STORM- AND TIDE-DOMINATED SHOREFACE DEPOSITS,

MILK RIVER FORMATION (UPPER CRETACEOUS),

SOUTHERN ALBERTA

STORM- AND TIDE-DOMINATED SHOREFACE DEPOSITS, MILK RIVER FORMATION (UPPER CRETACEOUS), SOUTHERN ALBERTA

BY

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ABSTRACT

Several sections of the Milk River Formation were measured and studied in detail at Writing on Stone Provincial Park in Southern Alberta. The observed vertical facies succession consists of, from base to top: 1) interbedded, sharp-based sandstones and bioturbated shales; 2) dominantly swaley cross-stratified sandstones; 3) dominantly cross-bedded sandstones; 4) non-marine shales and various thin sandstone and lignite interbeds; 5) local, non-marine cross-bedded sandstones.

The sharp-based sandstones have been episodically emplaced on top of offshore muds. The dominantly swaley cross-stratified sandstone is a storm-dominated shoreface deposit in which fairweather deposits (eg. medium scale cross-bedding), are rarely preserved. The cross-bedded sandstones record deposition in tidally-influenced estuaries which cut into beach and shoreface deposits. The section is capped by vertically accreted muds and thin lignite seams which represent floodplain and terrestrial deposition landwards of the strandline. The non-marine cross-bedded sandstones are local representatives of fluvial channel deposits.

Paleoflow directions measured in the cross-bedded sandstones indicate that the regional strandline was oriented southwest - northeast at Writing on Stone.

Petrographic analysis of the swaley cross-stratified and cross-bedded sandstones indicate that they are Subarkoses. A definite upward coarsening trend from fine to medium grained quartz is observed in the main sandstone body.

ACKNOWLEDGEMENTS

A lot of people have helped me make my little contribution to our beloved science. I would like to formally thank them all here and now.

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CHAPTER ONE: INTRODUCTION

INTRODUCTION

This project was undertaken to describe and interpret the excellent exposures of the Milk River Formation in the southern plains of Alberta. An attempt has been made to establish the depositional framework of these shallow marine sandstones using a sedimentologic approach based on observed field relations.

The basic stratigraphy of the Upper Santonian and Lower Campanian of Alberta and Montana is summarized in Figure 1-2 after McLean (1977). This interval is characterized by the marine shales of the Wapiabi Formation (Colorado Group) which grades upwards into a variously named sand body. In the southern Alberta plains, the sandstone is the Milk River Formation. In northern Montana, it is the Eagle Formation. In the southern foothills, the Chungo Member of the Belly River Group may be correlated with the Milk River and Eagle Formations. These sandstones are overlain by a transgressive marine shale named the Pakowki Formation on the plains, and the Nomad Member of the Belly River Group in the southern foothills. (See section to follow dealing with nomenclature).

The depositional framework is considered in context of recent studies of this stratigraphic interval in the south and central foothills by Rosenthal (in preparation), Ferguson (1984), Bullock (1981)and Hunter (1980).

Rosenthal (in preparation) has noted the variability of east trending paleoflows in the Chungo Member of the Wapiabi Formation in the central and southern foothills. Bullock (1981) and Rosenthal (in preparation) measured a section of the Wapiabi-Belly River Transition exposed at Lundbreck Falls, Alberta, and noted the presence of turbidites with north (016°) trending paleoflows. Ferguson (1984) has studied the same stratigraphy in the central foothills and has noted a regional north-east to southeast spread for paleoflow indicators. Hunter (1980) found northwest paleoflow directions for turbidites exposed in the Wapiabi-Belly River transition at Highwood River near Longview, Alberta.

The presence of continuous exposures in relatively undeformed, flat lying rocks of the same stratigraphic interval at Writing on Stone Provincial Park make it a likely location to study paleoslope characteristics in context of those described above. The location of the Southern Alberta Milk River Gas Pool at the depositional edge of the Milk River Formation's massive sandstone (Virgelle Member) make paleoslope, and hence paleogeographic reconstructions, a priority for understanding gas trapping mechanisms.

Rosenthal (in preparation), Ferguson (1984), Bullock (1981) and Hunter (1980) have all discussed storm-influenced deposition in the Wapiabi-Belly River Transition of the south central foothills. In his section from the Wapiabi shale to the basal Belly River sandstone, Bullock (1981) measured; marine shales - turbidite sandstones and shales - HCS sandstones - dominantly swaley cross-stratified sandstones - beach sandstones - non-marine fluvial sandstones and shales. The implication is that at Lundbreck Falls, swaley cross-stratified sandstones persist up to the beach.

Once again, the continuous exposures of the Milk River Formation at Writing on Stone may be utilized to provide insight into (i) storm influenced deposition and, (ii) the presence and extent of swaley cross-stratification with respect to the paleoshoreline.

GEOLOGICAL HISTORY

A broad, shallow epieric sea covered most of the western interior Great Plains of North America during Upper Cretaceous time (Figure 1-1). At times, the sea connected the Gulf of Mexico with the Arctic Ocean. The seaway was flanked on the west by the rising cordillera which provided thick, east-thinning clastic wedges. The east was bounded by a more subdued Canadian Shield, which may also have contributed sediments (Williams and Burk, 1964).

Weimer (1960) has documented the major transgressions and regressions of the Cretaceous Seaway for the northwestern U.S.A. Gradual retreat of the Wapiabi Sea, combined with local uplift in northwestern Montana, resulted in a regressive prograding shoreline with clastic material supplied from that area (see Figure 1-1). The lateral and vertical facies succession begins with offshore transitional deposits followed by shoreline sands and non-marine sediments, all of the Milk River (Eagle) Formation. These sediments were dispersed in a wide lobe which reached into the Cretaceous Seaway. A brief transgression of the Pakowki Sea in the late Santonian overwhelmed the Milk River (Eagle) shoreline and deposited marine shales over a thin chert pebble layer as far west as the Sweetgrass Arch. During the retreat of the Pakowki Sea, local shoreline fluctuations caused an interfingering of the Pakowki shales and the prograding marginal marine barrier islands of the Foremost Formation (Ogunoyomi and Hills, 1977). Deposition of the non-marine Oldman Formation above the Foremost represents the culmination of the Belly-River clastic wedge, which covers most of the southern plains of Alberta and Saskatchewan.

Figure 1-1: Lower Campanian paleogeography illustrating the extent of the Cretaceous Seaway at that time.
Note the clastic lobe in Southern Alberta and Northern Montana (From Williams and Burk, 1964).

MILK RIVER SEA (LOWER CAMPANIAN)

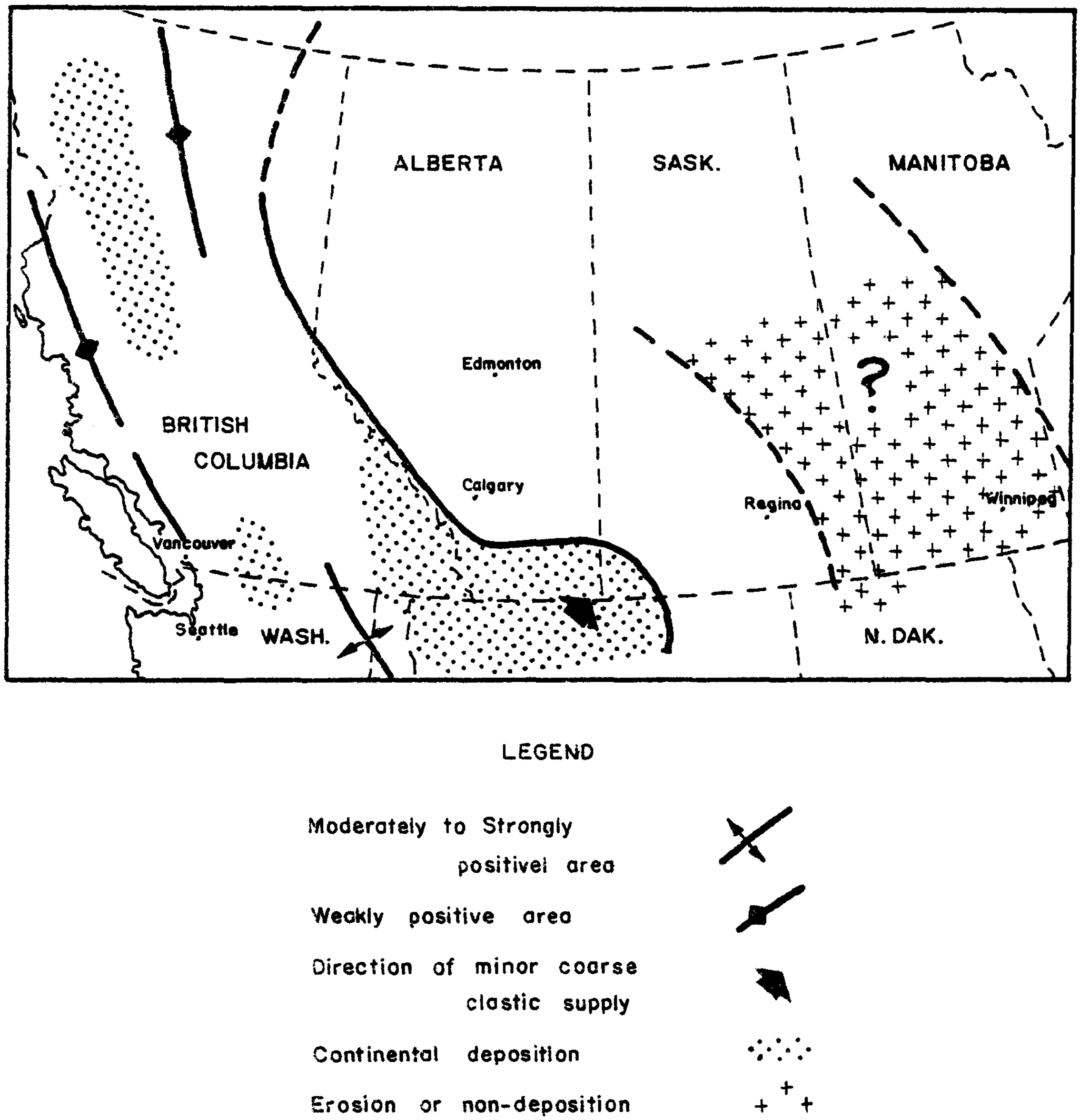


Figure I-1

In the foothills, the Wapiabi is gradationally overlain by marine sandstones and non-marine sandstones of the Belly-River Formation. The Foremost and Oldman Formations are not distinguished in the southern foothills, since the base of the Foremost is not defined by a transgressive marine shale. However, Hunter (1980) identified the Nomad Member of the Belly River in the south central foothills. This is probably correlative with the Pakowki Formation in the south.

NOMENCLATURE

Figure 1-2 illustrates the Upper Santonian - Lower Campanian stratigraphic nomenclature for southern Alberta and northern Montana from the foothills to the plains (McLean, 1977). Note how the Pakowki-Claggett transgressive shales do not reach as far west as the foothills. Basement control by the Sweetgrass Arch limited westward transgression of that sea (Stelck, 1973). Also note the similarities between the sequence in Alberta and Montana. Stanton and Hatcher (1905) and Russell and Landes (1940) traced the Eagle Formation of Montana into Southern Alberta and indicated that it is continuous with the Milk River Formation.

The "castellated sandstone" exposures found along the Milk River in southern Alberta were first described by Dawson (1875). Dowling (1916, 1917) first mapped the surface geology of Southern Alberta and introduced the name "Milk River Sandstone". He did not establish its upper and lower contacts, but noted its value as a freshwater aquifer and traced it in the subsurface northwards as far as Medicine Hat. Williams and Dyer (1930), Evans (1931), and Russell and Landes (1940) clearly established the Milk River Formation in Montana, as formerly defined by Stanton and Hatcher (1905).

Figure 1-2: A schematic illustration of the major transgressions and regressions of the Cretaceous Seaway showing Formation Nomenclature for Montana and Southern Alberta (adopted from McLean, 1977).

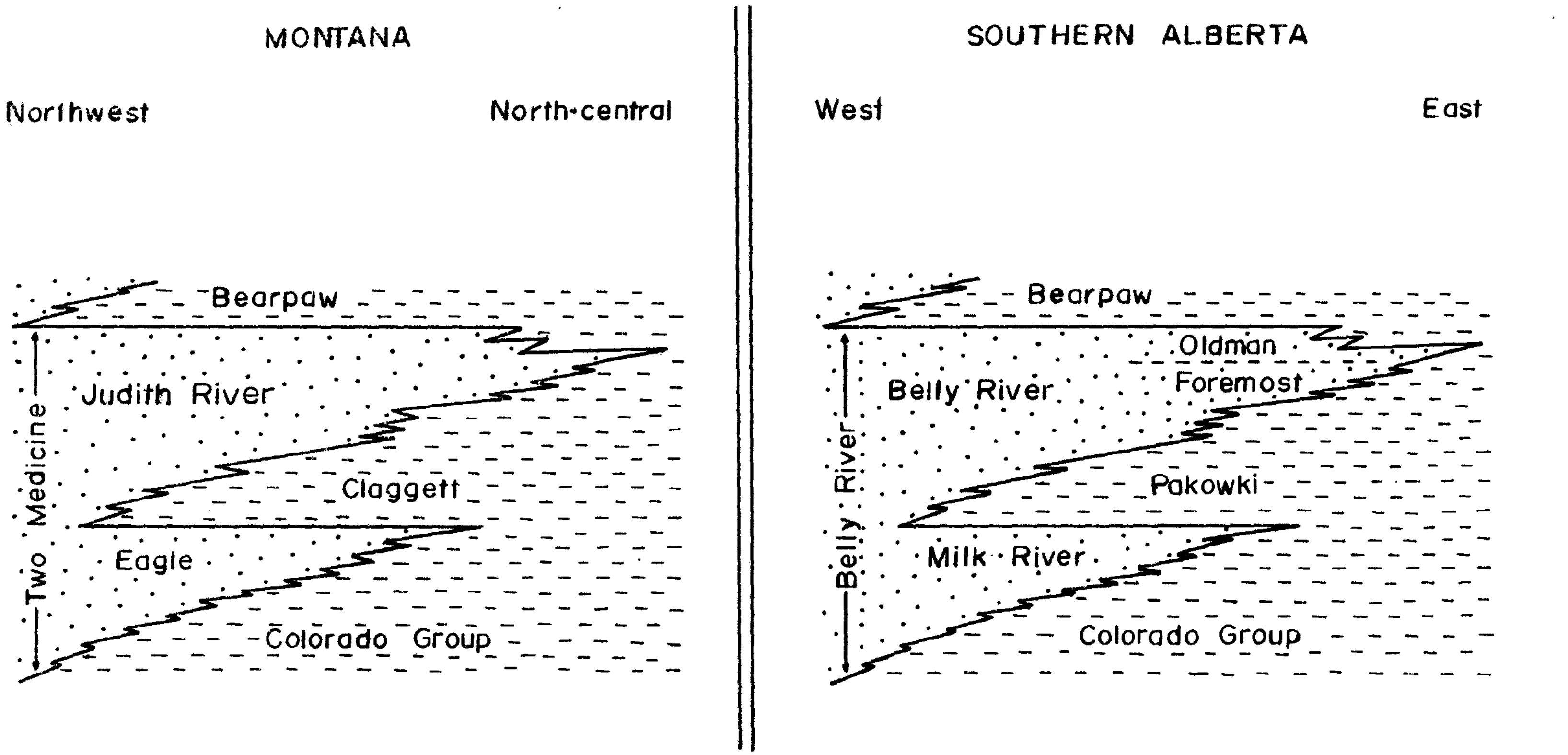

MONTANA
Northwest
North-central
Bearpaw
Judith River
Claggett
Eagle
Colorado Group
Two Medicine
SOUTHERN ALBERTA
West
East
Bearpaw
Oldman
Foremost
Belly River
Pakowki
Milk River
Colorado Group
Belly River

Figure I-2

Slipper (1935) included within the Milk River Formation the gas bearing shale beds drilled in the subsurface. Furnival (1946) proposed "Milk River Equivalent" for this interval, which was subsequently defined as the Milk River Formation's lower contact by Shaw and Harding (1954), and later recognized by the Alberta Society of Petroleum Geologists in 1960.

Tovell (1956) proposed a threefold subdivision of the Formation. The transitional interbedded sandstones and shales were aptly named the Transition Beds. The thick sandstone accumulation is named the Virgelle Member, after the same member of Montana's Eagle Formation. The upper shales and sandstones have been named the Deadhorse Coulee Member.

Drees and Mhyr (1981) have proposed that the member names Telegraph Creek, Virgelle and Deadhorse Coulee be adopted for both the Milk River and Eagle Formations. This is certainly a good idea for a formation which is mappably continuous across the international border. Hence, for the purposes of this paper, the subdivision of Drees and Mhyr (1981) is adopted (Figure 1-3).

PREVIOUS WORK

Previous investigations into the stratigraphic position and nomenclatural history of the Milk River Formation is well summarized by Drees and Mhyr (1981). It was first described as the Eagle Formation by Weed (1899) from exposures along the Missouri River near the mouth of Eagle Creek in central Montana. Dawson (1875) first described the castellated sandstone exposures along the Milk River in southern Alberta. Dowling (1916) mapped the surface geology in southern Alberta and introduced "Milk River" as the name of the sandstone exposed there. A long history of confused names, cross references and renaming has separated

Figure 1-3: A schematic illustration of the Milk River Formation and recently used nomenclature.

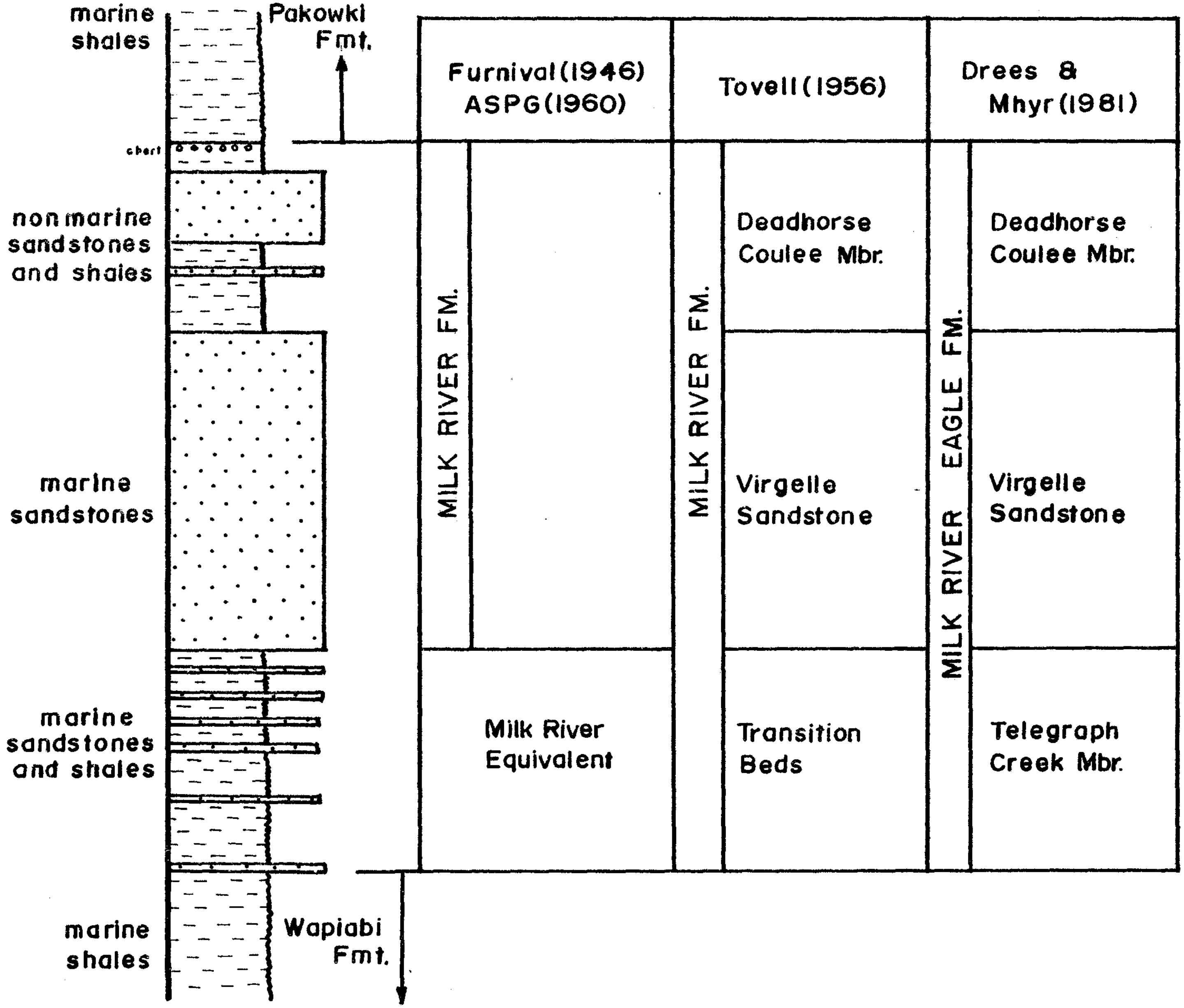

marine shales
Pakowki Fmt.
chert
nonmarine sandstones and shales
marine sandstones
marine sandstones and shales
marine shales
Wapiabi Fmt.
Furnival (1946) ASPG (1960)
Tovell (1956)
Drees & Mhyr (1981)
MILK RIVER FM.
Milk River Equivalent
MILK RIVER FM.
Deadhorse Coulee Mbr.
Virgelle Sandstone
Transition Beds
MILK RIVER EAGLE FM.
Deadhorse Coulee Mbr.
Virgelle Sandstone
Telegraph Creek Mbr.

