present (approximately 5%) and then at 92.5 m there is an approximate 1 cm bed where this black wispy material is approximately 50-60%.
- carbonate unit continues above 1 cm bed of wispy material.
- some of the units are a cross between the two dominant lithologies.

At 104.0 m

- silt unit is too steep so we moved upstrike (basinward).

- using prominent silt bed as marker.

104 m - 107.5 m

- silt unit.
- rusty - tan weathered with black patches.

107.5 m - 110.0 m: Recessive carbonate unit.

110.0 m - 114.5 m: Prominent

- silty unit with dark patches.
- small recessive carbonate unit at approximately 111.0 m.

114.5 m - 115.5 m: Recessive

- silty carbonate.
- same structure visible.

115.5 m - 117.5 m: Prominent silt.

117.5 m - 119 m: Recessive carbonate unit.

119 m - 126 m: Upper Graminia Member/Sassenach Formation

- rusty tan weathering surface - prominent.
- massive and continuous.
- rare (1 or 2) black blobs as before (near base) within 1/2 m of contact.
- fossils, brachiopods.

126 m - 133 m: Scree

133 m - 134 m

- fissile shale.
- light colored.

134 m - 134.3 m

- generally massive siltstone.

- fissile character further up unit.

134.3 m - 136.5 m

- fissile tan colored shale.
- well broken up.
- brachiopod fragments.

136.5 m - 139 m: Snow/Scree

139.0 m - 142. 0 m

- light colored (tan) fissile (shale) material.
- generally recessive and scree covered.
- at 140 m for 1.2 m - get silty more massive material.
- weak fissile character.
- some structure visible.

142 m - 153 m: Snow/Scree

153.0 m - 160 m

- bedded somewhat fissile.
- silty.

160 m - 164 m

- more massive vertical rockface.
- some horizontal features?

164 m - 165 m

- light sand with dark patches.
- as before and as at top of Sassenach Formation at Toma Creek Section 2.

165 m - 168 m

- light pink weathering material.
- more prominent than previous units.
- carbonate?

173 m: Palliser Formation

- light structures in dark matrix.
- black carbonate predominates.

168 m - 173 m

- estimate of thickness from measured rock to where Palliser is visible - rockface too shear to climb.

SCANNING ELECTRON MICROSCOPE SAMPLE DESCRIPTIONS

SAMPLE I - MM9-90: Upper Graminia Member Silt

- quartz grain - angular
- clay - illite
- quartz over grown
- fungal material - recent growth material
- pressure solution pits showing - grain-grain contacts
- aluminum (Feldspar) - as overgrowths and embedded grains
- Fe-oxide heavy
- possible volcanic ash Fe, Si
- chipping, due to grinding - not aeolian?
- heavy solution reworking - acidic environments
- many cycles of growth and regrowth

Sample II - NCP-10-90: Lower Graminia Member/Silt Doublet

- quartz and Feldspar grains - very dirty
- biological growth - very fresh
- tons of clays
- tons of secondary growth of quartz and Feldspar as overgrowths
- micaceous overgrowths as clay
- smectite clay
- water origin - everything pre-dates carbonate cement
- crushed grain with quartz overgrowth - which has been etched
- chert overgrowth - heavily etched
- very small if any amount of abrasion visible

Sample III - NCP-18-89: Silt Within Blue Ridge Member

- quartz grain
- \+ etching of overgrowth
- \+ fungal growth - occurred during overgrowth stage
- high degree of etching on quartz and feldspars
- quartz grains show overgrowths and solution pitting

Sample IV - TC-34-89: Upper Graminia Member

- K-feldspar grain surrounded by calcite cement
- quartz grain embedded in calcite cement.
- several different sizes of calcite cement up to 20 m.
- illite clays present up to 3% - likely detrital.
- minor amounts of dolomite around micropores appears corroded.
- large dolomite crystals associated with quartz grains
- dolomite grew around quartz
- quartz grains have quartz cement overgrowths
- essentially: quartz + feldspars + clay + etching+ carbonate cement