THE DEPOSITIONAL HISTORY OF THE LOWER CRETACEOUS VIKING FORMATION AT JOFFRE, ALBERTA, CANADA

THE DEPOSITIONAL HISTORY OF THE

LOWER CRETACEOUS VIKING FORMATION

AT JOFFRE, ALBERTA, CANADA

BY

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ABSTRACT

Detailed core and log correlations have shown that there are three erosion surfaces within the Viking at Joffre, and that each surface is overlain by unusually coarse sediment. The main sand development at Joffre overlies the E2 erosion surface and comprises cross-stratified, medium-grained to pebbly sandstones. The basal portion of this sandstone tends to be glauconitic. This sandstone is interpreted to be the remnant of a shoreface which developed at Joffre in response to a relative lowering of sea level. Evidence for exposure southwest of the shoreface was removed during the subsequent transgression, as was the upper shoreface and beach. Only the mid to lower part of the shoreface was preserved and blanketted by burrowed marine mudstone.

In total, five bounding surfaces have been defined at Joffre, three of them are demonstrably erosive and the other two are designated as core markers. These bounding surfaces serve to divide the formation into six distinct sedimentary packages which tend to coarsen upward. Viking deposition at Joffre appears to have been controlled by fluctuations of relative sea level.

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CHAPTER 1. STATEMENT OF THE PROBLEM

1.1. Introduction

This research project was set up in 1983 to contribute to the ongoing studies of shallow marine sedimentation, specifically within the Cretaceous Western Interior Seaway.

Many of the sandbodies within this seaway are mapped as long and linear features, encased in marine shale. The sands are potentially good hydrocarbon reservoirs, and their enclosing shales are effective stratigraphic traps. The resultant economic attractiveness of these sandbodies has led to prolific drilling programs. In this way, industry has provided research teams with an abundance of subsurface information with which to study these subcropping sandbodies.

1.2. The Problem - as defined in 1983

Many elongate Cretaceous sandbodies, which display a general NW-SE trend are indicated in GSC Maps 1558A and 1559A (1981). The depositional setting of these elongate sandbodies has been considered "offshore", perhaps as far as tens or hundreds of kilometres from land (Slatt, 1985; Walker, 1984, p.164). Evidence for their offshore placement has been based upon the following observations:

i) the sandbodies are rooted in marine shale and gradationally coarsen-upwards; some are capped with conglomerate, and all are blanketed by marine shale;

ii) the sandbodies themselves show no evidence of emergence (i.e. rooted horizons, desiccation cracks and soil developments are absent);

iii) the sandbodies lie seaward of the nearest established contemporaneous shoreline.

Granted that these sandbodies evolved in offshore settings, the problems then pertained to understanding the dynamic equilibrium which existed between these sandbodies and the surrounding shelf. The two main problems to solve and their "spin-off" queries were:

Problem 1. How was the sand transported offshore?

1a) Did episodic deposition have a role in offshore sediment transport?

1b) Is there evidence for geostrophic or turbidity current transport?

1c) Was deposition within wave base?

1d) Was deposition within tidal range?

Problem 2. How was the sand focussed into elongate features?

2a) How can the margins of the sandbody be defined?

2b) How does the sedimentology of off-field areas compare with on-field areas?

2c) What does the basal contact of the sandbody look like?

2d) Were the sandbodies resting in topographic lows or on highs?

2e) What is the relationship between the elongate sandbodies and the linear zone of reservoir sandstone?

Some of these questions pertaining to shallow marine settings have been addressed in ancient subsurface and outcrop studies as well as in modern studies.

1.3. Choosing the Study Subject and Area

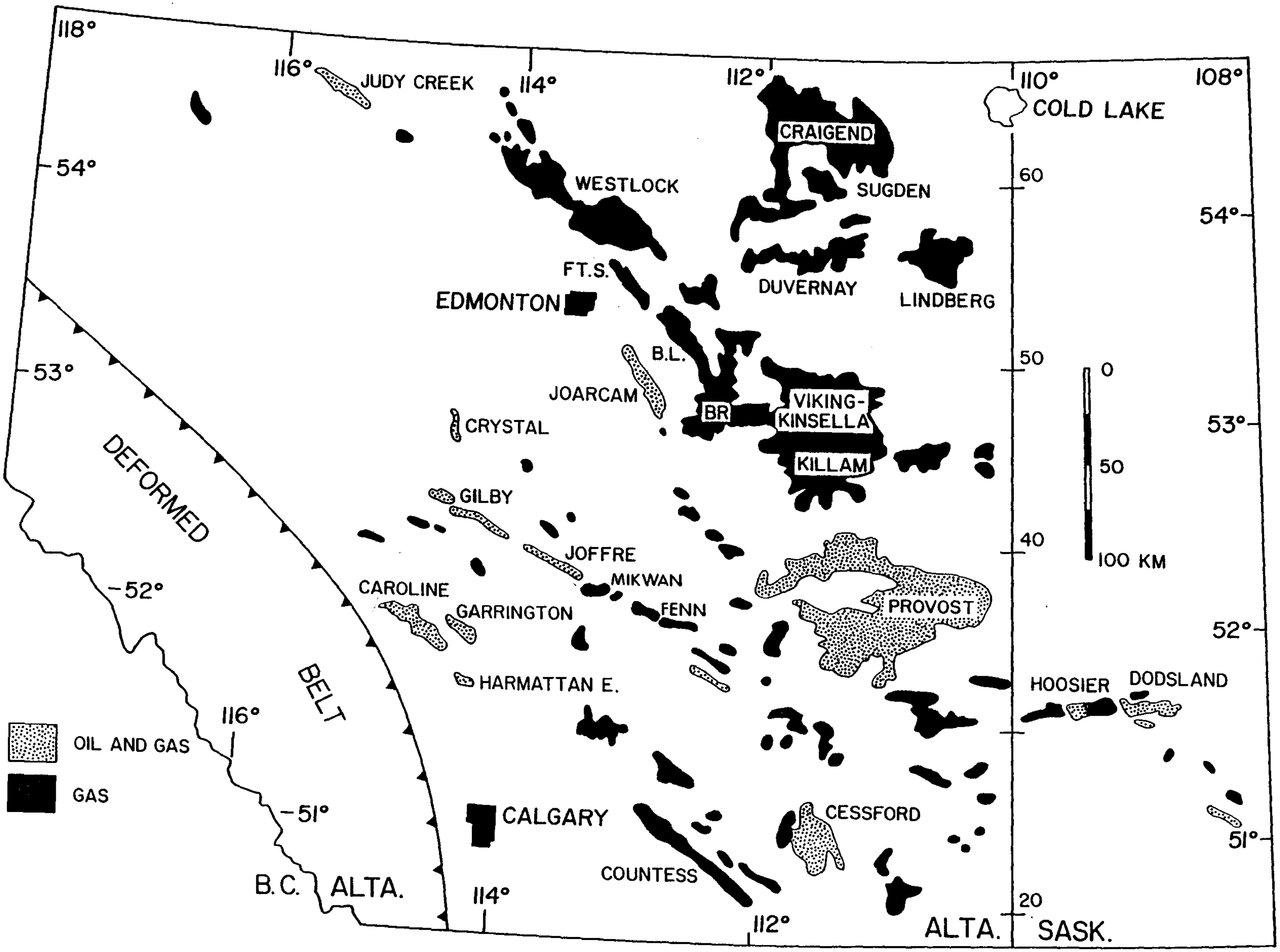
During the early 1980's at McMaster, several shallow marine research projects were already in progress. These studies of elongate sandbodies, encased in marine shale were directed at the Upper Cretaceous Cardium Formation.