Figure 1-3

the Milk River Formation and its equivalent, the Eagle Formation, in the literature. Drees and Mhyr (1981) have made a valid attempt to overcome the confusion.

Pre-1960, environmental interpretations of the Milk River (Eagle Formation) are few (Dowling, 1917; Williams and Dyer, 1930; Evans, 1931; Slipper and Hunter, 1931; and Russell and Landes, 1940) compared with the number of outcrop investigations of these rocks.

These authors have noted plant impressions, fresh water molluscs, lignite coal, silicified wood and dinosaur bones in the upper (Deadhorse Coulee) member. There seems to be a general agreement over its non-marine origin. Williams and Dyer (1930) interpreted the whole member as "deposited by rivers over a huge flood plain". Slipper and Hunter (1931) introduced the idea of lagoonal origin to the coals and shales. Russell and Landes (1940) interpreted the chert pebble conglomerate capping the formation as deposited by "stream action".

Environmental speculations of the lower sandstone (Virgelle) are even rarer. Most authors simply offer outcrop descriptions and discuss stratigraphy and correlation. Evans (1931) exhibits insight when he states that "the lower Milk River (Virgelle) is probably a marine deposit". Slipper and Hunter (1931) have admirably dealt with the "Stratigraphy of Foremost, Pakowki and Milk River Formations of the Southern Plains of Alberta". They mapped the subsurface northwest-southwest trend of the depositional limit of the Virgelle Sandstone, interpreting the Milk River Formation as a regressive deposit formed during retreat of the Colorado Sea due to upwarp in the southwest. The Virgelle Member represents beach sands, while the upper coals and shales represent lagoonal deposition.

The first modern sedimentologic study of the Eagle-Milk River Formation is that of Shelton (1965). He uses outcrop and subsurface well control in the area of Billings, Montana, to divide the formation into as many as five sandstone units. These units grade into shales laterally, and have a northwest-southwest (N20-25°W) orientation with normal trending, large scale, low angle inclined bedding (S60°W). Burrowing at the base of the sandstone units and an upward coarsening of grain size are compared with recent barrier island deposition at Galveston Island.

Rice (1980) examined outcrops of the Eagle Formation exposed along the Missouri River and a number of its southern tributaries in north central Montana. He has offered a member-by-member environmental interpretation of the Eagle Formation, which is summarized in Figure 1-4 for the Virgelle Sandstone Member.

The interbedded sandstones and shales of the Telegraph Creek Member are interpreted as offshore-to-shoreface transition, grading upwards into foreshore and shoreface sandstones of the Virgelle Sandstone Member. The Virgelle Member represents coastal plain deposition in which a wave-dominated, delta front sandstone was prograded by a "coastal plain unit". The upper Deadhorse Coulee Member disconformably overlies the Virgelle Sandstone and is represented by two distinct facies; interbedded sandstones, siltstones and shales of tidal flat origin and progradational cycles of shoreface sandstones.

Drees and Mhyr (1981) have also used the Galveston Island comparison (Davies et al, 1971). The presence of thinly interbedded, parallel laminated sandstones in bioturbated shales of the Telegraph Creek Member imply rapid deposition of the sand. The absence of small scale cross-beds and the presence of preserved graded and parallel laminated sandstones are interpreted to indicate deposition below fairweather wave base.

The Virgelle Member is described as consisting of indistinct parallel beds and tabular cross-beds, with the only trace being that of Ophiomorpha. This is interpreted as being due to "rapid deposition in agitated waters" in the presence of "small subaqueous channels" due to "tidal" or "longshore" influences.

An erosional contact with a seaward dip of 15° to 20° separates the upper and lower facies of the Virgelle Member. Meandering channels are interpreted to deposit large scale, planar tabular and trough cross-bedded sands, while scouring the underlying unit.

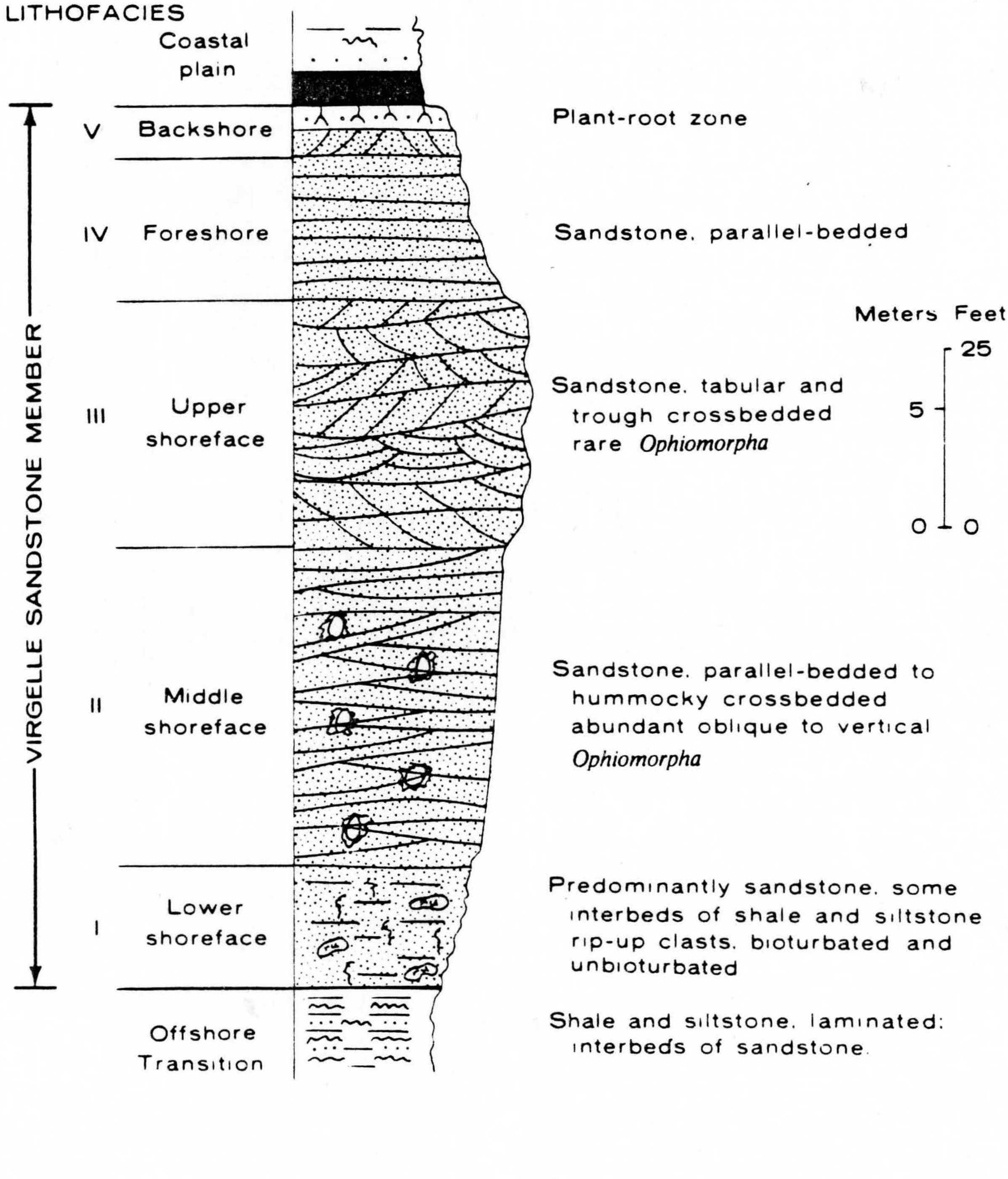
The Deadhorse Coulee Member, consisting of inter-bedded claystone and argillaceous sandstones with plant imprints and thin lignite seams, is interpreted to represent lagoonal or small deltaic deposits infilling local lakes or lagoons. Local thick (6 m), planar tabular cross-bedded sandstones represent channel deposits.

Rice and Shurr (1983) have examined the Eagle (Milk River) Formation and equivalents at localities around the northwestern U.S.A. They have made an extensive paleogeographic reconstruction of the Eagle depositional basin, indicating the shoreline positions at various transgression-regression maxima.

STRUCTURE

The Milk River Formation (and equivalents) is Upper Cretaceous, Upper Santonian to Lower Campanian in age. It is found throughout the subsurface of the western margin of the interior Great Plains. In the

Figure 1-4: A schematic illustration of environmental interpretations for various portions of the Virgelle Member of the Eagle (Milk River) Formation in Montana (after Rice, 1980).


LITHOFACIES
Coastal plain
V Backshore
IV Foreshore
III Upper shoreface
II Middle shoreface
I Lower shoreface
Offshore Transition
VIRGELLE SANDSTONE MEMBER
Plant-root zone
Sandstone, parallel-bedded
Meters Feet
25
5
0 0
Sandstone, tabular and trough crossbedded rare *Ophiomorpha*
Sandstone, parallel-bedded to hummocky crossbedded abundant oblique to vertical *Ophiomorpha*
Predominantly sandstone, some interbeds of shale and siltstone rip-up clasts, bioturbated and unbioturbated
Shale and siltstone, laminated: interbeds of sandstone.

subsurface of Alberta, it mimics the shallow dip of the northeast plunging Sweetgrass Arch, but is relatively underformed otherwise.

Outcrop of the Milk River Formation in Alberta is restricted to reaches of the Milk River, where the river bends northwards into Canada around the elevated Sweetgrass Intrusives of northern Montana (see Figure 1-5).

The depositional edge is marked by the disappearance in the subsurface of the Virgelle Sandstone Member, which is so well exposed at Writing on Stone. It trends northwest to southeast (Figure 1-5), just southwest of Medicine Hat, Alberta (Slipper and Hunter, 1931), where it is replaced by interbedded sandstones and shales of the "Transition Beds" (Tovell, 1956).

MILK RIVER GAS FIELD

The fresh water aquifer potential of the Milk River Formation has been known by prairie farmers for more than a century. The connection of the massive sandstone with the Milk River at or near Writing on Stone has provided a subsurface conduit for the fresh water.

As early as 1884, the Canadian Pacific Railway Company encountered natural gas in the sandy shale beds of the Milk River Formation when drilling for water. Williams and Dyer (1930) reported that the first wells drilled in southern Alberta in search of natural gas, spudded in 1901 near Medicine Hat by CPR, were targeted at the same sandy shale beds. Subsequent drilling revealed that much of southern Alberta was underlain by a low production gas reservoir (200 MCF or 5663.3 m^3 per day). It wasn't until the early 1970s when higher wellhead prices, newer drilling and productions techniques and an expanding international market prompted increased drilling for natural gas in this region.

It is apparent from Figure 1-5 that the gas of the Milk River Gas Pool is located beyond the depositional limit of the Virgelle Sandstone Member. Gas is produced from interbedded sandstones and shales of the Milk River Equivalent (Lea Park) (Furnival, 1946), which are poorly exposed in Alberta. The Virgelle Sandstone provides a waterlogged, up-dip cap to the gas reservoir.

The present Southern Alberta Milk River Gas Pool produces from the sandy shale beds of the Milk River Formation. The Energy Resources Conservation Board of Alberta reports a total of 27 pools covering 1,884,385.2 hectares, with an estimated 141.5 billion m^3 (5000 MMCF) of gas recoverable (Figure 1-5).

Figure 1-5: A Township and Range map of Southeastern Alberta illustrating the location of; Milk River Gas Pools, Milk River Formation outcrop and the depositional limit of the Virgelle Sandstone Member (after Drees and Mhyr, 1981).

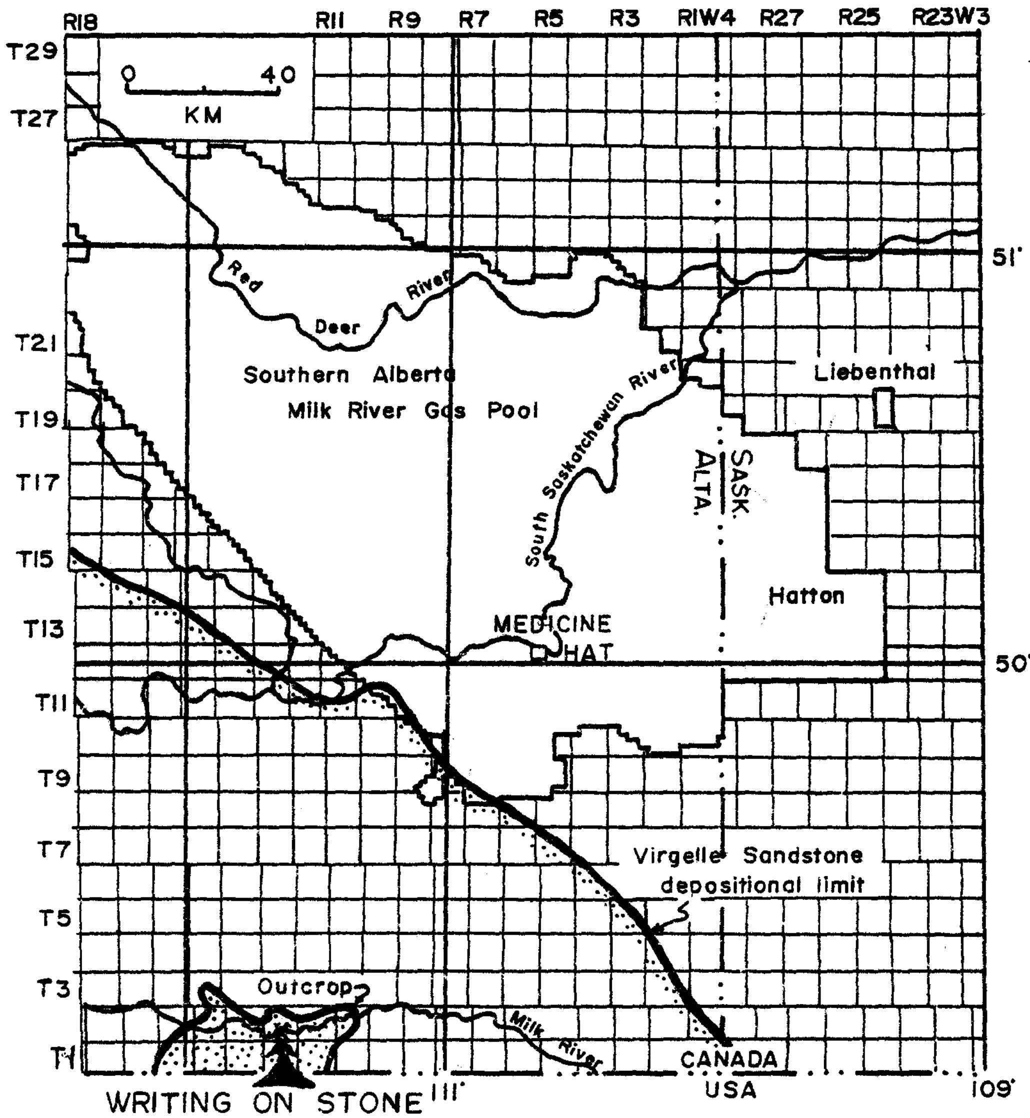

R18
R11
R9
R7
R5
R3
R1W4
R27
R25
R23W3
T29
T27
T21
T19
T17
T15
T13
T11
T9
T7
T5
T3
T1
0
40
KM
51°
50°
Red Deer River
Southern Alberta
Milk River Gas Pool
South Saskatchewan River
Liebenthal
SASK.
ALTA.
Hatton
MEDICINE HAT
Virgelle Sandstone
depositional limit
Outcrop
Milk River
CANADA
USA
WRITING ON STONE
111°
109°

Figure 1-5

CHAPTER TWO: FACIES DESCRIPTIONS

INTRODUCTION

The Milk River Formation at Writing on Stone has been divided into four easily recognized facies. Facies have been defined based on grain size, sandstone to shale content and dominant sedimentary structures. Local variations within individual facies have led to definition of subfacies.

Figure 2-1 is a synthesis of sections measured at Writing on Stone. It illustrates the field relations of facies and subfacies described in the text to follow.

FACIES A:INTERBEDDED SANDSTONES AND SHALES

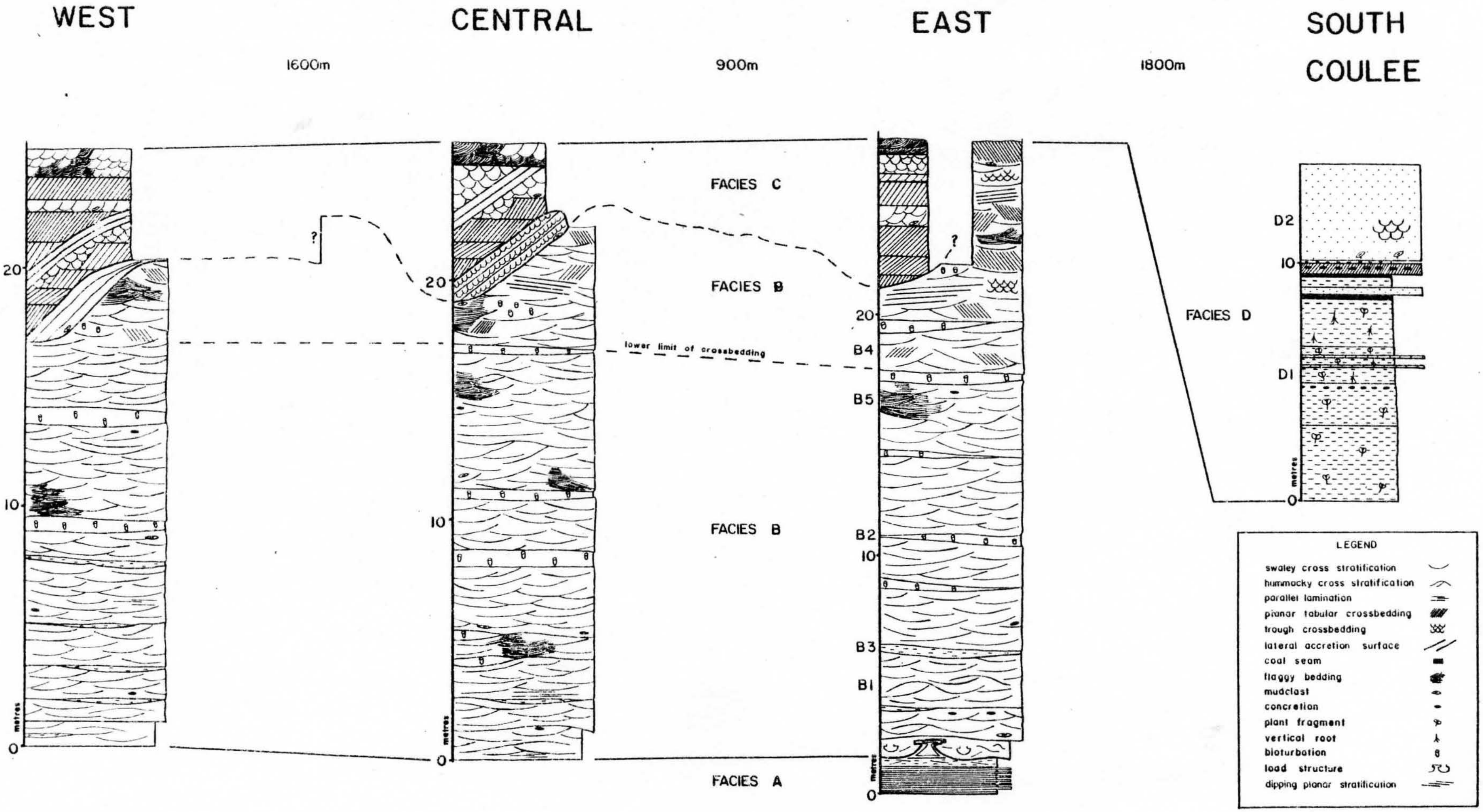
Facies A is poorly exposed in the study area and is limited to points where the present day Milk River undercuts the upper cliff-forming sandstone east of the trailer park. A maximum of 2 metres is exposed, but this is largely covered by talus from the cliff.

Facies A consists of fine-grained, grey silty sandstones and interbedded grey fissile and bioturbated shales. Sandstone beds are commonly sharp-based and may be massive to parallel laminated. In places, they scour into the interbedded shales. Sandstone thickness is generally less than 5 cm but may be up to 10 cm. Mud rip-up clasts are common in the sandstone beds, the largest found being 4 by 2 cm. The sandstone to shale ratio is variable but generally close to one.

The lowest exposures of sandstone beds exhibit well-defined parallel laminations. Well-developed hummocky cross-stratification occurs within a flat based sandstone which averages 20 cm thick. The hummocky

Figure 2-1: A schematic diagram which synthesizes the facies relations for sections of the Milk River Formation measured at Writing on Stone Provincial Park, Alberta.

MILK RIVER FORMATION: WRITING ON STONE PROVINCIAL PARK



is 25 cm in height and approximately 1.5 to 2.0 metres in wavelength. A number of other examples of hummocky cross-stratification may be found within Facies A laterally.

The upper metre of Facies A is deformed into large flame structures which have made the contact with overlying Facies B very irregular. Contact relief is up to 1 metre. In the vicinity of the flames, bedding within Facies A is distorted. Sandstones are cross-cut by shales and folded. The shales show evidence of remobilization and forceful injection into overlying Facies B. Plates 2-1 and 2-2 illustrate the nature of the contact between Facies A and Facies B.

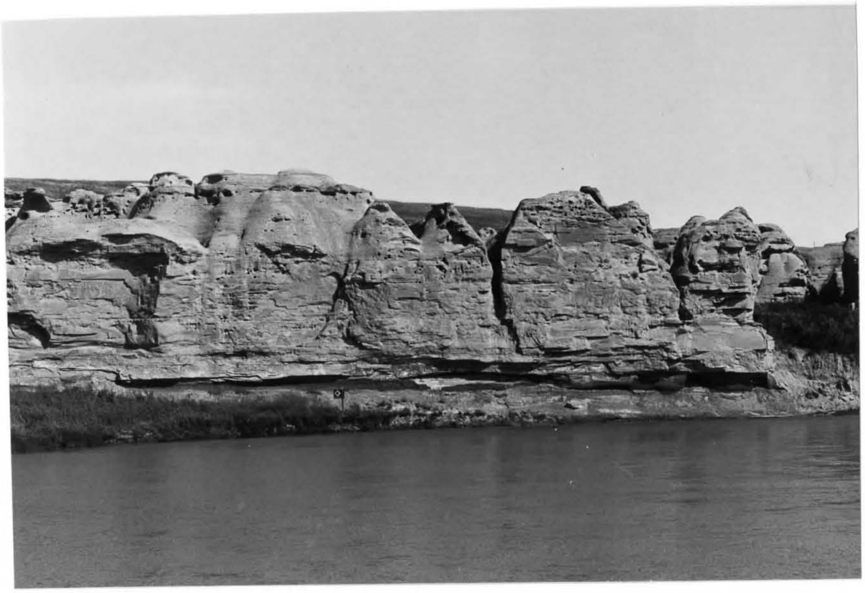
INTERPRETATION

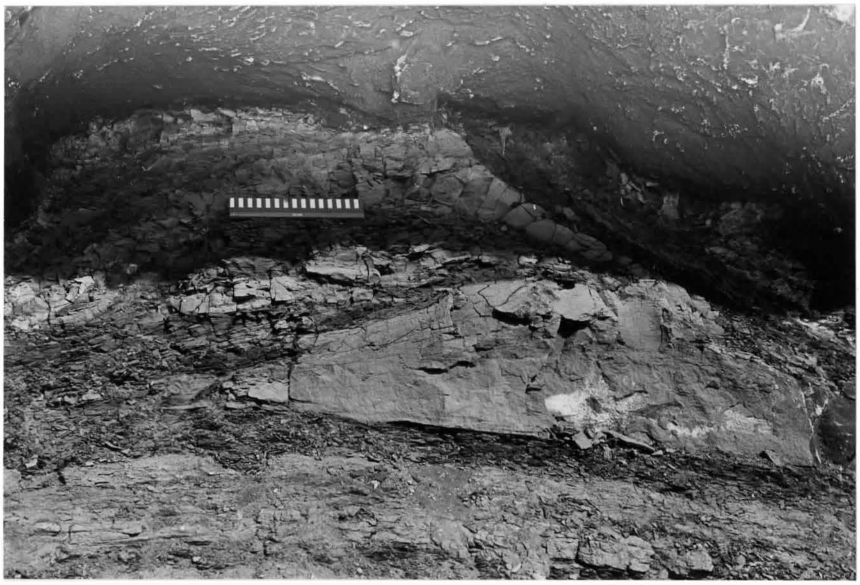
Facies A is fundamentally an association of sharp-based, erosive sandstones and interbedded bioturbated shales. The sharp bases imply that the sands were episodically deposited on top of the shales. Mudclasts and scours indicate that the flows depositing these beds were competent enough to erode and transport pre-existing sediments. The presence of parallel laminations indicate emplacement of the beds by rapid currents. The absence of medium scale cross-bedding implies that no post-depositional reworking by fairweather processes has taken place. However, the presence of hummocky cross-stratification indicates that some beds have been reworked below fairweather wave base by large storm waves (Hamblin and Walker, 1979).

Thus, Facies A was deposited below fairweather wave base by sediment ladened currents. The exact nature of such currents is not resolvable based on observations made at the relatively small outcrop exposed at Writing on Stone.

Plate 2-1: Illustrates the undulatory nature of the contact between Facies A exposed at river level and Facies B exposed in the cliff.

Plate 2-2: The contorted nature of the sandstones and shales is illustrated here. The scale sits in Facies A shales, the sandstone of Facies B is just above.





FACIES B:AMALGAMATED SWALEY CROSS-STRATIFIED SANDSTONES

Facies B is a fine to medium grained, light brown sandstone which is dominated by swaley cross-stratification. It varies from 20-25 metres in thickness and is the cliff-forming sandstone so well exposed at Writing on Stone. It is characterized by well-defined beds averaging between 10 and 40 centimetres.

Ironstone concretions ranging from coarse sand-sized to fist-sized balls are very common and bands are observed to crosscut bedding planes. Mud clasts, anywhere from pebble size to 40 by 2 cm sheets of mudstone are common and are most often associated with the bases localized beds.

Facies B exhibits sufficient variations within its vertical and lateral extent that it may be subdivided into five easily recognized subfacies.

SUBFACIES B1:SWALEY CROSS-STRATIFIED SANDSTONES

Subfacies B1 is the dominant subfacies of Facies B. It is dominated by amalgamated swaley cross-stratification which is best described by bedding planes 10 to 50 cm apart. Swales have long wavelengths of 4 to 5 metres and amplitudes which are commonly less than 20 centimentres. Gently curving, concave up laminae never have dips exceeding 9° to 10° and are randomly oriented bed to bed. Laminae are commonly seen to truncate against other swales within a bed and against bedding planes. Beds thin and amalgamate laterally (see Plates 2-3, 2-4, 2-5).

Rare upward domed hummocky surfaces are seen, however, these are rarer upwards within the section and never comprise more than 5 per cent of any portion of the outcrop. The hummocky cross-stratification observed generally has an amplitude less than 10 to 20 cm and an average wavelength greater than 2 or 3 metres. Hummocks are always found amalgamated with the swales (see Plate 2-5).

Plate 2-3: A typical photograph of swaley cross-stratified sandstones (scale bar, centre, is 30 cm long).

Plate 2-4: A close up of the curved bedding planes characteristic of swaley cross-stratification from Writing on Stone. Note how differential cementation causes bedding planes to stand out (scale bar is 30 cm long).

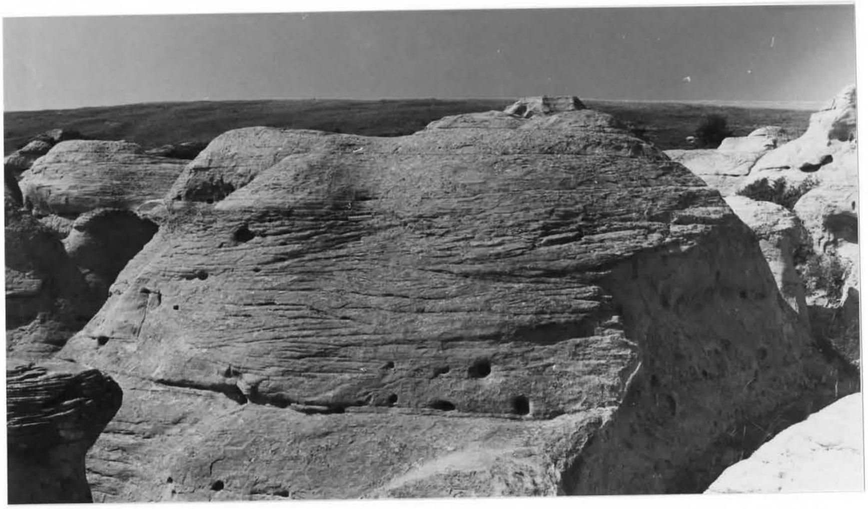


Plate 2-5: Predominantly swaley cross-stratified Hoodoo with a hummock at lower left below scale bar (scale bar is 30 cm).

Plate 2-6: Parallel laminations capped by thin development of Subfacies B3 shales (scale bar is 30 cm).

Parallel laminations are also found within Subfacies B1. Beds which are parallel laminated generally remain so for the whole bed thickness or may grade upwards into curved laminae in the form of swaley cross-stratification, or into thin shales of Subfacies B3 (see Plate 2-6). Parallel laminated rocks may occur in localized beds within the outcrop or may dominate parts of the outcrop. It is found most abundant in the lower half of Facies B rocks.

SUBFACIES B2:BIOTURBATED SANDSTONES

Subfacies B2 occurs in laterally discontinuous beds on outcrop scale. Zones up to 50 cm at their thickest persist, but thin and disappear over a 100 to 200 metre radius. No laminations are observed between bedding planes which appear distinctly mottled.

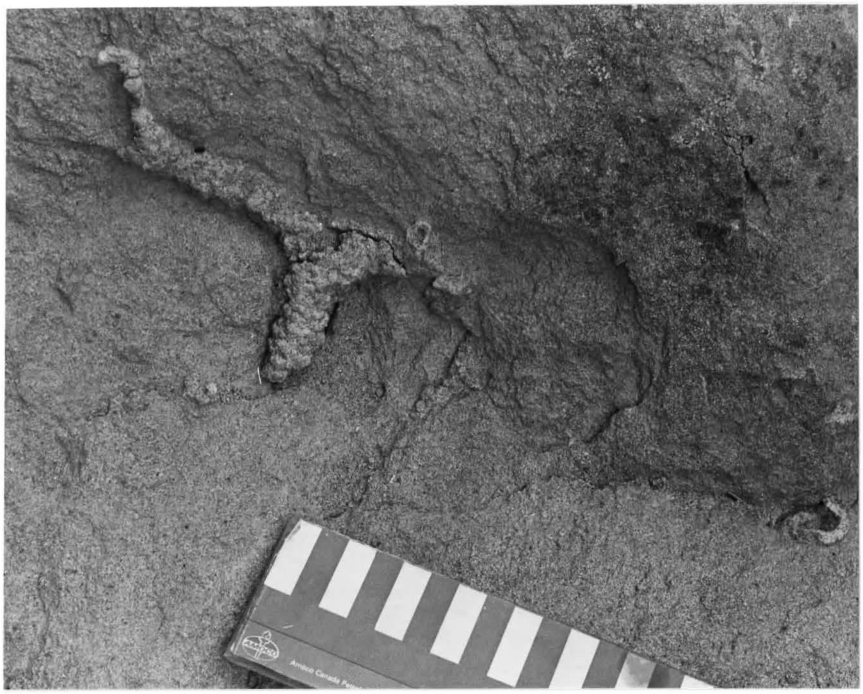
Bioturbated beds commonly contain numberous red-stained, randomly oriented burrows up to 2 cm wide. Individual traces may be well preserved, including some good examples of *Ophiomorpha* and *Thalassinoides*. Particularly good examples of these traces are preserved close to the contact between Facies B and overlying Facies C (see Plates 2-7 and 2-8). The frequency and lateral persistence of Subfacies B2 increases markedly upwards.

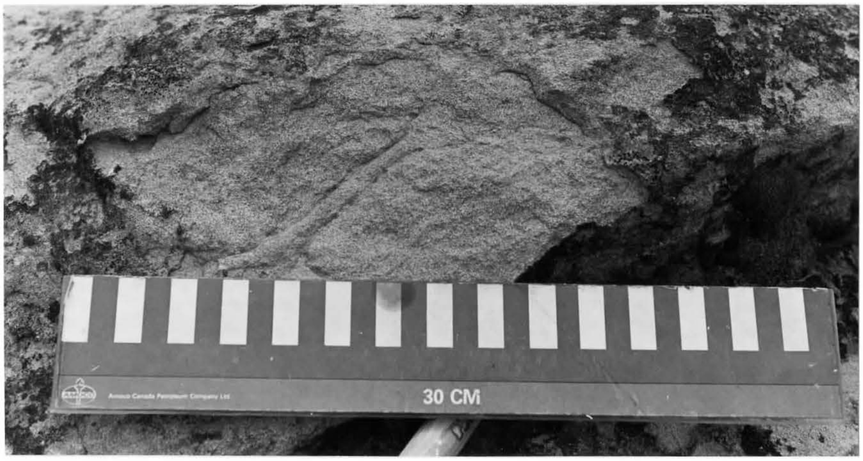
SUBFACIES B3:INTERBEDDED SHALES

Subfacies B3 is marked by the presence of recessive weathering shaley zones. Grey sandy shales occupy lenticular zones up to 50 or 100 metres wide and a maximum of 10 to 15 cm thick. These zones pinch out between swaley beds laterally and are rarer upwards in the section.

Plate 2-7: Textbook example of Ophiomorpha nodosa found in Facies B near the contact with Facies C (scale divisions are 1 cm each).

Plate 2-8: Smooth trace of Thalassinoides with typical rounded and thickened bifurcation.


Amoco Canada


Amoco Canada Petroleum Company Ltd.
30 CM

SUBFACIES B4:CROSS-BEDDED SANDSTONES

Within the upper reaches of Facies B, rare trough and planar tabular cross-bedded sets are found within predominantly swaley cross-stratified rocks. The cross-bedded zones are poorly developed. They are difficult to trace laterally since they most often are found in the upper parts of Facies B in discontinuous Hoodoos. The cross-bedded rocks of Subfacies B4 are, in fact, rare and quite restricted.

SUBFACIES B5:FLAGGY SANDSTONES

Subfacies B5 shows a characteristic flaggy style of weathering into 1 to 5 cm layers. Zones are discontinuous both laterally and vertically and pass into other subfacies sharply. Flaggy beds are generally strongly cemented and often have a distinct reddish-brown colour.

Both swaley and cross-bedded rocks may be flaggy. This subfacies is not restricted to Facies B; Facies C also includes zones which are flaggy. Certain horizons within the outcrop show a higher ratio of flaggy style weathering.

INTERPRETATION OF FACIES B

The significance of swaley cross-stratified sandstones must be studied in context of the interbedded sharp-based and hummocky cross-stratified sandstones and shales located stratigraphically above (Subfacies B4 and Facies C). The interbedded sandstones and shales are not reworked by fairweather processes, whereas the presence of medium scale cross-bedding above indicates the action of fairweather waves and currents. Swaley cross-stratification resembles hummocky cross-stratification without the hummocks and is often observed to contain some hummocks, suggesting a genetic link between the two (Leckie and Walker, 1982). As such, swaley cross-stratification may also be formed by large storm waves feeling bottom between fairweather and storm wave base.

Parallel laminated sandstones are formed by rapid deposition of suspended sands from currents with high velocities (Harms et al, 1982). The preservation of parallel laminations requires that no subsequent reworking by fairweather currents takes place. The fact that it is most commonly preserved near the base of Facies B is consistent with the presence of swaley and hummocky cross-stratification and with the absence of large scale cross-bedded sands there. Again, the implication is that large scale cross-beds represent the actions of fairweather currents reworking sand.

Locally persistent colonies of Callianassid-type shrimps must have occupied habitable regions of the sea floor. *Ophiomorpha* and *Thalassinoides* have often been found associated with the nearshore zone of both ancient and modern sediments (Howard and Frey, 1984).

Shaley zones within swaley cross-stratified sandstone units represent drapes of fairweather muds which are not subsequently reworked. Large mud clast sheets, often found in the bases of swaley beds have probably been ripped up during storm reworking of these shaley horizons.

FACIES C:CROSS-BEDDED SANDSTONES

Facies C is formed from a white to light grey, medium grained sandstone which is dominated by cross-bedding. It forms the upper 5 to 8 metres of the cliff-forming sandstone at Writing on Stone and is easily distinguished from the underlying sandstone.

Most of Facies C is weathered into Hoodoos averaging 3 to 5 metres in height with variable breadths. Shale drapes between cross-bed sets make the Hoodoos unstable. As a result, they topple over and weather recessive with respect to underlying Facies B.

Facies C is difficult to summarize because of its lateral variability. The most prominent sedimentary structure is large scale planar tabular cross-bedding; however, epsilon cross-beds, gently dipping planar stratification, trough cross-beds and thin shaley horizons are locally important. Flaggy bedding similar to Subfacies B5 is also observed.