The Lower Cretaceous Viking Formation was chosen because of the similar offshore settings of elongate sandstone and pebbly sandstone bodies. These sandbodies were likewise enveloped by marine shales. It was hoped that comparisons and contrasts would be found, which would both test some of the evolving ideas about the Cardium Formation, and shed light on Viking deposition. Of particular interest at the time were features which could be attributed to storm-related processes and channelized scour.

The Joffre area was chosen because it contains several representative elongate sandbodies as indicated on GSC Maps 1558A, 1559A (1981). In fact, the area contains four colinear elongate sandbodies (Figure 1.1): Gilby, Joffre, Mikwan and Fenn. The colinear arrangement of the sandbodies affords the opportunity to study NW-SE downtrend variations over a total distance of 100 kilometres. The discontinuous nature of these successive sandbodies is also intriguing. The location of the Viking paleoshoreline is unknown, and it seems that these sandbodies were sitting out in the middle

Figure 1.1 **Distribution map of Viking sandbodies in Alberta and Saskatchewan.** These sandbodies have been delineated from hydrocarbon production estimates provided by the Energy Resources Conservation Board. Note the linearity exhibited by the majority of sandbodies. Evidence of subaerial exposure (rooted horizons) has been found in cores of the Crossfield area, near Calgary (Amajor, 1980), but the exact position of the shoreline has not yet been determined.

The Gilby-Joffre-Mikwan-Fenn trend is shown in the central portion of the map. Map redrawn from GSC Maps 1558A and 1559A, 1981.


118°
116°
JUDY CREEK
114°
112°
110°
108°
COLD LAKE
CRAIGEND
SUGDEN
54°
WESTLOCK
60
54°
FT.S.
DUVERNAY
LINDBERG
EDMONTON
B.L.
53°
50
0
JOARCAM
BR
VIKING-KINSELLA
53°
CRYSTAL
KILLAM
50
DEFORMED
GILBY
JOFFRE
40
100 KM
MIKWAN
-52°
CAROLINE
FENN
GARRINGTON
PROVOST
52°
BELT
HARMATTAN E.
HOOSIER
DODSLAND
116°
OIL AND GAS
GAS
-51°
CALGARY
CESSFORD
51°
COUNTESS
B.C.
ALTA.
114°
20
112°
ALTA.
SASK.

of nowhere, therefore, satisfying the "offshore" setting prerequisite for a shallow marine study.

The logistics of the Joffre vicinity were also appealing. The closely-spaced well density at Gilby and Joffre easily supports a detailed sedimentological study. In fact, the study area was later reduced in size; Gilby was undertaken as a separate thesis by Holly Raddysh (1986).

The main thrust of this thesis is aimed at Joffre because of the abundance of well data associated with this field. The remaining two fields, Mikwan and Fenn, have more limited data. One of the ultimate intentions of this thesis is to prepare for a "link up" with Raddysh's research of the Gilby area.

In summary, the Viking Formation in the Joffre vicinity provides an opportunity to study several colinear, elongate offshore sandbodies.

1.4. The Problem - redefined in 1985

As research progressed, it became obvious that the original problem needed to be redefined. The original questions were not the most appropriate ones in light of evolving ideas concerning the recognition of erosional breaks within vertical facies sequences. Regionally extensive scour surfaces documented in this (Joffre) area began to suggest that sea level changes may have had a critical role in the depositional history.

Changing sea levels and "shifting" shorelines became possiblities which conflicted with previous assumptions of a "fixed" shoreline with long distances of offshore sediment transport and focus. A new set of "main problems" and "spin-off" questions had to be defined:

1. **Did the scour surface have an effect on the development of an elongated sandbody?**

1a) What does the scour surface look like in core?

1b) What is the three-dimensional shape of the scour surface?

1c) What is the maximum depth of scour associated with each erosional surface?

2. **What was the history of the sea level changes?**

2a) Do sedimentary structures indicate significant changes in the depositional conditions before and after each scour event?

2b) Where is the closest approximation of shoreline advance?

These revised problems are also being studied for the previously mentioned Cardium Formation (Plint et al., 1986: Bergman and Walker, 1986 and in press).