Planar tabular cross-bedding with sets ranging from 20 cm to 2 metres are observed. Cross-laminations dip up to a maximum of 30°, ranging from about 15° to 30°. Coarser grained material, including small mud clasts and coalified wood fragments, are commonly found within cross-laminae. Thin, discontinuous shaley horizons often separate sets. Within localized areas, consistent dip directions are measured for different sets, however, a vertical set size trend is not apparent.

A number of good examples of epsilon cross-bedding are exposed in Facies C. The epsilon cross-beds consist of beds 10 to 20 cm thick which dip between 13° and 30°. Individual beds are marked by shaley drapes and coarse debris such as plant fragments and mudstone clasts. The vertical thickness of the epsilon set may be estimated from one location to be between 4 and 5 metres. Lateral continuity of beds over 10 metres or more may be observed or inferred from outcrop.

Gently dipping, planar stratification is observed in Facies C. These beds are parallel laminated with shallow dip angles from 3° to 7°. Beds are generally continuous laterally with consistent dip directions. This structure is a kin to what is commonly described as beach swash lamination.

Trough cross-beds preserving only low angle curving laminations occur in abundance in Facies C. Sets range from 20 cm to 1.0 metres with maximum dips averaging from 15° to 20°. Within a local area, trough cross-beds tend to exhibit a bit more variability in dip direction than do planar tabular sets.

The flaggy subfacies at Facies B is also present in Facies C. It seems to be localized more within trough cross-bedded zones than in other areas. Often trough cross-bedded zones may be identified at a distance by this particular habit of weathering.

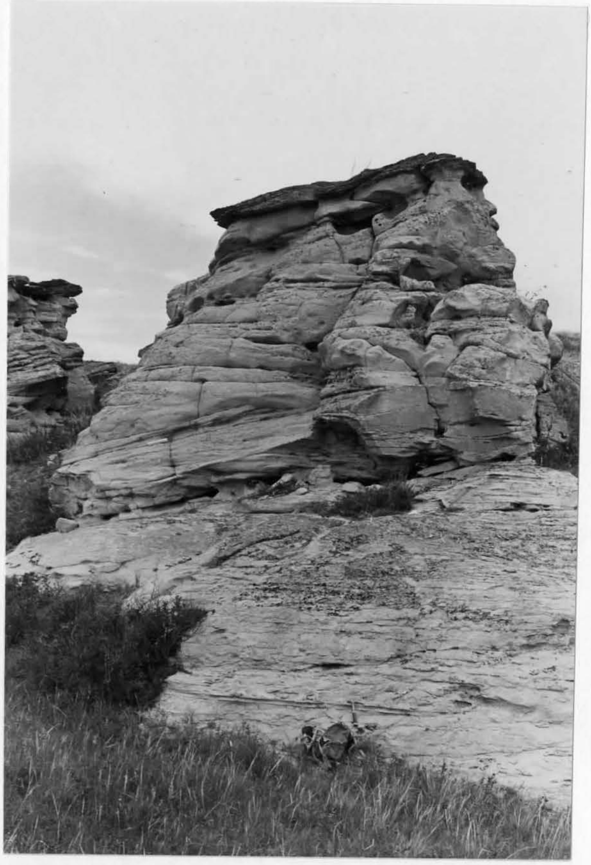
An erosive contact is often observed between Facies C and underlying Facies B. As a result, a topographically irregular surface exists between the two. Facies C begins at various elevations, beginning from 17 to 20 metres into Facies B and generally continuing to the top of the sandstone facies.

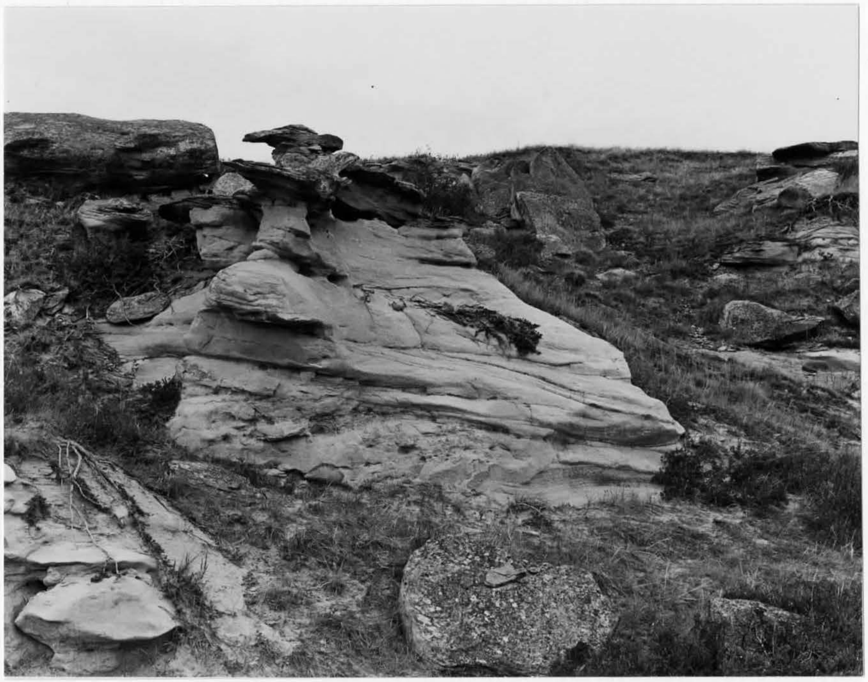
Epsilon cross-beds are always found at, or close to, the contact between Facies C and Facies B where they are observed to erosively cut into Facies B (see Plate 2-9). In general, they are overlain by planar tabular and trough cross-bedded rocks. Occasionally, planar tabular sets independent of epsilon cross-beds are seen to cut into Facies B.

The best exposures of gently dipping planar stratification occur in outcrops laterally adjacent to epsilon cross-bedded Hoodoos. Often the contact between Facies C and Facies B is not as visibly erosive in these adjacent areas, but appears to be more gradational from Facies B swaley cross-stratification and cross-bedding.

Plate 2-9: This Hoodoo sits on the eastern margin of the gully described in the text. Two epsilon cross-bedded sets are visible dipping towards the southwest (vector mean = 222°, mean angle of dip = 21°). One set cuts erosively into Facies B rocks (at scale bar), the other is visible at the top of the Hoodoo.

Plate 2-10: This Hoodoo sits on the margin of the same gully, fifty metres to the west. Epsilon cross-strata dip towards the northeast (vector mean = 069°, mean angle of dip = 19°).





PALEOCURRENTS

The availability of well-exposed cross-bedding at Writing on Stone is condusive to the study of paleocurrent directions. Sections measured and presented in Figure 2-1 were chosen in the field based on the availability of interesting and well-exposed rocks. Figure 2-2 illustrates, in map form, the location of the measured sections. Cross-beds exposed within Facies C and located in the general area of the various sections were measured with a Brunton compass. A synthesis of that data is presented below.

Figure 2-3 is a rose diagram of dip directions measured from epsilon cross-beds exposed at the top of the "WEST" section (see Figure 2-1). The strong bimodality of the data is evident in outcrop. A gully exposes predominantly southwest (222°) dipping beds on its eastern margin and northeast (069°) dipping beds on its western margin. The mean angle of dip for these epsilon cross-beds is 20 degrees.

A Hoodoo from the eastern margin is shown in Plate 2-9. Facies B rocks are eroded by the epsilon cross-bed set dipping to the southwest. A second epsilon cross-bed set is observed at the top of the Hoodoo separated by some flat laminated and cross-bedded rocks.

Fifty metres away, to the west margin of the gully, the Hoodoo shown in Plate 2-10 exhibits epsilon cross-beds dipping to the northeast. Thus, within 50 metres, epsilon cross-beds are observed at approximately the same stratigraphic elevation to have opposing dip directions.

The best exposures of epsilon cross-beds are found near the top of the section labelled "CENTRAL" on Figure 2-1. The long, continuous epsilon cross-beds, dipping towards the southwest are illustrated in

Plate 2-11. Plate 2-12 is a shot of the same Hoodoo looking up-dip from the down-dip direction taken at A, towards B as in Plate 2-11. From this perspective, one may see planar tabular cross-beds within individual epsilon cross-strata, with implied flow directions across the epsilon cross-strata.

Figure 2-5 is a rose diagram which plots the dip directions of the epsilon cross-beds and the planar tabular cross-beds (shaded black) from a number of Hoodoos in the same general area. Note how the planar tabular cross-beds (vector mean = 315°, mean angle of dip = 21°) trend almost normal to the dip direction of the epsilon cross-beds (vector mean = 236°, mean angle of dip = 23°).

Figure 2-6 is a rose diagram of the dip directions of a number of cross-bedded Hoodoos about 150 metres northeast of these epsilon cross-beds. The vector mean of these planar tabular cross-beds (316°) closely resembles the vector mean of the planar tabular cross-beds found within the epsilon cross-strata (315°).

INTERPRETATION

The presence of abudant large scale planar tabular and trough cross-bedding implies that Facies C represents deposition influenced by fairweather currents. Larger scale epsilon cross-beds are formed from lateral accretion of associated point bars within a channel environment.

A number of lines of evidence support a "channel" interpretation for the cross-beds exposed at Writing on Stone.

Figure 2-2: A map view of Writing on Stone Provincial Park illustrating the locations of measured sections as depicted in Figure 2-1.

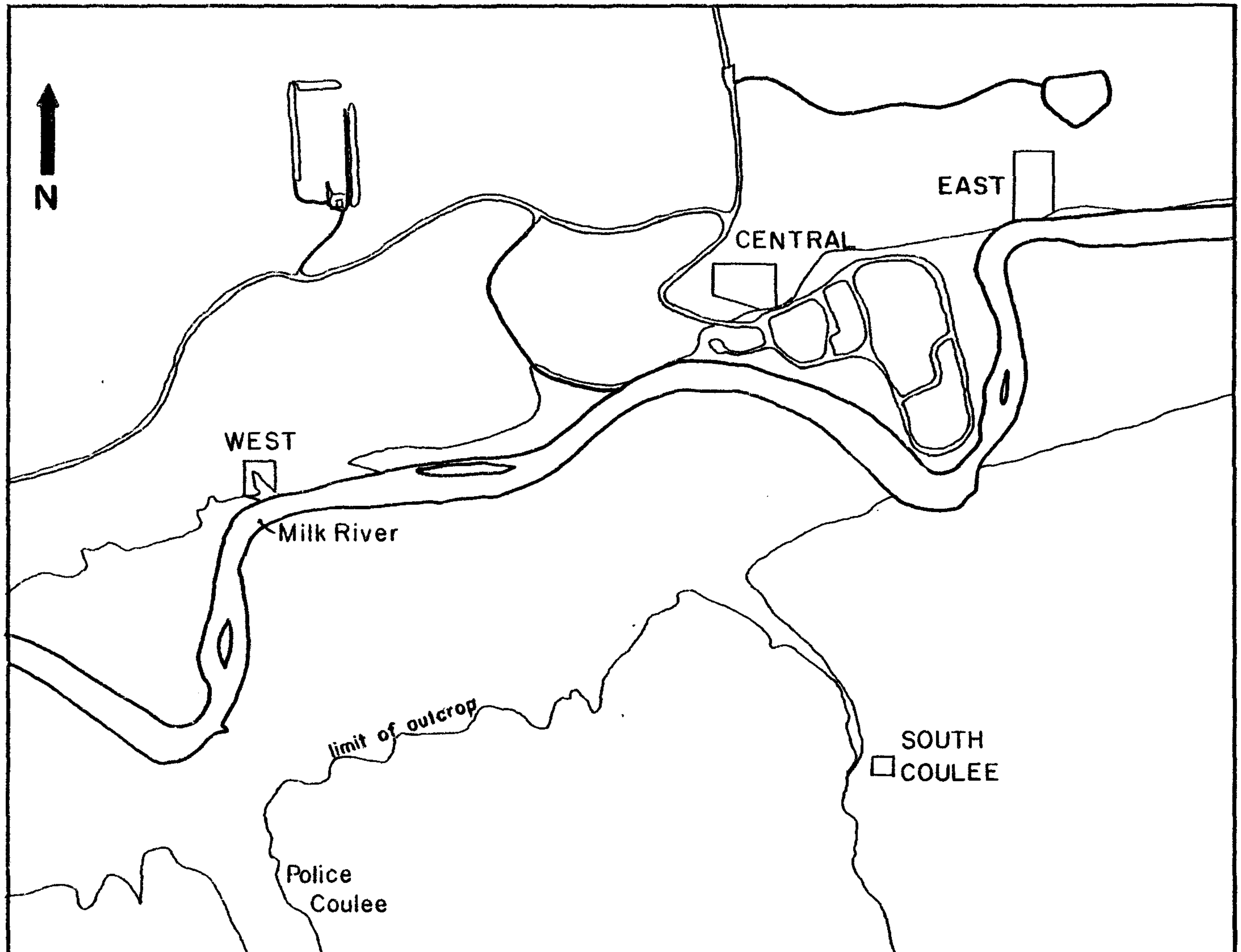

N
EAST
CENTRAL
WEST
Milk River
limit of outcrop
SOUTH
COULEE
Police
Coulee

Figure 2-2

Figure 2-3: A rose diagram which illustrates the bimodality of epsilon cross-beds exposed at the top of the "WEST" section (see Figure 2-1). The mean angle of dip for cross-strata with the vector mean of 222° is 21°, while those with the vector mean of 069° is 19°.

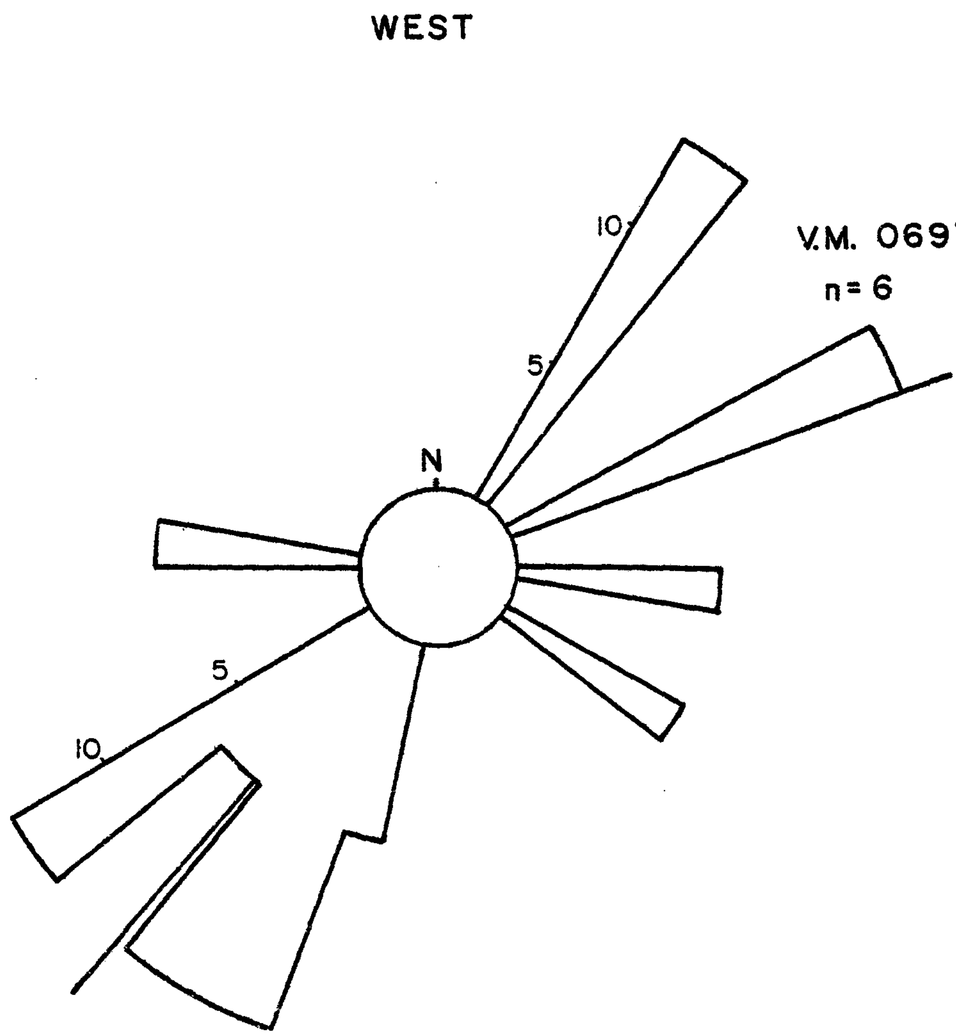
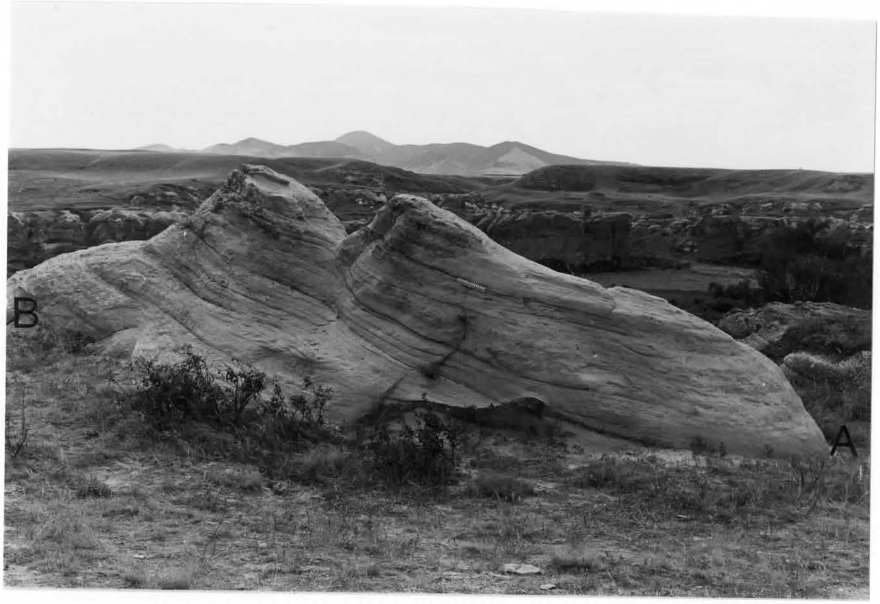


Figure 2-3

Plate 2-11: A Hoodoo of epsilon cross-strata from the "CENTRAL" section. The photograph looks approximately southeast, while the epsilon cross-beds dip approximately southwest (vector mean = 236°, mean angle of dip = 23°0. The "A" and "B" correspond to those in Plate 2-12 below.

Plate 2-12: The same Hoodoo looking from "A" towards "B" as in Plate 2-11 above. It illustrates the planar tabular cross-beds dipping approximately northwest (vector mean = 315°, mean angle of dip = 21°) within individual epsilon cross-strata.


B
A

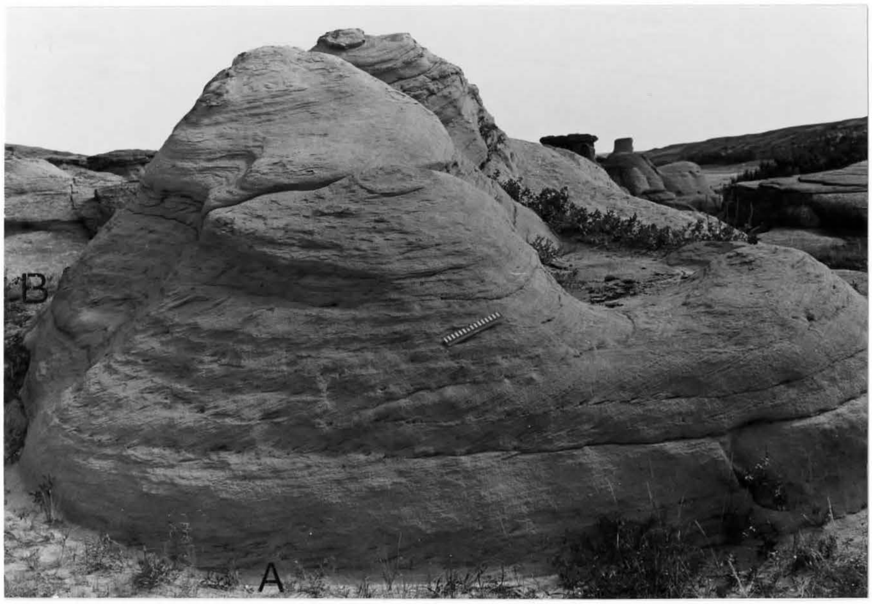

B
A

Figure 2-4: A rose diagram illustrating the relationship between epsilon cross-strata and planar tabular cross-beds (black) illustrated in Plates 2-11 and 2-12 at the top of the "CENTRAL" section.

CENTRAL

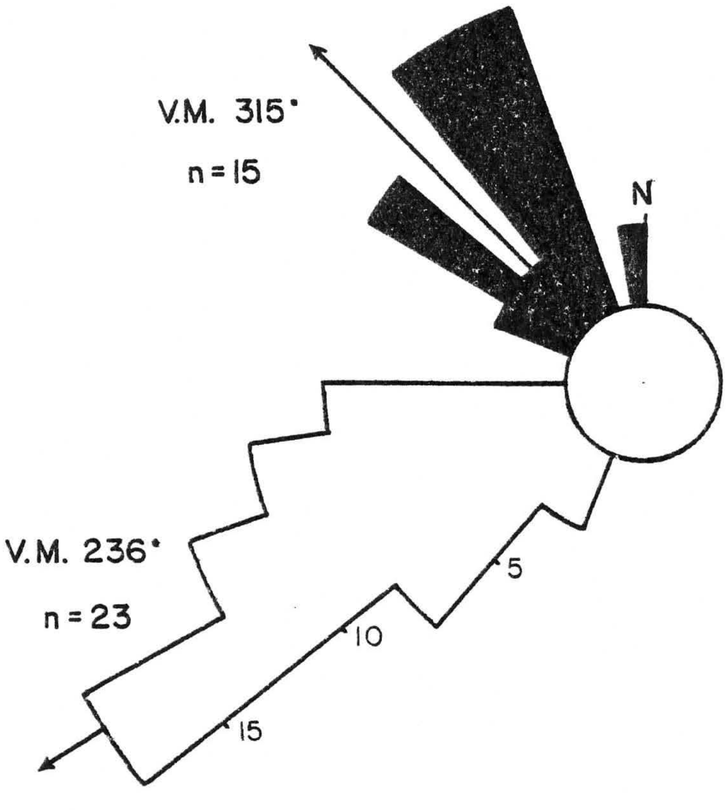


Figure 2-4

Figure 2-5: A rose diagram for planar tabular cross-beds exposed to the east of the epsilon cross-beds from the "CENTRAL" section. Note the close vector means for cross-bed dip directions here (316°) and in Figure 2-5 (315°).

CENTRAL

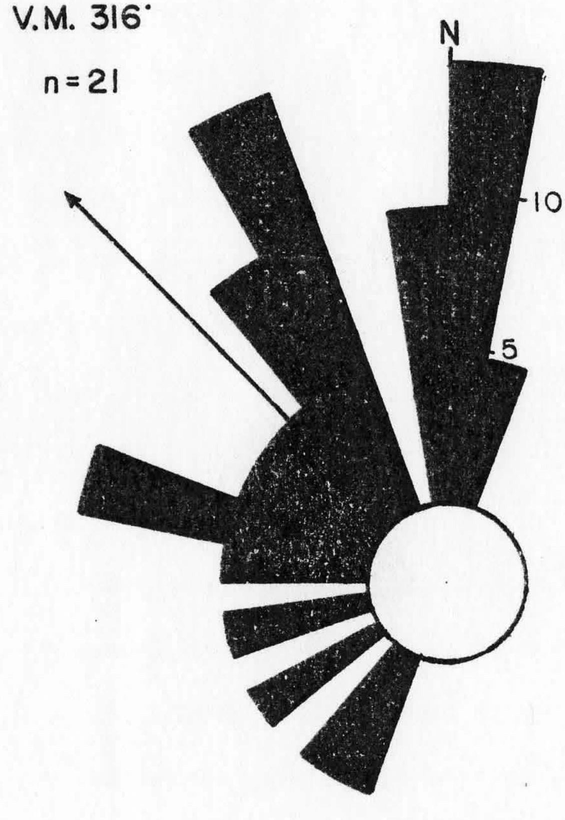


Figure 2-5

A channel geometry is suggested from observations made at the "WEST" field location. The opposing dip directions of epsilon cross-beds which face one another (see Figure 2-3 and Plates 2-9 and 2-10), suggest that they represent channel margin lateral accretion deposits. Justification for proposing that both margins of the inferred channel contain lateral accretion surfaces require that both surfaces were not active at the same time. This is apparent from the easternmost Hoodoo (Plate 2-9), which contains epsilon cross-beds at two levels.

It is interpreted that a relatively stable channel was present here. Local random shifting of the channel margins explains the bimodality of the epsilon cross-bed dip directions. Successively higher levels of lateral accretion (see Hoodoo in Plate 2-9) may have formed if the channel switched the sense of its lateral movement while the whole channel was aggrading. If the Virgelle Sandstone shoreline was prograding sufficiently fast, this scenario may explain the channel geometry exposed at the "WEST" section. (For a more detailed interpretation, see Chapter 4)

The epsilon cross-bedding from the "CENTRAL" field location is the best lateral accretion surface exposed at Writing on Stone. A second channel margin is not found at this location.

These lateral accretion sets (Plates 2-11 and 2-12) have a vector mean dip direction of 236°, which is similar to other southeast dipping epsilon cross-beds found at the WEST section (222°) and the EAST section (250°). At this location, one is also able to infer a paleoflow direction over the accretion surfaces. The dip direction of the planar tabular cross-beds within individual epsilon cross-strata is taken to indicate a preserved paleoflow direction. As illustrated in Figure 2-5, the vector mean of the dip directions of these planar tabular cross-beds (315°), is almost normal to the dip direction of the lateral accretion surfaces (236°).

There also exists a good correlation between a random sampling of planar tabular cross-beds measured away from the lateral accretion surface (316°) and those measured within it (315°). This data allows one to make a more confident proposal that the preserved paleoflow was approximately northwest (315°).

The presence of abundant planar tabular cross-beds outside the immediate influence of the lateral accretion surface may be interpreted to indicate that this channel deposit was more free to move laterally than the one exposed at the WEST section. The absence of a second channel margin may attest to this fact.

The presence of gently dipping planar stratification, similar to that exposed at Writing on Stone, has been interpreted by many authors to be beach lamination. The fact that this structure is most often found laterally adjacent to the channels where no sharp erosive contact between Facies B and Facies C exists is consistent with their being interpreted as beach lamination here.

In summation, Facies C consists of shoreline deposits which are underlain by Facies B swaley cross-stratification. The shoreline is occasionally marked by the presence of channels which cut down through the beach sediments into Facies B rocks. Preserved planar tabular cross-beds indicate that at least a component of the paleoflow was to the northwest. The strandline trend is oriented approximately normal to this paleoflow direction as indicated by the trend of the lateral accretion deposits (approximately southwest to northeast).

FACIES D:NON-MARINE SHALES AND SANDSTONES

Facies D may be divided into two easily recognized subfacies. Subfacies D1 consists of vari-coloured dark shales, while Subfacies D2 is made up of relatively thick, cross-bedded sandstones.

The nature of the contact between Facies D and Facies C is poorly known simply because good exposures are not available. The shales of Subfacies D1 are eroded far back from the underlying sandstones and, in most cases, are covered by prairie grasses and glacial material. When exposed, the shales are severly leached. Good exposures were found only where a recent rainfall had cut runnels into the thick muddy crust, coating most of the outcrop.

SUBFACIES D1:VARI-COLOURED SHALES

Subfacies D1 consits of a number of beds of various dark grey, brown and black shales. These shales contain large amounts of coalified plant material, and silt and sand-sized detrital grains. Vertical in situ roots are common in some horizons. Large flat-lying concretions dominate various levels within the outcrop. Infrequent, discontinuous, red-stained sandy beds less than 5 cm thick and lignite coal beds up to 15 cm thick are also found.

SUBFACIES D2:SANDSTONES

Subfacies D2 consists of medium-grained, brown sandstones, generally more than 20 cm thick. Some are observed to contain planar tabular cross-beds, while others appear to be massive with rare cross-laminations visible. These sandstone beds commonly contain concretions, mud rip-up clasts and coarse material between cross-laminations.

A four metre sandstone locally forms a resistant cap to the underlying shales. However, the sandstone is not observed laterally a few hundred metres away from the measured section. It is not known for sure if the sandstone is recessed, and thus covered in grassland, or if it is, in fact, laterally discontinuous.

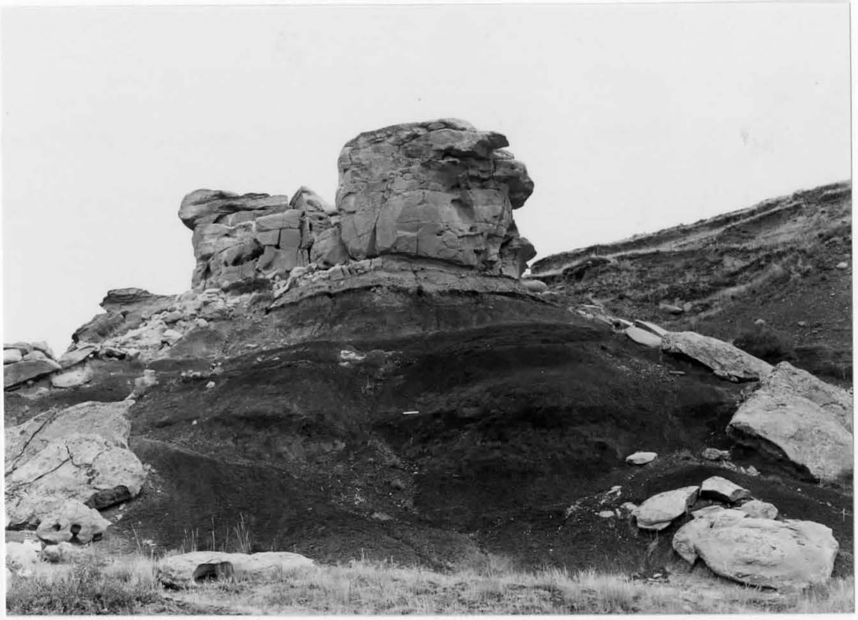
INTERPRETATION OF FACIES D

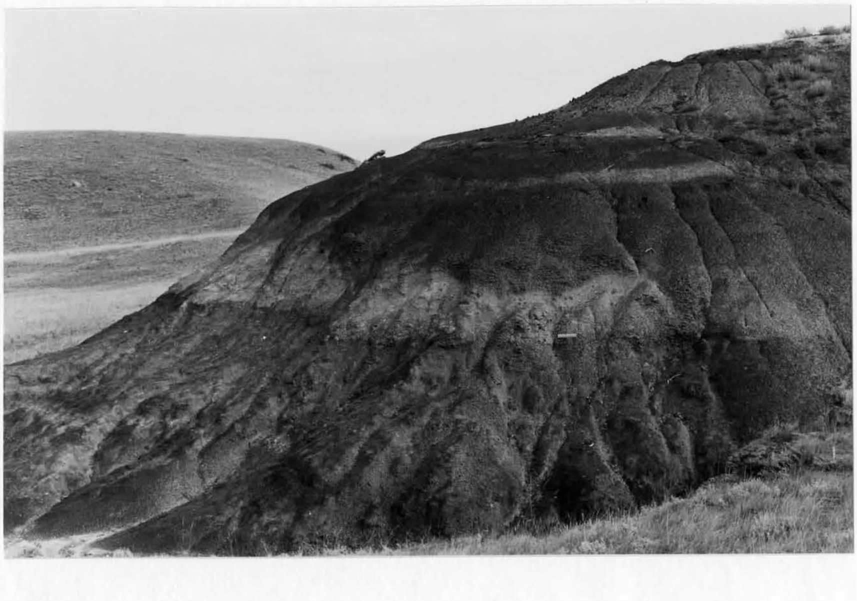
The characteristics of Subfacies D1 indicate that non-marine processes dominate. Abundant coalified plant material and the lignite beds indicate the accumulation of plant material. In situ, vertical roots also imply the presence of local vegetation. Silt and sand-sized clastic material, together with thin sandy beds, represent distal overbank deposition.

All of the above indicate that Subfacies D1 represents vertically accreted fine-grained sediments. The thick, cross-bedded to massive sandstones described in Subfacies D2 probably represent some sort of channel influenced deposition.

Plate 2-13: Photograph of the measured section at "South Coulee" (Figure 2-1), illustrating the Subfacies D1 vari-coloured shales and Subfacies D2 thick sandstone.

Plate 2-14: Photograph shows the same stratigraphic interval as Plate 2-13 (above) only 400 metres away. Note the absence of the thick Subfacies D2 sandstone.





CHAPTER THREE: PETROGRAPHY

METHODS

Twenty thin sections were prepared from field samples collected from Facies B and Facies C within the Virgelle Sandstone. An attempt to define the petrography was made by counting 400 points per section. These data were used to characterize sandstone composition.

One hundred additional counts for each of twelve stratigraphically ordered slides were used to measure quartz long axis grain size. These were in turn used to identify grain size trends and make further petrographic distinction of field defined facies.

Thin sections were impregnated with blue epoxy to help enhance porosity determinations. All samples were photographed for textural and mineralogical relationships using a standard petrographic microscope and a Scanning Electron Microscope.

RESULTS

The major detrital components of the sandstone are quartz and chert with significant feldspar, carbonates, oxides, rock fragments and micas (see Table 3-1). Rock porosity varies due to the development of carbonate cements, authigenic clays and tar.

Each section has been classified following McBride (1963) on a ternary "Percent Quartz plus Chert" vs "Percent Feldspar" vs "Percent URF" (see Figure 3-1). The data groups closely within the Subarkose field.

CONSTITUENTS

Quartz

Quartz grains were classified and plotted under four subdivisions after Basu et al (1975). These types are; (i) monocrystalline, non-

Table 3-1(i) (opposite); Table 3-1 (ii) (next page): Modal percentages of the mineral components of the Milk River Formation, (Virgelle Member) as determined from 400 point counts per thin section.

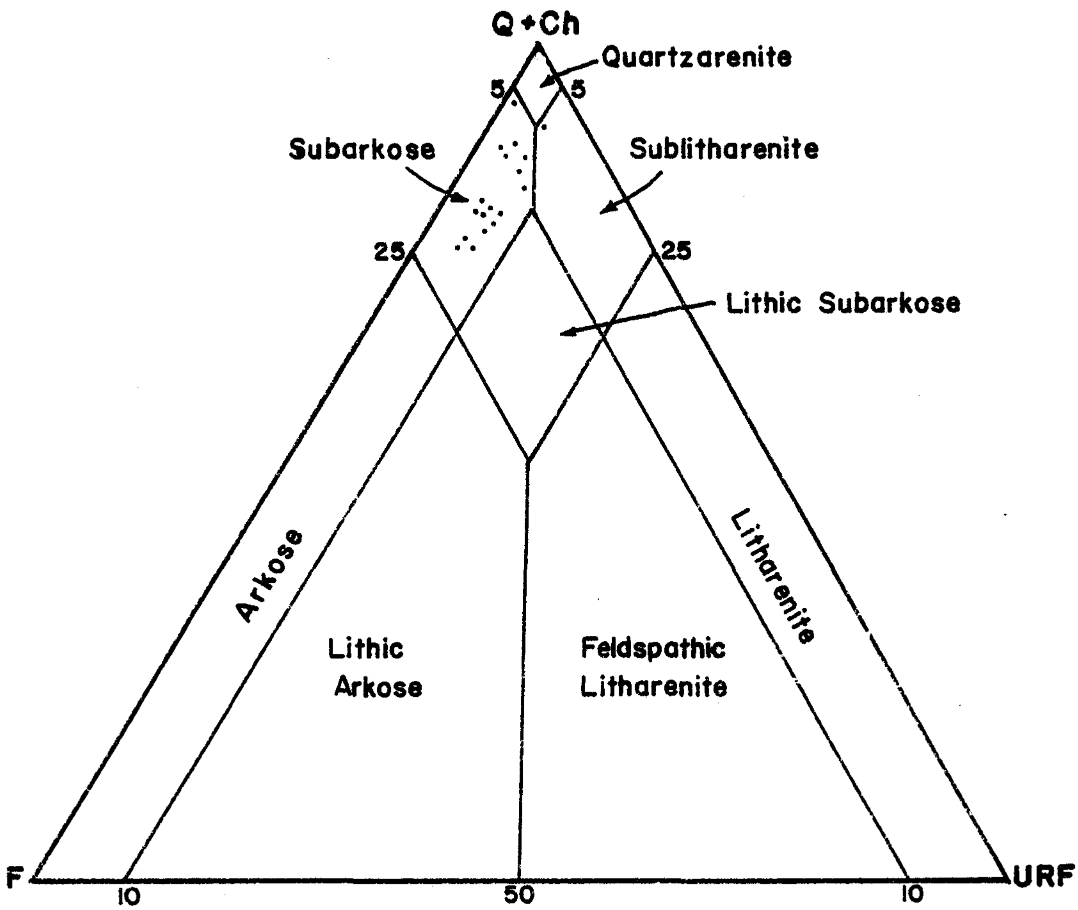
Section	Quartz	Chert	Feldspars	Rock Fragments	Opaques	Porosity	Carbonate	Clay	Mica
221	55	15	06	04	01	07	01	10	01
321	44	15	02	03	02	--	28	04	02
2-1	35	09	02	--	05	--	43	02	04
2-2	35	17	05	04	04	04	23	05	03
2-3	33	14	05	02	09	06	21	06	04
2-4	31	11	05	01	12	01	33	02	04
2-5	38	14	05	02	08	01	25	04	03
2-8	35	20	10	05	11	01	09	09	--
2-9	30	16	08	04	24	03	08	02	05
2-10	40	14	11	04	02	11	06	10	02

Table 3-1(i)

Section	Quartz	Chert	Feldspars	Rock Fragments	Opaques	Porosity	Carbonate	Clay	Mica
3-2	28	07	04	03	11	02	17	18	10
3-3	36	10	09	02	06	04	14	15	04
3-5	31	15	12	02	05	12	11	11	01
3-6	31	18	08	03	04	06	18	10	02
3-7	32	23	10	07	06	10	01	08	03
3-8	36	15	09	03	06	09	02	19	01
3-9	31	16	08	04	05	03	14	18	01
3-10	37	13	10	05	08	12	08	07	—

Table 3-1(ii)

Figure 3-1: Sandstone composition ternary diagram illustrating how data from this study groups closely within the subarkose field (after McBride, 1963).



McBride, 1963.

Figure 3-1

undulatory grains, (ii) polycrystalline with two or three crystals per grain, (iii) polycrystalline with greater than three crystals per grain, and (iv) monocrystalline grains exhibiting undulatory extinction requiring more than 5° rotation of the stage under crossed nicals.

For each thin section, the type of quartz was noted during point counting and is tabulated in Table 3-2. Since the quartz composition of each slide varied slightly, the Quartz Total category matches the number of grains counted as quartz for each individual slide.

From Table 3-2 it is evident that the majority of quartz grains are monocrystalline and non-undulatory. It is also seen that the majority of polycrystalline grains have greater than three crystals per grain.