Recognition of scour surfaces does not detract from the initial purpose of studying the peculiarly elongate shallow marine sandbodies. The erosional breaks in the Viking at Joffre seem to be found within previously described "continuously coarsening-upward sequences". This in turn may warrant a careful re-examination of similarly described "offshore sandbodies" at other locations. Although the precise relationship of the elongate Viking sandbodies to their shoreline remains unknown, the interpretation suggested in this thesis will show that the setting is probably within the shoreface, such that it was distinctly influenced by sea level fluctuations. The shoreface setting proposed here removes the depositional complexity of transporting sand offshore, and focussing it into linear strips.

CHAPTER 2. STRATIGRAPHY AND STUDY METHODS

2.1. Study Area

The detailed study is centred on Joffre, covering Townships 37-39, and Ranges 24-27 west of the fourth Meridian (Fig. 2.1). Several cores and logs were examined from a reconnaissance viewpoint in the Mikwan and Fenn area to the southeast of Joffre. The study area is along strike from the Gilby field and links up with Raddysh's B.Sc. thesis (1986) covering Townships 39-42, and Range 28 west of the fourth Meridian to Range 5 west of the fifth Meridian. The study area was selected because of the colinear arrangement of the Gilby and Joffre fields.

The stratigraphic cross section lines shown on Figure 2.1 are discussed in Chapter 5.

2.2. Stratigraphy

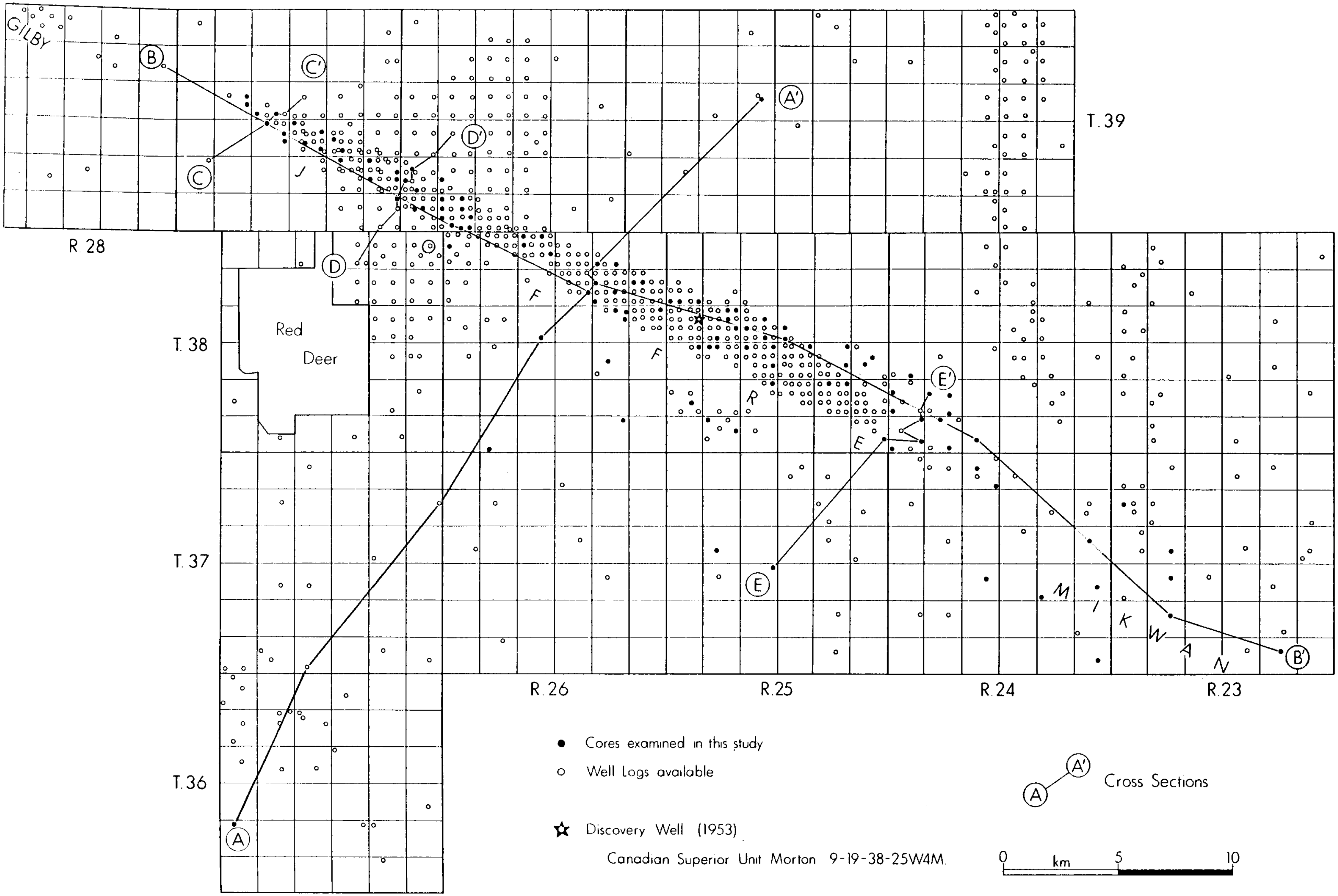
The Viking is dominantly a marine sandstone unit overlain and underlain by marine mudstones (Fig. 2.2). The formation was first defined by Slipper in 1918. In Canada, it is equivalent to the Paddy Formation of northwestern Alberta (Stelck, 1958; Oliver, 1960), the Pelican Formation of northeastern Alberta, and the Silt Member of the Ashville Formation of Manitoba (Rudkin, 1964, his Fig. 11-1). It is mostly known as the Viking Formation in Saskatchewan (Rudkin, 1964). The bentonitic horizons within the formation have been correlated with the Crowsnest Volcanics in southwestern Alberta (Amajor, 1985).

Figure 2.1 **Base map of the Joffre study area showing the distribution of wells and cores with respect to the fields.**

The Joffre field is outlined by the density of wells. The southeastern tip of Gilby appears in Township 39, Range 28, along strike from Joffre. At the other end of Joffre is the Mikwan field (Township 37, Range 23), but it does not feature the same density of wells as do Gilby and Joffre.