Basu et al (1975) have proposed that the quartz crystallinity is indicative of original quartz provenance. They argue that on average, polycrystalline quartz grains with less than four crystals per grain are derived from plutonic sources, and polycrystalline grains with more than three crystals per grain are derived from metamorphic terranes. Figure 3-2 is a plot of quartz variety and indicates that the quartz provenance is from a mid to high-rank metamorphic complex.

Regional paleogeographic reconstructions of the Upper Cretaceous Milk River Seaway and the equivalent Niobrara Seaway from the north-western USA have been made by Williams and Burk (1964) and McGookey et al (1972). Both authors indicate the presence of moderate to strongly positive areas in northwestern Montana and northeastern Washington which might be considered as a source of mid-rank metamorphic quartz (see Figure 1-1).

Quartz overgrowths and or cements are not abundant and are, in fact, rarely observed. In general, grains appear poorly sorted and angular to subangular, although more sorted and rounded samples may be differentiated.

Since quartz is the dominant detrital mineral found in these sandstones, it was used for a thin section grain size analysis. The long axis of 100 grains were measured sequentially for twelve stratigraphically ordered samples. The "mean grain diameter" is plotted against stratigraphic height of the sample in Figure 3-3. A trend of increasing grain size is clearly evident from bottom to top of this section. In fact, facies described in the field are separable on this basis. The degree of roundness as compared with grain projections of Powers (1953) also accentuates this facies subdivision. Facies C, as shown, contains better sorted and subrounded grains compared with Facies B poor sorting and angular grains.

Chert

Chert is common and abundant in all slides observed. It ranges from coarse to cryptocrystalline, but these end members tend to be most abundant. Chert is occasionally seen to alter to quartz. Grains seem to mimic quartz grain sizes but tend to be more subrounded than the subangular quartz. In many cases, the chert is identified in plane polerized light by its reddish hue and rounded habit.

Microcrystalline zebraic chalcedony with radiating crystal habit is observed adjacent to recrystallized chert, however, this seems to be little more than a petrographic curiosity.

Figure 3-2: Plot of Quartz Crystallinity versus Quartz Extinction after Basu et al (1975). Note that the data groups closely within the Mid to High Rank Metamorphic provenance field.

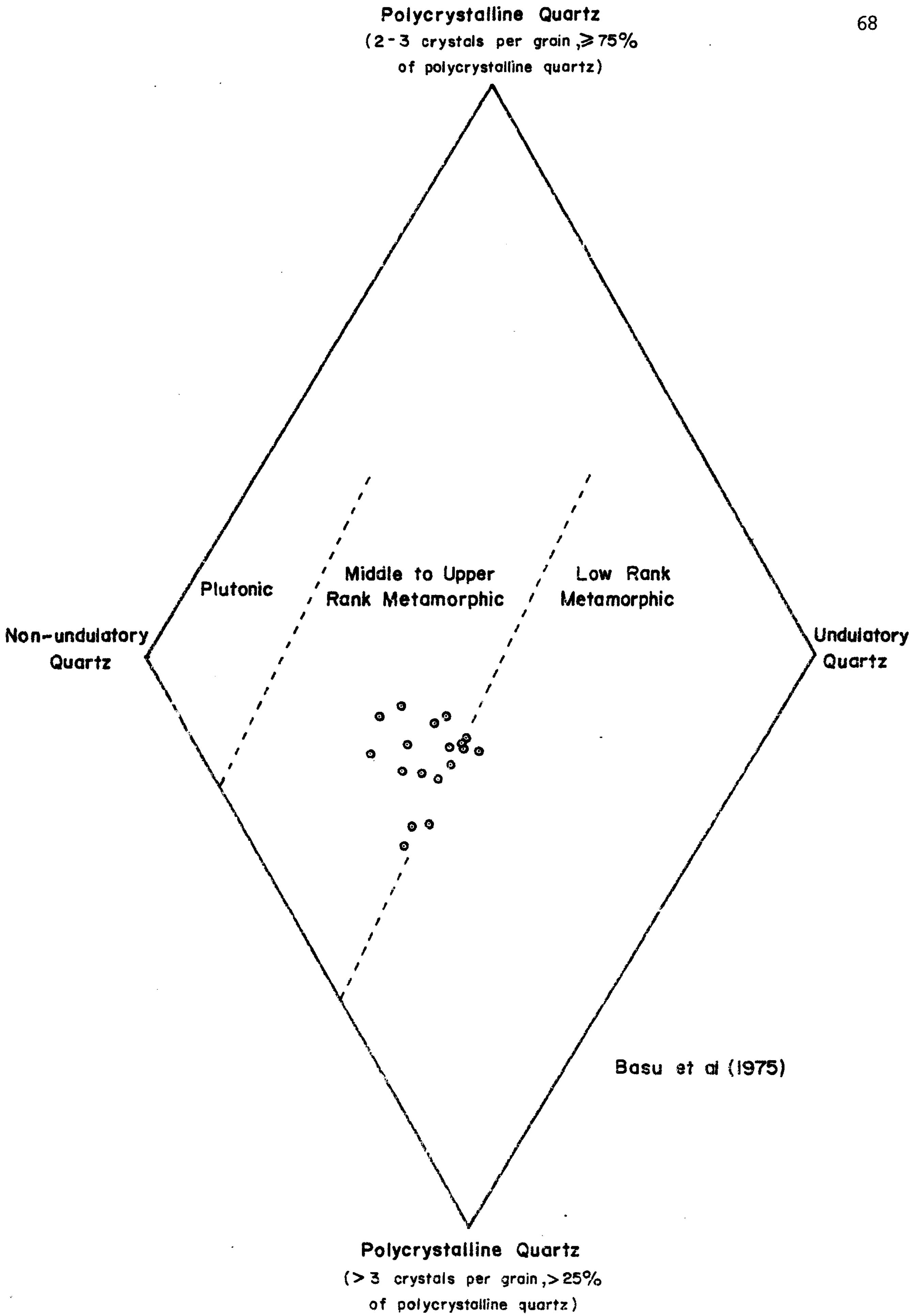
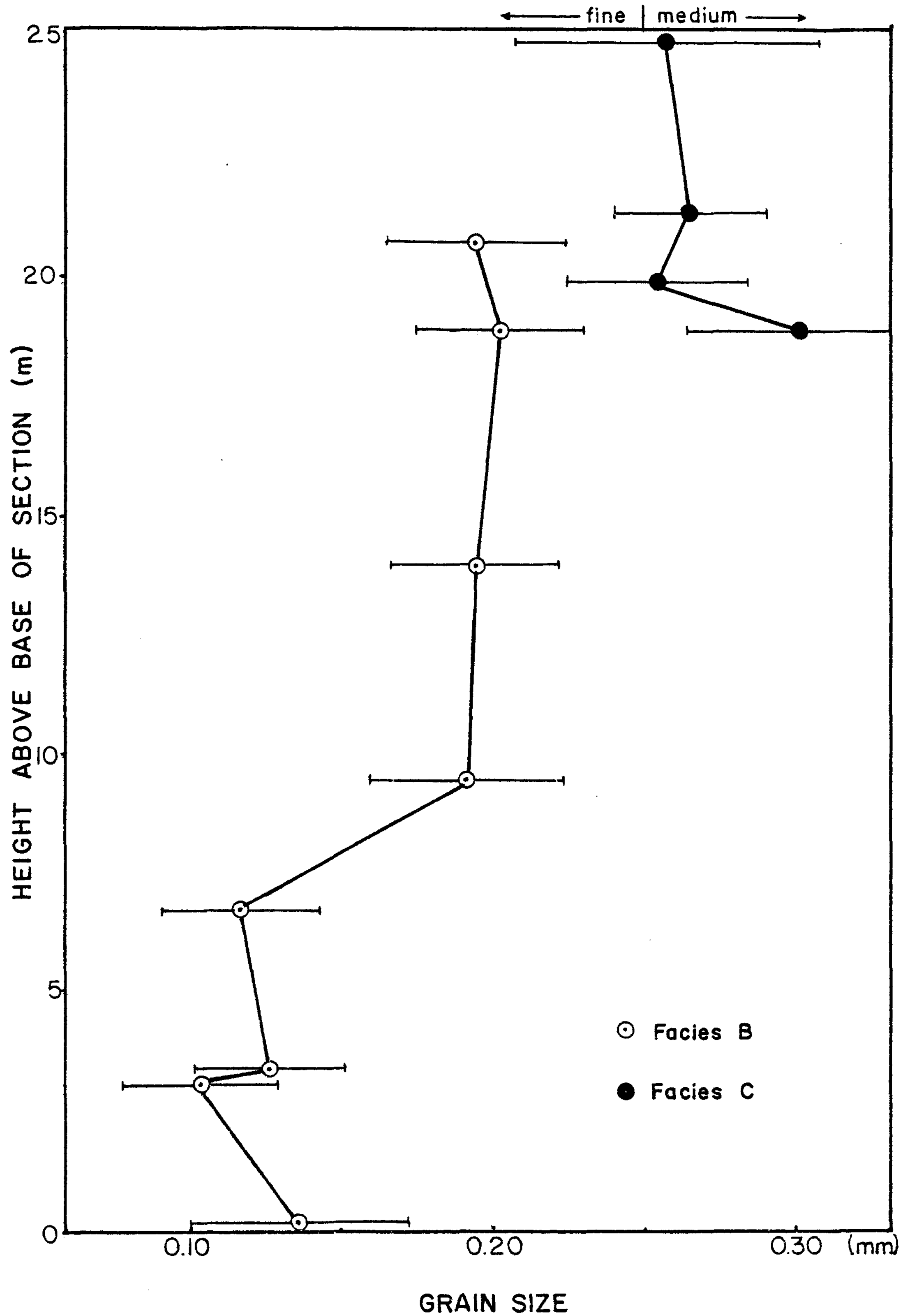

Polycrystalline Quartz
(2-3 crystals per grain, ≥75%
of polycrystalline quartz)
Plutonic
Middle to Upper
Rank Metamorphic
Low Rank
Metamorphic
Non-undulatory
Quartz
Undulatory
Quartz
Basu et al (1975)
Polycrystalline Quartz
(> 3 crystals per grain, > 25%
of polycrystalline quartz)

Table 3-2: This table shows the distribution of the various types of Quartz crystallinity after Basu et al (1975). The Total Quartz catergory represents the number of quartz grains counted per thin section.

Section Number	Monocrystalline, Non-undulatory, extinction(%)	Polycrystalline, 2-3 crystals per grain(%)	Polycrystalline, 3 crystals per grain(%)	Monocrystalline, Undulatory, extinction(%)	Total Quartz (#)
221	49	05	14	32	219
321	47	05	10	37	175
2-1	57	02	08	33	139
2-2	43	03	12	42	141
2-3	47	01	10	42	131
2-4	51	03	06	40	124
2-5	54	03	09	34	152
2-8	48	02	12	38	139
2-9	51	02	08	39	120
2-10	45	02	13	40	161
3-2	45	05	11	39	110
3-3	59	03	08	30	142
3-5	58	02	15	25	122
3-6	47	02	18	33	124
3-7	45	02	27	26	128
3-8	52	02	17	29	145
3-9	43	03	20	34	124
3-10	44	04	28	24	147

Table 3-2

Figure 3-3: A plot of Grain Size versus Height above the base of the section, illustrating the coarsening upward nature of the Virgelle Member. Error bars are one standard deviation either side of the mean grain size.



fine
medium
HEIGHT ABOVE BASE OF SECTION (m)
0
5
10
15
20
25
0.10
0.20
0.30
(mm)
GRAIN SIZE
Facies B
Facies C

Feldspars

Both alkali and plagioclase feldspars are present in all samples. A diagnostic replacement texture of plagioclase, in which twin planes and or cleavage planes are utilized as replacement channels, may result in the development of authigenic kaolinite. This textural relationship is well illustrated in Plates 3-1 and 3-2. Carbonate replacement of plagioclase feldspars is also observed but is not volumetrically significant.

Rock Fragments

Three types of rock fragments have been identified, but their relative abundances have not been differentiated in Table 3-1. Sedimentary rock fragments are generally fine-grained, quartz and chert mudrock fragments. Plutonic rock fragments contain polycrystalline quartz, biotite, chlorite and feldspars. These two types of rock fragment are most commonly encountered. Volcanic rock fragments, consisting of tiny lath-like feldspars in a fine grained matrix, are also present.

Accessory Minerals

A number of minerals occur as accessories. Biotite and muscovite micas and iron and titanium oxides are common. Detrital carbonate grains, mostly calcite and siderite with perhap abraded dolomite, are frequent in some sections. Zircon and tourmaline are also found.

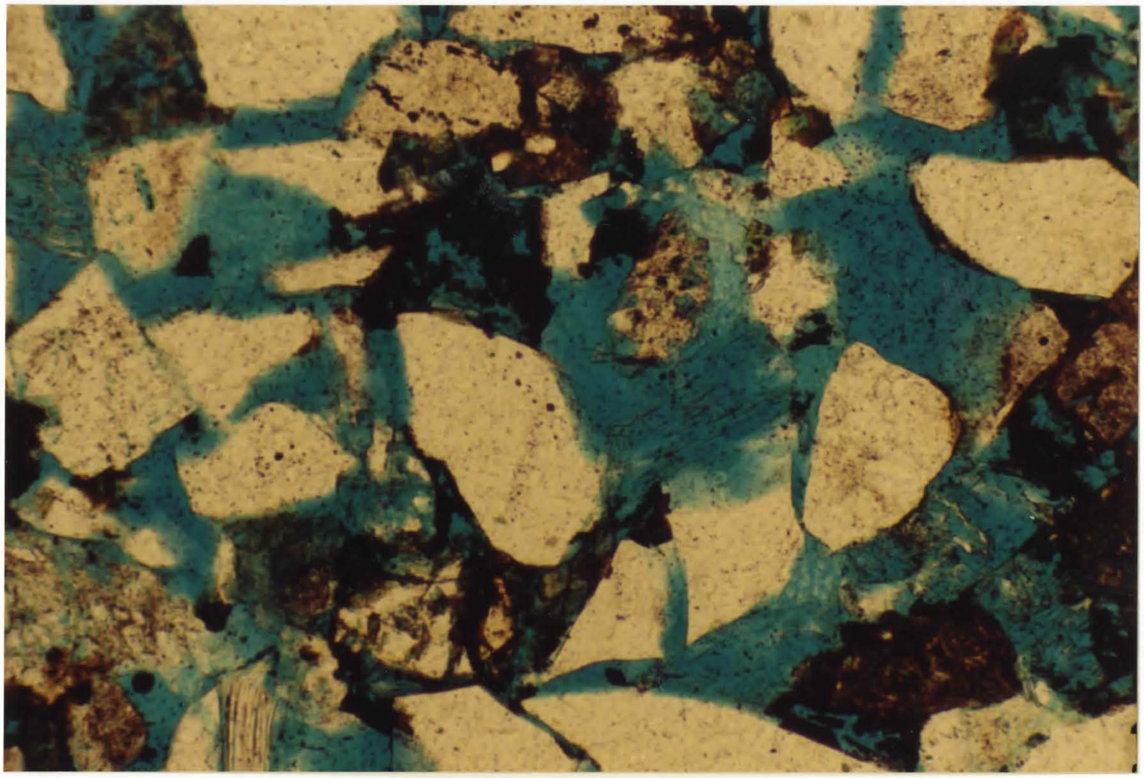
CEMENTS

Unraveling the sequence of cementation events is dependent on obtaining fresh field samples. This is quite a problem when working in a severely leached outcrop, and is further complicated by restrictions on sampling within the provincial park.

Patchy zones of carbonate cement, shown in Plates 3-3 and 3-4 are found in some sections. A vigorous fizz of acid on the outcrop suggests

Plate 3-1: Spiked remnants of plagioclase feldspar as observed in plane polarized light. (print width is 0.5 mm)

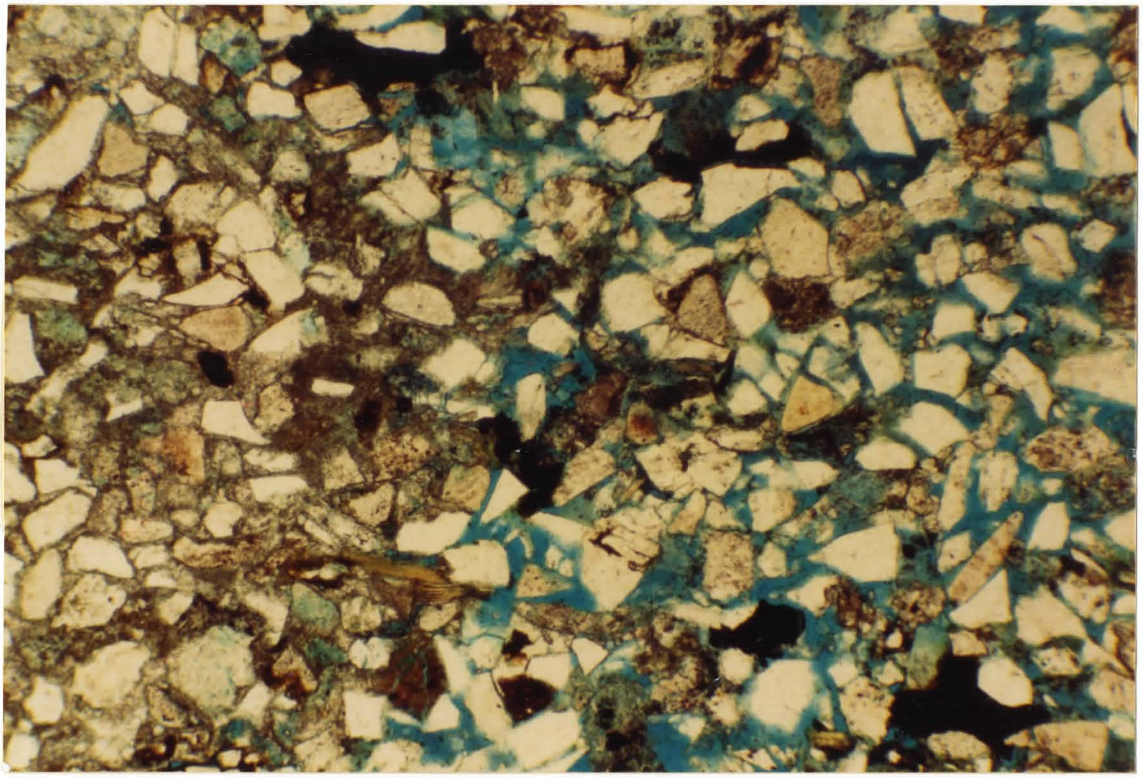
Plate 3-2: SEM photomicrograph of albitic plagioclase feldspar grain identified by EDAX. The disintegration of the grain leaves remnant cleavage spikes. Note tiny authigenic kaolinite flakes on (black arrow) and around the grain. (large scale bar 0.01 mm)

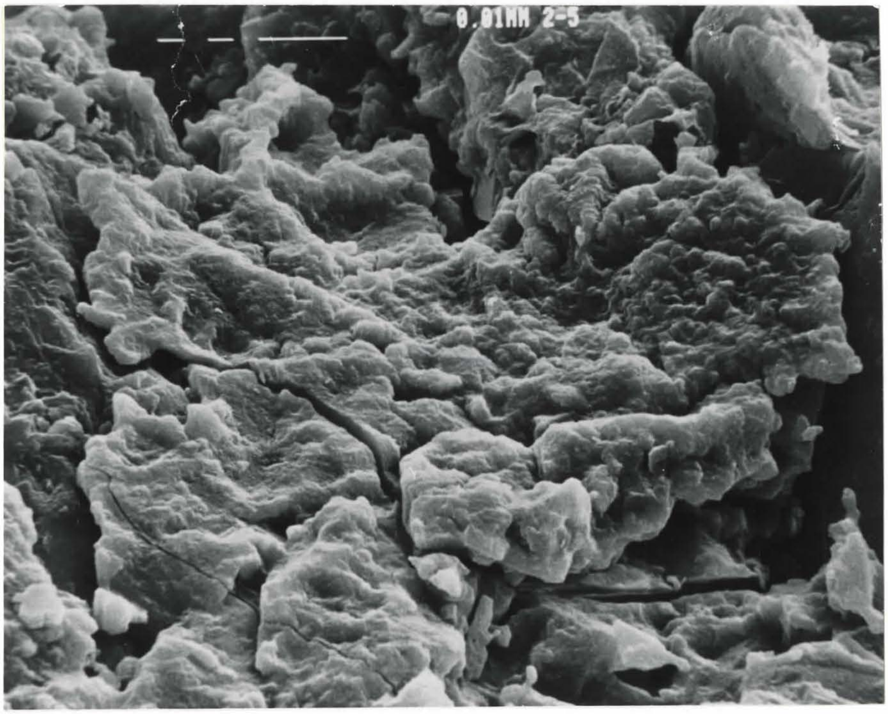



0.01MM 3-6

Plate 3-3: Plane polorized light photomicrograph of carbonate cemented zone (left) which is leached on the rim (middle). To the right, the sandstone is poorly cemented as illustrated by blue epoxy denoting porosity. (print width is 2.5 mm)

Plate 3-4: SEM photograph of calcite cement, identified by EDAX. Note etched and rounded surface. (large scale bar is 0.01 mm)




0.01MM 2-5

that carbonates are an important cement. Often, pod-like zones in thin sections appear leached and permeable on the outside edges and tightly cemented internally.

Rhombohedral carbonate grains are common constituents of carbonate cemented zones. SEM EDAX analysis revealed the presence of calcite cements (Plate 3-4) as well as rhombohedral dolomite and siderite grains. Plate 3-5 presents a number of rhombohedral dolomite grains in the absence of other carbonate cements. The corroded grain boundaries may suggest that they have been transported, however, the euhedral shape, together with the fact that similar looking grains occur in well cemented zones, (see Plate 3-3) indicates that these dolomite crystals are, in fact, diagenetic.

Plate 3-6 is an SEM photo which illustrates well the growth of diagenetic dolomite in a surrounding carbonate cement. Subsequent removal of some cement has etched the surface of the dolomite rhomb.

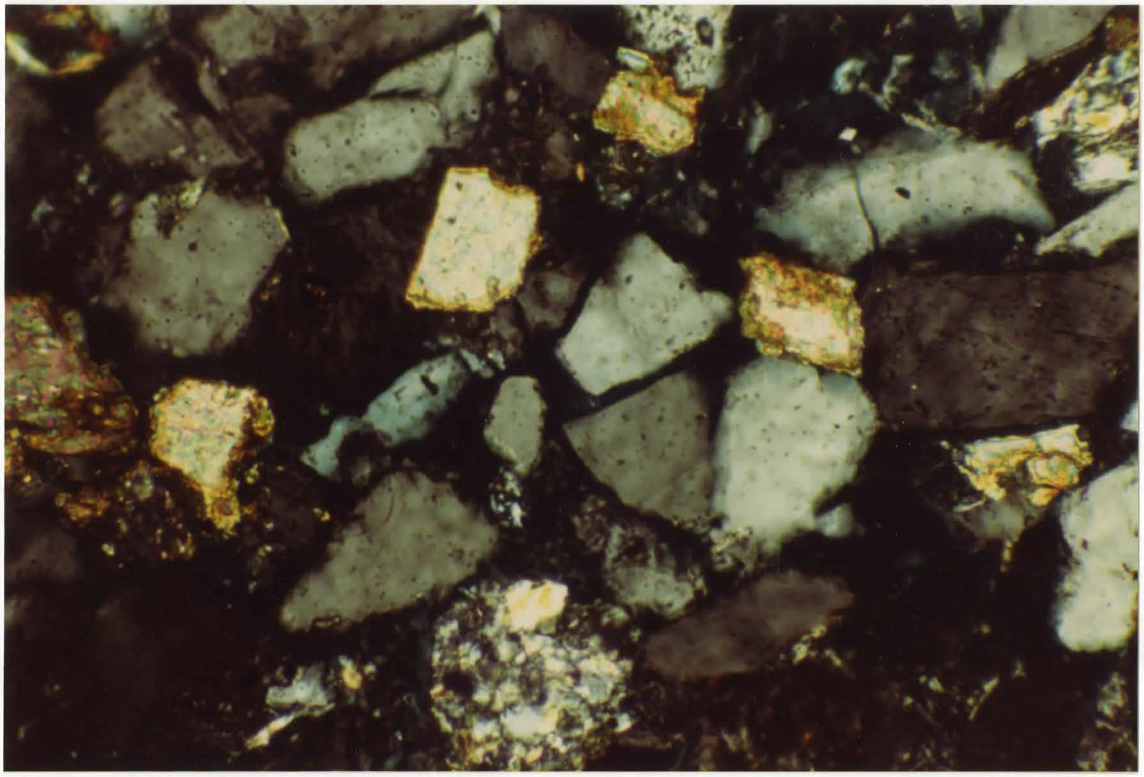
Rhombohedral siderite grains (Plate 3-7) are also observed in some samples. Groups of fresh looking crystals may be observed growing on top of detrital grains, indicating that they, too, are post-depositional diagenetic constituents.

The importance of authigenic clay as a cementing agent is not well known. From thin section counts, "clay cements" make up more than 10% by modal analysis of a number of slides (3-2, 3-3, 3-5, 3-6, 3-8, 3-9, 221, see Table 3-1).

The problem of whether or not clay minerals are cements in the strict sense or, in fact, simply detrital or authigenic grains sitting within pore space will be dealt with in a later section on clay mineralogy.

Plate 3-5: Corroded, rhombohedral dolomite grains in the absence of other carbonate cements. (print width is 0.5 mm)

Plate 3-6: Etched dolomite grain in a matrix of calcite between detrital quartz grains. (large scale bar is 0.01 mm)



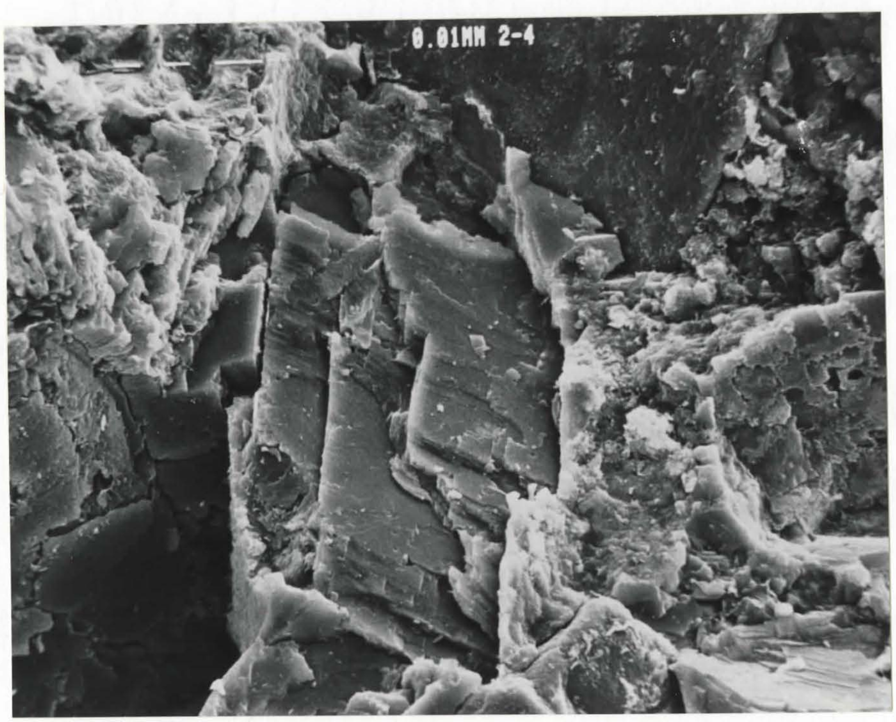
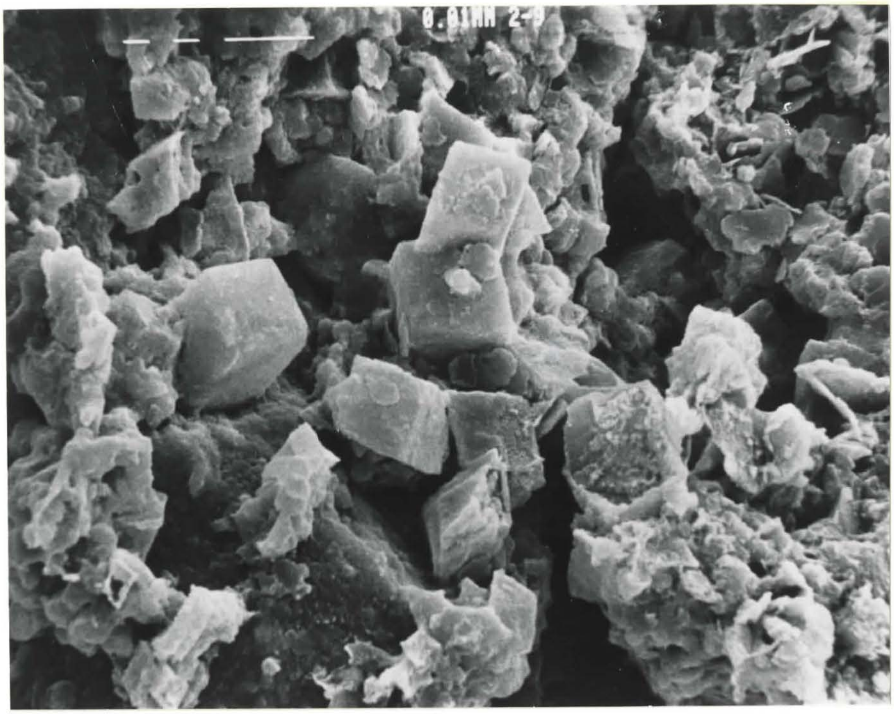
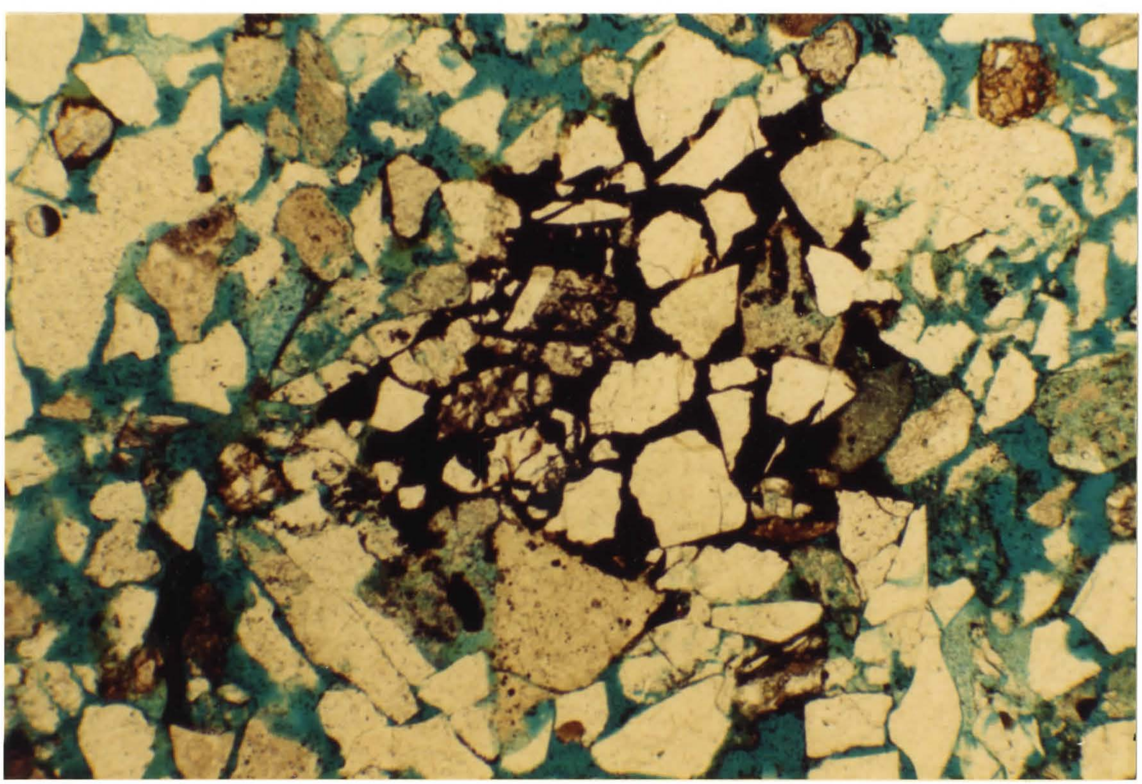

0.01MM 2-4

Plate 3-7: Clustered siderite crystals have grown on the surface of detrital quartz grains. (large scale bar is 0.01 mm)

Plate 3-8: A good example of lithified tar. It is a very tight cementing agent which may dominate some slides. (print width is 2.5 mm)


0.01MM



It should be added at this point that in thin section carbonate cements and clay minerals appear to be mutually exclusive. Presumably, the conditions of formation and preservation of these are intrinsically related.

A jet black, opaque material, tentatively identified as a lithified tar, appears to cement localized zones in some sections (Plate 3-8). These zones are generally tightly cemented, with porosity formed primarily at the expense of detrital grains.

Siderite also cements some rocks, giving them a reddish colour in outcrop. The presence of abundant ironstone concretions within the Milk River Formation probably represents a further stage of development of sideritization.

CLAY MINERALOGY

Authigenic kaolinite, smectite and chlorite are all abundant in the Milk River Sandstone. The well-developed crystalline habit of these minerals suggests that most are authigenic, not detrital in origin. Clay identifications were made by the use of EDAX and by comparison with photographs from Scholle (1979) and Reich (1983).

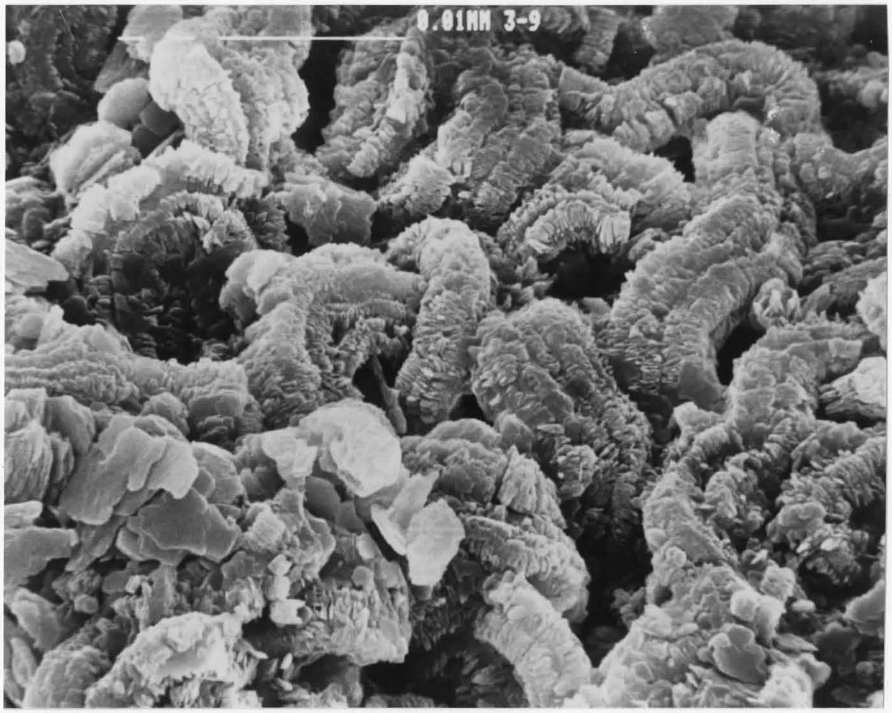
Kaolinite is most easily identified as vermicular stacks of pseudohexagonal plates (Plates 3-9 and 3-10). It may be found sitting within pore space (Plate 3-11), or as a cement, densely packed between detrital grains (Plate 3-12).

Chlorite is seen in thin section as a light olive green cement (Plate 3-13). SEM photographs reveal that chlorite occurs as thin, interlocking, densely packed grain coatings and pore fillings (Plate 3-14).

Smectite is mostly found as a grain coating cement. It occurs as crenulate, leafy sheets which are distinctive under the SEM (Plate 3-15). It may be observed to coat earlier formed kaolinite (Plate 3-16).