Note the scarcity of core data beyond the northeastern margin of Joffre. The stratigraphic cross sections labeled on this map are presented and discussed in Chapter 5, they have been assembled to maximize the off-field core data.

All wells in this study are situated west of the fourth Meridian; the western limit of Township 39, Range 28 coincides with the fifth Meridian.



GILBY
T. 39
T. 38
T. 37
T. 36
R. 28
R. 26
R. 25
R. 24
R. 23
Red Deer
JOFFRE
MIKWAN
A
A'
B
B'
C
C'
D
D'
E
E'
Cores examined in this study
Well Logs available
Discovery Well (1953)
Canadian Superior Unit Morton 9-19-38-25W4M
Cross Sections
0 km 5 10

In the United States, the Viking is correlative with the Newcastle Formation of North Dakota, the Muddy Sandstone of Montana and Wyoming, and the J Sandstone of Colorado (McGookey et al., 1972, their fig.9).

The Joli Fou Formation, defined by Wickenden (1949), underlies the Viking. This shale formation is known everywhere in the Canadian Plains as the Joli Fou Formation except in southern Alberta where it coalesces with the Viking Formation to become the Bow Island Formation (Glaister, 1959). In the United States, the Joli Fou is equivalent to the Skull Creek Shale of Montana and North Dakota, and the Thermopolis Shale of Wyoming (McGookey et al., 1972).

The "Lloydminster Formation" appears to be an informal designation for the mostly un-named marine shales above the Viking. Tizzard and Lerbekmo (1975) used the name "Lloydminster Formation" without a definitive stratotype. The shales are otherwise known as the "un-named shale of the Colorado Group" amongst the industry in Calgary. The Lloydminster Formation is equivalent to the Mowry and Graneros Formations in the American Great Plains (McGookey et al., 1972).

Capping the LLoydminster Formation is the Fish Scales sandstone. The lower contact of the Fish Scale sandstone marks the boundary between Lower and Upper Cretaceous (Stelck and Armstrong, 1978). The "Base of Fish Scales" is a widespread and popular stratigraphic marker in industry.

Figure 2.2 **Viking Stratigraphy at Joffre.**

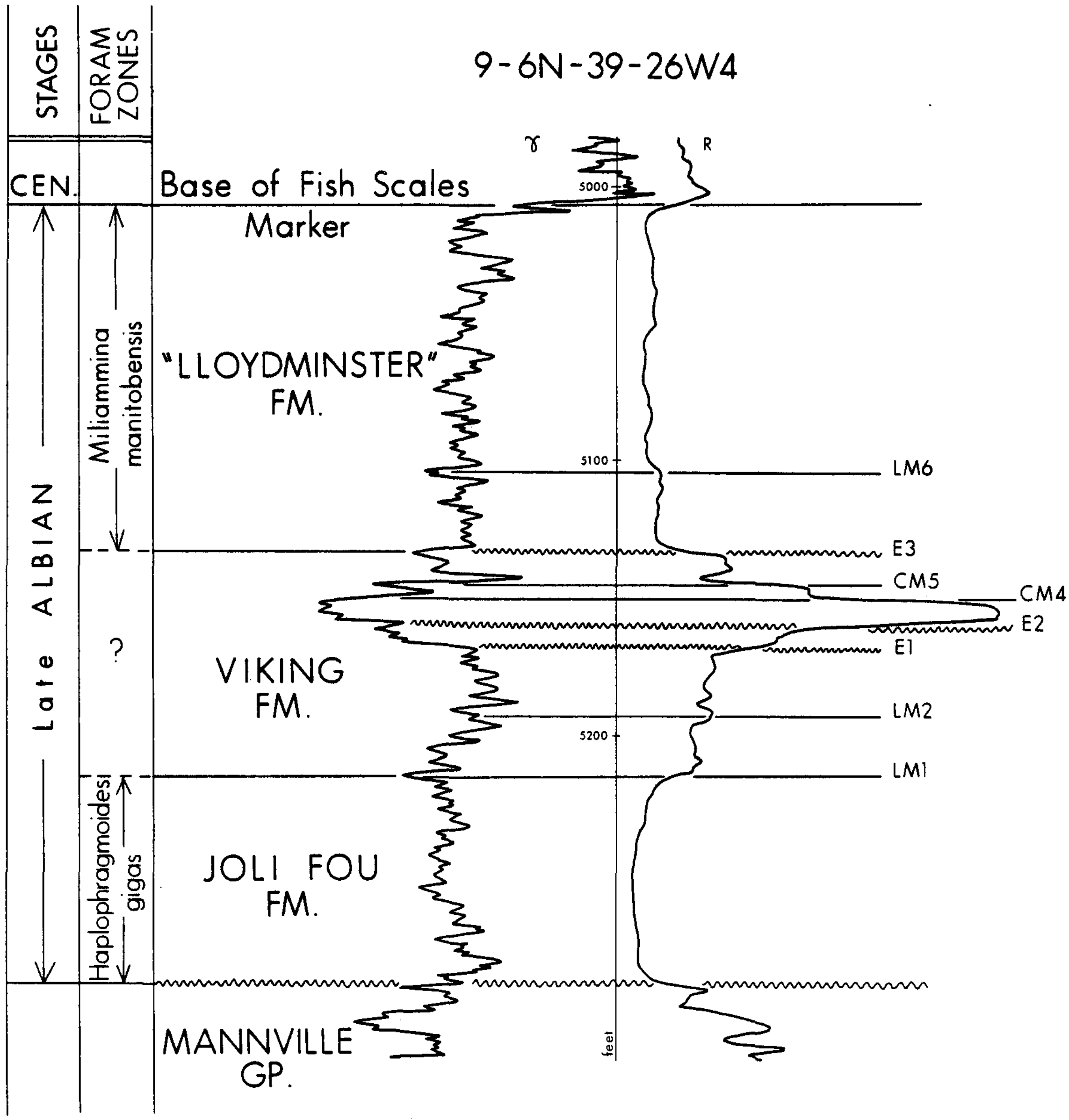
Well 9-6N-39-26W4 is chosen to represent the Viking at Joffre because:

a) it contains both a gamma ray log and a resistivity log,

b) it shows the entire formation and its stratigraphic context,

c) the log (LM) and core (CM) markers, and erosion (E) surfaces can be clearly recognized in both log profiles (as shown). These features will be explained in Chapter 5.