Plate 3-9: Wormy vermicular kaolinite. (scale bar 0.01 mm)

Plate 3-10: Book-like vermicular kaolinite. (scale bar 0.01 mm)


0.01MM 3-9

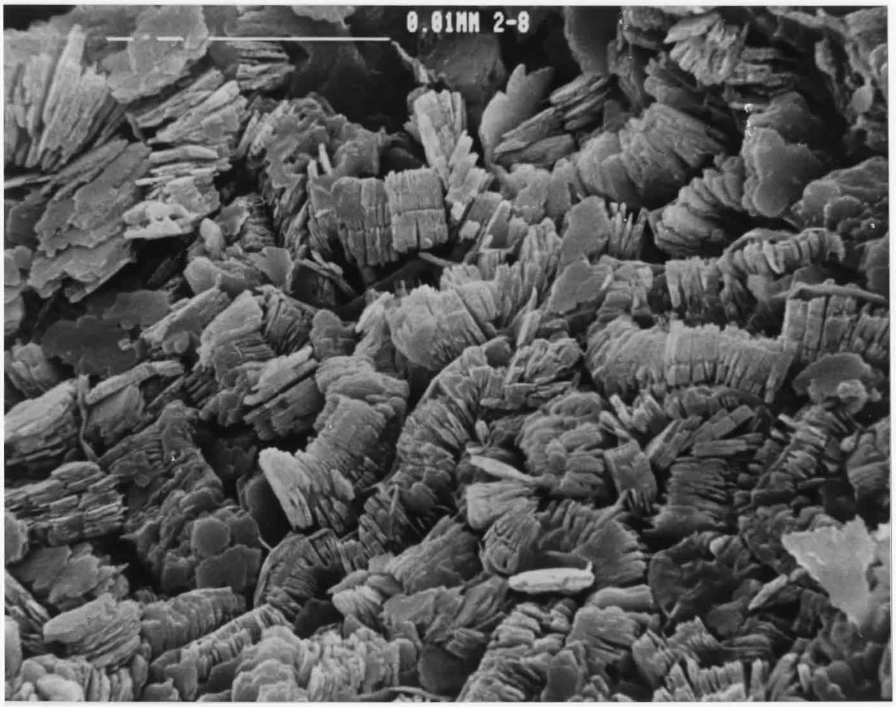
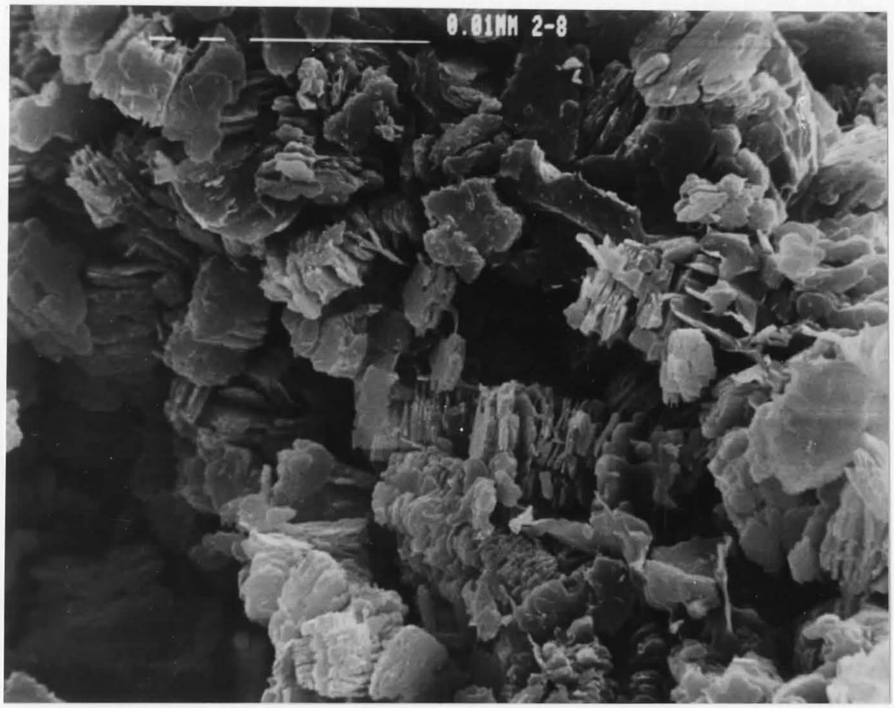

0.01MM 2-8

Plate 3-11: Pore lining kaolinite booklets. (scale bar is 0.01 mm)

Plate 3-12: Densely packed kaolinite cement between detrital grains. (scale bar is 0.01 mm)


0.01MM 2-8

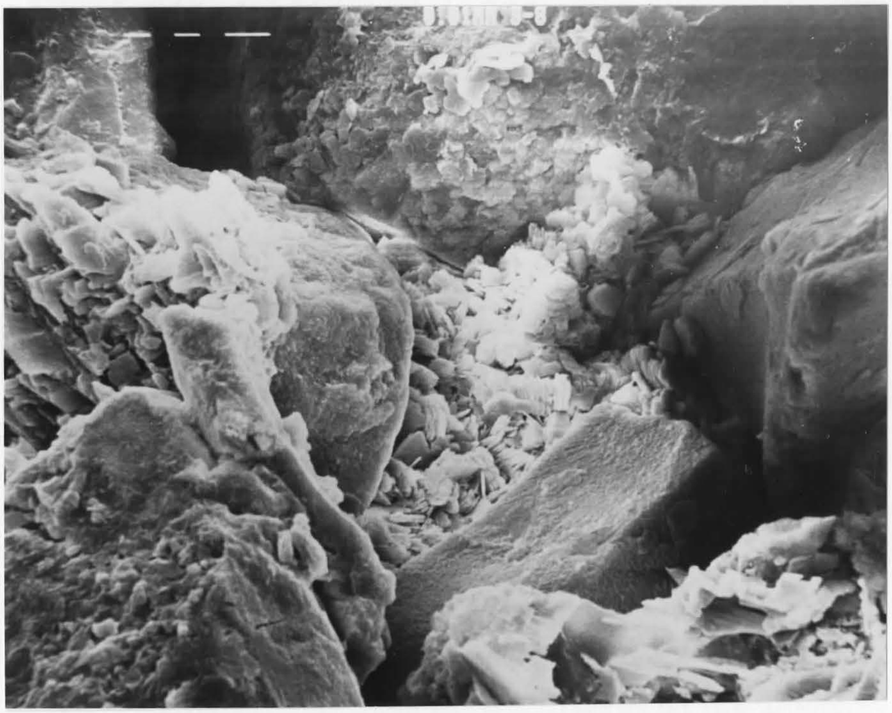
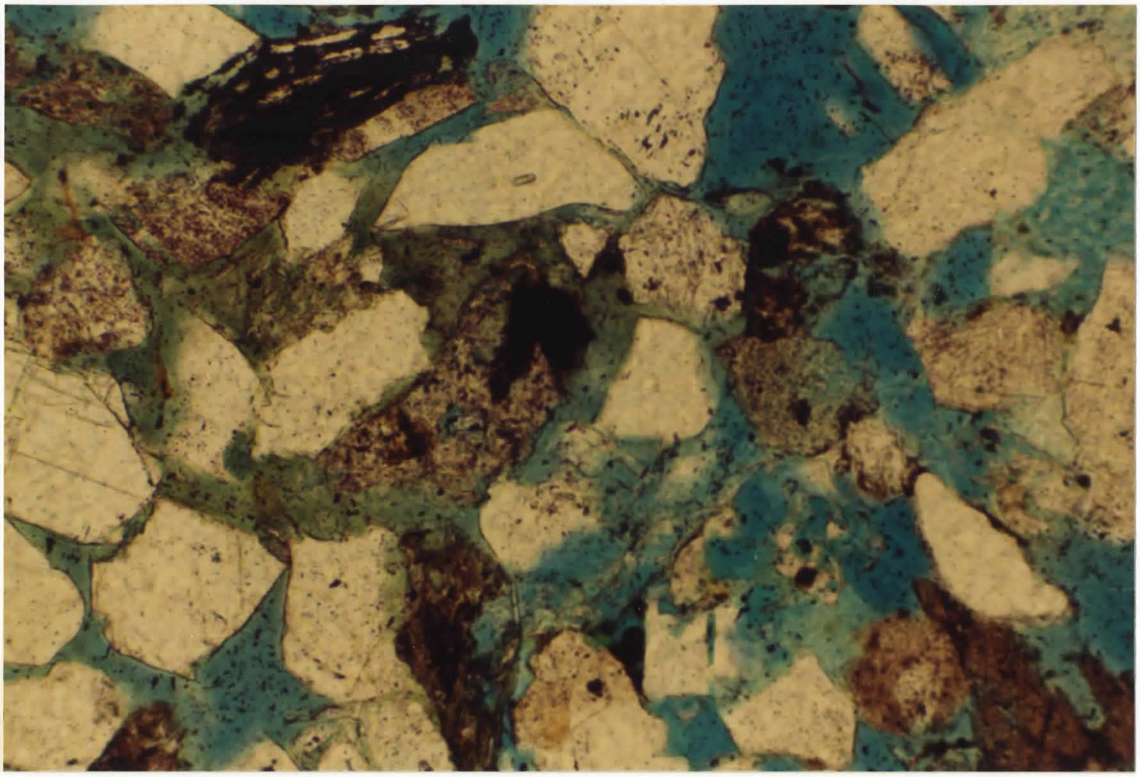


Plate 3-13: Light olive green chlorite cement. (print width is 1.0 mm)

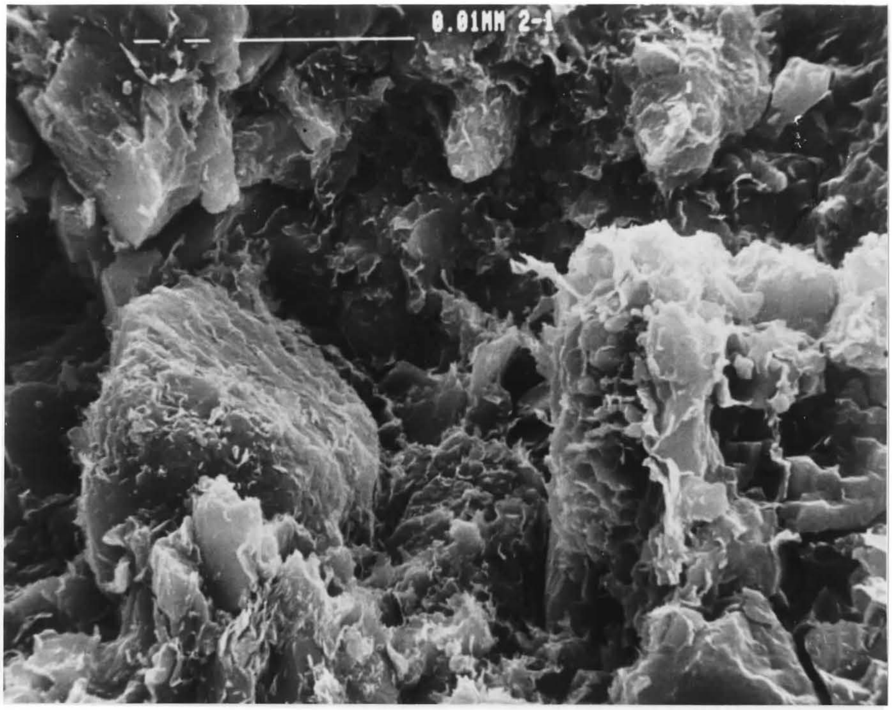
Plate 3-14: Interlocking habit of chlorite crystals coating and cementing detrital quartz. (scale bar is 0.01 mm)

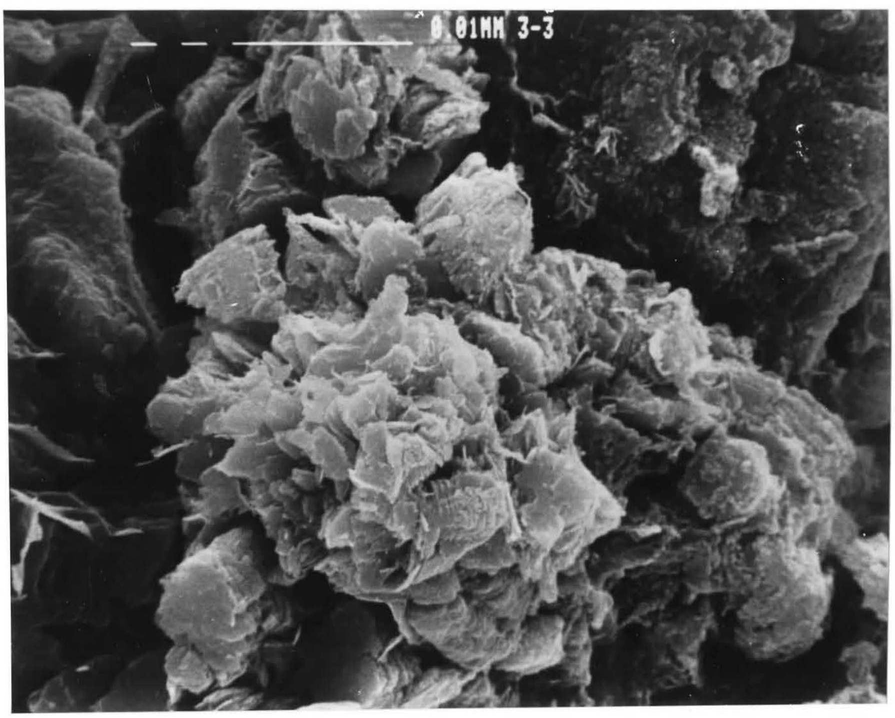



0.01MM 2-3

Plate 3-15: The leafy sheets on the surfaces of larger detrital grains is authigenic smectite. (scale bar is 0.01 mm)

Plate 3-16: Kaolinite booklets coated with smectite. (scale bar is 0.01 mm)


0.01MM 2-1


0.01MM 3-3

CHAPTER FOUR: INTERPRETATION AND DISCUSSION

Interpretation and Discussion

In Chapter 2 a facies subdivision was outlined and sedimentary structures were interpreted. This chapter is an integrated interpretation and discussion of the entire vertical sequence exposed at Writing on Stone.

The Milk River Formation has been interpreted to represent a regressive (prograding) shoreline on the western margin of the Upper Cretaceous Seaway (Weimer, 1960; Williams and Burk, 1964; Gill and Cobban, 1973; McGookey et al, 1972). Several lines of evidence suggest that the Milk River Formation at Writing on Stone was deposited within a marine to non-marine transition.

The succession of; Facies A marine sandstones and interbedded shales--Facies B swaley cross-stratified massive sandstone--Facies C cross-bedded massive sandstone--Facies D non-marine shales, sandstones and lignite seams, is consistent with deposition in a prograding marine shoreline environment. The upward increase in grain size from fine to medium sand (see Figure 3-3) within the Virgelle Member, is consistent with the similar shoreward coarsening of grain size observed in many modern offshore to onshore transitions (Howard and Reineck, 1972; Bernard et al, 1962).

Modern nearshore environments are commonly described in terms of their morphological features which both control and reflect the dominant processes operating there. Nearshore profiles show common similarities along both mainland coasts and the seaward coasts of barriers for a wide variety of settings, in terms of tidal range and wave regime (Clifton et al, 1971; Davidson-Arnott and Greenwood, 1976; Hunter et al, 1979).

McCubbin (1982) has described a generalized nearshore profile consisting of beach and shoreface elements. The beach is subdivided into the backshore consisting of a nearly level berm, and the foreshore consisting of the beachface with associated bars and troughs. The gently sloping shoreface extends seaward from the beach to depths from 6 to 20 metres. A break in the slope of the relatively flat shelf marks the end of the nearshore zone.

The shoreface is subdivided again into an upper and a lower element. The upper shoreface commonly contains one or more shore parallel bars. The lower shoreface has a concave upward profile and is relatively smooth.

A prograding shoreline sequence which exhibits an offshore to beach transition in the lateral sense, will exhibit the same transition in a vertical column. Thus, the vertical facies sequence observed in the Milk River (Eagle) Formation may be compared with a lateral facies sequence model like the one discussed above (Rice and Shurr, 1983; Rice, 1980).

At Writing on Stone, exposures of Facies A are correlative with the offshore to lower shoreface transition. The fissile and bioturbated shales represent normal background shelf sedimentation. The sharp-based, erosive sandstones are formed by rapid, episodic emplacement of sand on top of the shales. The presence of hummocky cross-stratification within some sandstone beds indicates that they have been reworked below fair-weather wave base by large storm waves feeling botton (Hamblin and Walker, 1979; Harms et al, 1982).

Facies B swaley cross-stratified sandstones form both the upper and lower shoreface deposits. The lower shoreface deposits consist of sandstones dominated by amalgamated swaley cross-stratification with rare hummocks and occasionally abundant parallel laminated beds of Subfacies B1. Subfacies B3 shales are also more common in the lower shoreface.

The presence of parallel laminations in the lower shoreface indicates that rapid deposition of sand is an important process. The fact that swaley cross-stratification, hummocky cross-stratification and parallel laminations are preserved here in the absence of any large scale cross-bedding implies that fairweather currents have not reworked these bottom sediments. It also implies that storm-influenced deposition is important (Harms et al, 1982; Leckie and Walker, 1982). The thin accumulations of shales (Subfacies B3) within the lower shoreface represent fairweather accumulation between depositional events. Large mudclasts found in some swaley beds were most likely ripped up from local accumulations of these shales during storms.

The upper shoreface is marked by the appearance of Subfacies B4 cross-bedded sandstones amalgamated with swaley cross-stratification. The "lower limit of cross-bedding" line in Figure 2-1 (see page 23), marks the approximate position of the transition from lower to upper shoreface deposits. The appearance of cross-beds within dominantly swaley cross-stratified rocks may be interpreted to represent an upward increase in the relative effectiveness of fairweather processes.

In the lower shoreface, fairweather processes cannot effectively rework sand. Thus, only the storm-generated sedimentary structures are preserved there. In shallower water, fairweather currents get progressively stronger and are able to rework sand more efficiently. Although storm deposition still dominates, a few fairweather cross-beds are preserved in the upper shoreface.

It should be mentioned at this time that the upper shoreface deposits are observed to grade upwards into Facies C beach swash lamination, in areas away from epsilon cross-beds, where a sharp, erosional contact between Facies B and Facies C is not observed. The implication here is that swaley cross-stratification may persist up to the beach, indicating that storm-influenced deposition overwhelms fairweather processes. A similar observation has been made by Bullock (1981) working at the same stratigraphic interval in the foothills.

In summary, the Milk River Formation can be interpreted in terms of an offshore transitional to shoreface to beach lateral facies sequence. The persistence of swaley cross-stratification up to the beach implies that the Milk River shoreline was storm-dominated.

At Writing on Stone, the above interpretation is complicated by the presence of epsilon cross-beds of Facies C. These have been interpreted in Chapter 2 to represent lateral accretion deposits on the margin of some type of channel.

Because these channel deposits cut into beach and upper shoreface, they must have existed contemporaneously with these environments. Two types of channel may be considered; a barrier tidal channel or a tidal estuary. Tidal channels are intimately associated with barrier islands, lagoons, washover fans and ebb and flood tidal delta complexes. Tidal estuaries are more commonly associated with strandplains. They, too, are influenced by ebb and flood tides, but are also affected by their own freshwater discharges.

A tidal estuary environment is favoured over barrier tidal channels for channel deposits found at Writing on Stone for a number of reasons. For one, there is no evidence of a flood tidal delta complex, which is expected to be preserved in a prograding coastline (Reinson, 1979). Secondly, no distinct washover fan deposits can be distinguished above (landward) the beach level and thirdly, a lagoonal facies is not recognized. Also, it is felt that a tidal estuary environment better explains the paleocurrent data.

In a barrier tidal channel, one might expect to get bimodal paleoflows corresponding to the ebb and flood tides (Reinson, 1979). The preserved paleoflow directions implied from cross-beds within lateral accretion surfaces (315°) and from cross-beds independent of the lateral accretion surfaces (316°) at the CENTRAL section are roughly northwest. This represents unimodal, ebb-oriented flow in a northward prograding strandline which itself is oriented roughly northeast - southwest.

In a tidal estuary, the flood tide opposes the normal estuarine discharge, thus, the probability of forming abundant flood-oriented cross-bedding is remote. However, during ebb tide, tidal currents and normal estuarine discharge are combined. Thus, dominantly ebb-oriented cross-bedding is expected to be preserved within the channel and in the ebb tidal delta complex which forms at the mouth of the estuary. Note that the ebb tidal delta complex related to barrier tidal channels has a low preservation potential. Constant alongshore drift is constantly forcing the channel mouth and ebb-oriented cross-beds to migrate down drift.

It is concluded that the "channel deposits" at Writing on Stone represent deposition in a tidal estuary. Consequently, parts of the Milk River shoreline are tidally influenced as well as storm influenced.

The vari-coloured dark shales and the sandstones of Facies D are demonstrably non-marine. Terrestrial accumulation of abundant plant material, lignite seams and in situ roots, together with vertically accreted muds and poorly developed sandy beds, are aspects of deposition landwards of the beach strandplain. The thick 4 metre cross-bedded sandstone observed at the top of the SOUTH COULEE section may represent actual deposition within a fluvial channel. The poor nature of the outcrop makes further interpretation difficult. It is safe to say that Facies D probably represents terrestrial and vertically accreted deposits on a non-marine flood plain.

In summation, the Milk River Formation at Writing on Stone can be interpreted as a progradational nearshore strandline deposit which is storm- and tide-influenced.

Finally, determination of the regional paleoslope direction from the complex nearshore zone at Writing on Stone is difficult. However, a more general definition of the strike of the paleoshoreline is possible. Since lateral accretion is driven by alongshore currents, the dip direction of epsilon cross-beds should roughly parallel the trend of the strandline. At Writing on Stone, the shoreline is approximately southwest - northeast. This compares with the northwest - southeast shoreline trend at the deposition edge near Medicine Hat (see Figure 1-5).

CONCLUSIONS

1. The vertical facies succession at Writing on Stone can be interpreted in terms of a storm- and tide-dominated offshore to non-marine transition.

2. Fairweather deposition of medium-sized cross-bedding within the shoreface has been overwhelmed by storm deposition of swaley cross-stratification which persist up to the beach.

3. Analysis of paleoflow data from within what are interpreted to be tidal estuaries suggests that the regional strandline at Writing on Stone trends roughly southwest to northeast.

4. Petrographic analysis of the main sandstone body indicates that it is a Subarkose which exhibits a coarsening upward grain size trend.

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