The "N" included in the well identification refers to the northerly location of this well with respect to its twin well. The lithostratigraphic and biostratigraphic nomenclature is explained in the text.



STAGES
FORAM ZONES
9-6N-39-26W4
γ
R
5000
5100
5200
feet
CEN.
Base of Fish Scales
Marker
Late ALBIAN
Miliammina manitobensis
?
Haplophragmoidesi gigas
"LLOYDMINSTER" FM.
VIKING FM.
JOLI FOU FM.
MANNVILLE GP.
LM6
E3
CM5
CM4
E2
E1
LM2
LM1

2.3. Definition of the Viking at Joffre

The Viking Formation is approximately 30 metres thick at Joffre. Previous studies in the area do not clearly characterize the base of the formation. In this thesis the base of the Viking is defined at the inflection point of the first prominent shoulder of the resistivity profile above the Joli Fou Formation. The top of the Viking Formation is lithologically defined at the top of the uppermost conglomerate horizon, this translates as the inflection point of the uppermost prominent resistivity shoulder below the Lloydminster Formation. The upper contact of the formation occurs very slightly above the "E3" horizon in Figure 2.2. Log markers (LM) and core markers (CM) are numbered consecutively upward to form the local stratigraphic framework; the erosion surfaces (E) are numbered separately (Fig. 2.2).

2.4. Biostratigraphy

The Joli Fou, Viking and Lloydminster Formations all belong to the Late Albian. The foraminiferal zones (Caldwell et al., 1978, p.521) are shown in Figure 2.2. The Viking is devoid of diagnostic foraminiferal assemblages and, therefore, could belong to either the *Haplophragmoides gigas* Zone, the *Miliammina manitobensis* Zone, or could span both of the zones.

2.5. Absolute Age

Bentonites occurring within the formation have been dated at 100 m.y. (+/- 2) using Potassium-Argon geochronology (Tizzard and Lerbekmo, 1975). This age agrees with the biostratigraphic dating.

2.6. Structure

The study area is situated in the Central Plains, well east of the Cordilleran Deformed Belt. The strata dip to the southwest at approximately 1/2 degree. Jones´ (1980) structural cross sections indicate two vertical faults, one on either side of the field, which trend parallel to Joffre´s long axis. He suggests that vertical movements along these fault planes occurred during the Late Carboniferous and again later between the Miocene and present, and thus that the faults probably did not affect Viking deposition., However, subtle vertical movements along the fault planes during Late Albian time cannot be ruled out.

2.7. Paleogeography

The Canadian portion of the Western Interior Seaway is generally depicted as a shallow basin dominated by southerly expanding Boreal waters. Bentonitic horizons within the Viking attest to intermittent volcanism associated with the tectonically active Cordillera. The vigorous thrusting and volcanism which characterized the basin´s western margin contrasted with the quiescent craton along the basin´s eastern margin.

2.8. Study Methods

The data base for this thesis comprises about 350 well logs and 108 measured cores in the area of Figure 2.1, and approximately 30 other wells toward Mikwan and Fenn.

The logs consist mostly of resistivity and micro-resistivity profiles. Very few good quality gamma ray logs are available for the Viking in this area. Relatively detailed comparison is possible between the cores and logs, although the core markers are not always obvious "picks" in the log profile. Stratigraphic cross sections were built using a log marker datum within the formation (datum LM2 Fig.2.2) which could be consistently picked in both resistivity and micro-resistivity logs. Structural cross sections were not attempted.

The cores were measured in detail to note sedimentary structures and grain sizes. The Can-Strat card was used to measure grain sizes. A facies scheme of fourteen facies was set up based upon grain size and physical and biological sedimentary structures. Detailed photos of individual facies and facies contacts were taken as were photos of continuous boxes of core. Core cross sections were assembled and also hung on the LM2 marker (Fig.2.2).

The core lithologs which are not presented in this thesis are stored at McMaster University under the care of Dr. R. G. Walker. Copies of the core photographs are likewise stored at McMaster.

CHAPTER 3. VIKING LITERATURE REVIEW

3.1. Introduction

Slipper (1918) first named the Viking sandstone after the discovery of the Viking-Kinsella gas reservoir in 1917. Following several encouraging Viking discoveries in the 1940's and 1950's, several papers were written about the depositional patterns and processes of the Viking sand. Researchers were intrigued by the widespread distribution of pebble horizons and put forth several ideas to explain the problematic transport of the gravels comprising them. One can sense two viewpoints emerging in the literature at this early stage to explain the widespread distribution of coarse sediment:

i) ideas suggesting **offshore transport** of the pebbles;

ii) ideas suggesting **mobile shorelines**, shifting in response to relative sea level changes.

3.2. The "Offshore Transport Viewpoint"

Beach (1955) suggested that the chert pebbles had been transported great distances from the shoreline by turbidity currents. The implied depositional setting involved isolated shelf sand bodies which were supplied with coarse sediment transported offshore by powerful currents.

Roessingh (1959) supported Beach's ideas, agreeing with sediment dispersal by turbidity currents. Roessingh suggested that the continuous nature of the chert pebble beds and bentonites argued against diachronism.

Beach's ideas resurfaced in a published discussion between himself and **Jones (1961).** Jones did not see evidence for turbidty currents in his Saskatchewan study.

Koldijk (1976) proposed that the currents transporting the pebbles offshore were more likely storm-driven. He also suggested that sand accumulated as long, narrow deposits in offshore settings by a shoaling process over localized topographic "highs", although a mechanism was not specified. His ideas are elaborated below (Section 3.5).

In his Garrington study, **Robb (1985)** subscribed to the idea of offshore transport of coarse sediment by storm-related or sediment gravity flows, although this idea is later modified in Hein et al.,(1986).

3.3. The "Mobile Shoreline Viewpoint"

DeWiel (1956) did not agree with Beach's ideas of turbidity current transport of coarse sediment, suggesting that the Viking basin was regionally too flat and shallow to initiate and sustain turbidity currents for sediment dispersal. Instead, he proposed sediment distribution by nearshore processes, specifically "long shore currents in front of a shifting strandline" (1956, p.174). DeWiel envisaged the Viking basin and bordering floodplain "as essentially flat, [such that] even the slightest oscillation of the Cretaceous exogeosyncline [could bring]...about a considerable lateral displacement of the shoreline..." (1956, p.174). Implicit in this idea is the responsiveness of shorelines to relative changes of sea level. Today, thirty years after DeWiel proposed this idea for the Viking, several studies are finding sedimentological evidence in support of this concept for Cardium (Plint et al., 1986; Bergman & Walker, 1986, and in press) as well as Viking deposition.

The "Mobile Shoreline Viewpoint" initiated by DeWiel appears to have fallen dormant for many years until modern contributions by seismic stratigraphers rejuvenated the concepts of mobile shorelines within dynamic basins. It is interesting that DeWiel did not invoke erosional breaks in the resulting stratigraphy rather, he reasoned that lateral shifts of the shoreline would not necessarily produce "conspicuous disconformties" (1956, p. 174).

Twenty years after DeWiel, **Lerand and Thompson (1976)** documented three transgressive deposits each overlying a scour surface within the Viking at Provost. They suggested that each "transgressive [bed was] laid down by an advancing shoreline across the eroded surface of the underlying sand" (1976, p.B-27). Their´s is the first Viking paper to suggest that the preserved rock record (at Provost)"...may represent an incomplete record of the environment in which [it] formed".

In **1984, Beaumont** proposed a major basinward shift of the shoreline during earliest Viking time such that streams were able to subaerially transport pebbles out across an exposed shelf. This coarse sediment was redistributed across the shelf during the following transgression. His ideas are more fully discussed below (Section 3.5).

At Crystal, **Reinson (1986)** documented coarse-grained estuarine sediments underlain by a regional unconformity. I assume the unconformity represents a scour surface created by fluvial downcutting during a relative lowering of sea level. During the subsequent transgression, the incised river valley was later modified and the estuarine sediments were deposited.

A hiatal surface was noted to underlie coarse sediment in the Viking at Caroline by two separate studies **(Leckie, 1986; Hein et al., 1986)**. Both studies attributed the sharp break in the facies sequence to relative changes of sea level. The former author invoked erosion of the underlying substrate and subsequent coarse sediment deposition during one phase of relative deepening, while the latter authors invoked a two stage change of sea level. Specifically, Hein et al. attributed the erosion to a relative lowering of sea level, followed by a relative deepening during which coarse sediment was deposited.

H. Raddysh (pers. comm., 1986) noted a regionally significant scour which underlies the coarse sediment at Gilby. This thesis will attempt to suggest a correlation between the Gilby erosional surface and one of the Joffre erosional surfaces.

In his Saskatchewan study of the Viking at Dodsland, **J. G. Pozzobon (pers. comm., 1986)** has also observed several erosional surfaces within the Viking; currently these cannot be correlated with any in Alberta.

3.4. Other Viking Studies

Evans (1970) mapped a series of diachronous sandstone members in southwestern Saskatchewan. Each member is of the order of 5 m in thickness, 10 km in width, and 80 km in length. They overlap each other towards the south, and Evans attributed their diachronism to shifting tidal currents.

Amajor (1980) subdivided the formation into three "chronostratigraphic intervals" using bentonite correlations. He suggested that deposition of the Basal Chronostratigraphic Interval took place furthest "offshore" (in the northeast), and that the loci of sand deposition of the two succeeding "intervals" had shifted southwestward through Viking time. This is essentially similar to Beaumont's (1984) interpretation. He identifed linear, subparallel sandbodies within each "interval", and postulated that most of them had been deposited in offshore settings, but did not address problems of sediment transport.

The area covered by Amajor's thesis is approximately 100,000 square kilometres; he used few cores to address problems of sediment transport and environment in any particular area. The erosion surfaces and core markers presented in Figure 2.2 of this thesis occur within only one of Amajor's chronostratigraphic intervals. His study, therefore, only relates to this thesis at the scale of regional geology.

3.5. History of Ideas in the Joffre and Gilby Area

Several recent publications pertain directly to the Joffre-Gilby area. They offer a wide variety of ideas about the depositional processes and geometry of the sandbodies.

In his 1976 paper, **Koldijk** suggested that the long and linear Gilby "gravel bar" formed in an offshore setting. He invoked the transport of "pebbles...as a gravel pavement...during severe storms" and suggested that an existing "linear shoaling feature...would localize the accumulation of pebbles during local stormy conditions" (1976, p.77). The origin of the "linear shoaling feature" was not discussed.

Reinson et al. (1983) explained the depositional history of the coarse sediment at Joffre slightly more elaborately, suggesting initial offshore transport by "strong density currents" and subsequent reworking of the coarse sediment into a linear bar by tidal currents. They also observed significant differences between the fine-grained facies underlying the coarse detritus and the fine-grained facies overlying the coarse detritus. From this they suggested that a major change had occurred in the depositional conditions in conjunction with the introduction of coarse-grained detritus. They related this change in depositional conditions to tectonically induced alterations of the basin's depth, gradient, climate or circulation system (1983, p.104).

Although the ideas presented in these two papers fall within the "offshore transport" classification scheme, Reinson et al., 1983) also alluded to basin-wide changes in the depositional environment associated with onset of coarse sediment deposition.

The most recent Viking contribution to the Joffre area solidly invokes sea level changes and thus can be classified as supporting the "mobile shoreline" viewpoint. **Beaumont's** (1984) ideas about regional Viking sedimentation involve:

a) the emplacement of coarse sediment out onto the shelf during earliest Viking time at a sea level lowstand;

b) shoreline retreat in response to a more or less continual transgression;

c) the development of a series of shoreward-younging sediment sheets during pauses in the overall transgression.

Figure 3.1 shows the shingling relationship between the sediment sheets. Beaumont suggested that stillstands or brief periods of regression interrupted the overall transgression. He suggested that during these pauses, the "trailing edge" of the youngest sediment sheet prograded over top of the adjacent older, and more basinward sheet. This is shown in Figure 3.1 by the lobe of sheet 4 which has prograded over sheet 3 to rest on sheet 2. Beaumont referred to the resultant shingling geometry of the shoreward-younging sediment sheets as "retrogradational".

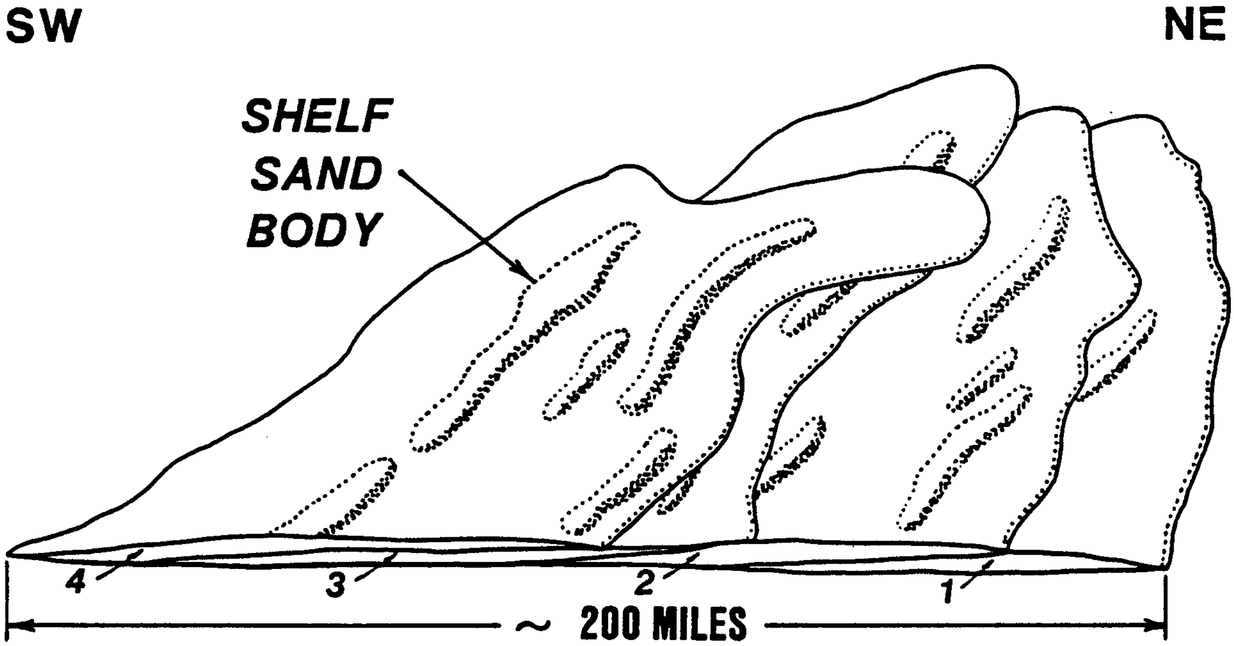


Fig. 3.1 Conceptual diagram of "shingling" relationship between Viking Formation sediment sheets. Note that each sheet contains several shelf bodies. (from Beaumont, 1984)

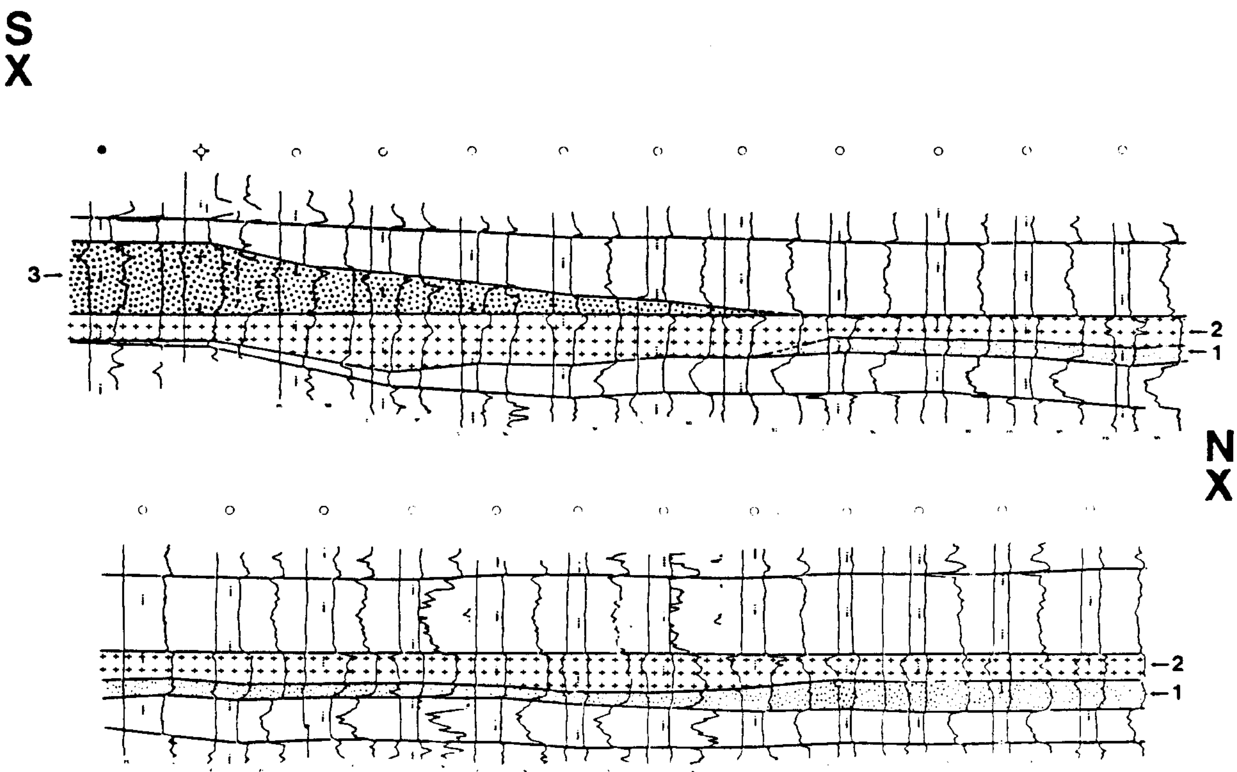


Fig. 3.2 Electric log cross-section (two adjoining segments) extending between Joffre and Joarcam Fields, which illustrates shingled relationship of Viking sediment sheets. Viking Formation is contained within shaded section of cross-section. Different patterns represent different sediment sheets. Sheet labeled with number 1 was deposited first; sheet labeled 2, second; and sheet labeled 3, last. (from Beaumont, 1984)

Beaumont's contribution to the evolution of specific linear sandbodies (i.e. Joffre) is more vague. Linear sandbodies are shown within each sediment sheet in Figure 3.1. He simply states on page 171 (1984) that the "sand [supplied] to the shelf...was subsequently restructured into linear sandbodies...by the shelf hydraulic regime."

Although some of Beaumont's ideas are intriguing, his evidence is difficult to follow. He presented an electric log cross section to illustrate the overlapping nature of the various sediment sheets (Figure 3.2). The sheets are not characterized lithologically in either the figure caption or text, and it is hard to justify his log correlations. It seems that the southernmost expressions of sediment sheet 2 are mis-correlated; based upon my experience in this (Joffre) area, that interval corresponds to the Joli Fou Formation. There is another difference of opinion concerning the "randomly occurring" conglomerate facies as described by Beaumont (1984, p.167). This thesis will attempt to illustrate that the conglomeratic facies are <u>not</u> randomly occurring, rather, they occur predictably in association with scour surfaces.

In a recent publication, **Amajor (1986)** presented two cross sections of the Joffre field. The cross section perpendicular to the strike of Joffre (1986, his fig.7) shows a single sandbody, the lower contact of which converges toward a lower marker. There is no description of this convergence provided in the text nor in the figure caption. The second cross section (1986, his fig.6) trends parallel to Joffre, and is also presented without comment. As correlated, his section shows three shingling sandbodies. In Chapter 5 of this thesis, it will be shown that there are four distinct facies sequence "belts" which trend parallel to the long axis of the field. It will be suggested that Amajor's "chronotaxial" (overlapping) sand bodies result from the juxtaposition of wells from different facies sequence belts (reflecting across-field changes rather than overlapping down-field changes).

3.6. Summary of the Reviewed Literature

Two different viewpoints can be distilled from Viking research papers which explain the depositional patterns of coarse-grained Viking sediment. The first one invokes transport of sediment a long way offshore, and implies that the shorelines have remained essentially in one position throughout Viking time. The second viewpoint invokes shoreline mobility, that is, shifting positions of the shoreline in response to relative sea level fluctuations.

It is interesting to note that the ideas from both viewpoints have been suggested to explain the coarse sediment occurring along the Gilby-Joffre trend. This thesis offers further support for the idea of shifting shorelines as suggested thirty years ago by DeWiel. However, the erosional surfaces, interpreted in this thesis to exist at Joffre, have not been previously documented.

CHAPTER 4. FACIES DISCUSSION

The Formation has been divided into fourteen facies. These are defined on the basis of grain size, and physical and biological structures as observed in core. The facies are depicted schematically in a fold-out reference page as Appendix I. The thicknesses of these facies range from a few centimetres to several metres. Laterally, the facies extend over many townships, and most of the facies can be recognized in both the Joffre and Gilby areas (Raddysh, personal communication, 1985). Table 4.1 cross-references the Joffre-Gilby facies schemes.

The facies discussion generally follows the stratigraphic order of the Formation, proceding from the earliest deposited facies towards the final blanketting facies. Each facies write-up contains a basic description of the facies and a preliminary interpretation of its depositional environment. Representative core photographs are integrated into the text.

Table 4.1 Cross-reference of the Joffre-Gilby Facies schemes

GILBY FACIES (Raddysh, 1986)		JOFFRE FACIES (this study)	
Black Mudstone	(K)	(14)	**Black Mudstone**
		(13)	**Loaded Sandstone**
Conglomerate	(J)	(12)	**Conglomerate**
Laminated Mudstone-Conglomerate	(I)	(11)	**Banded Gravel**
		(10)	**Hummocky-bedded Sandstone**
		(9)	**"Mixed"**
Laminated Mudstone/ Pebbly Conglomerate	(G)		
Massive Pebbly Sandstone; Pebbly Cross-bedded Sandstone	(H,F)	(8)	**Pebbly Sandstone**
Pebbly Cross-bedded Sandstone	(F)	(7)	**Granular Sandstone**
Cross-bedded Sandstone		(6)	**Cross-bedded Sandstone**
		(5)	**Glauconitic-Sideritic Sandstone**
Burrowed-Laminated Sandstone/Mudstone	(D)	(4)	**Burrowed-Laminated Sandstone Mudstone**
Pervasively Bioturbated Muddy Sandstone	(C)	(3)	**Bioturbated Muddy Sandstone**
Sideritized Muddy Siltstone	(B)		
Homogeneous Muddy Siltstones	(A-3)	(2)	**Pale Siltstone**
	(A-1;A-2)	(1)	**Muddy Siltstone**

Facies 1: MUDDY SILTSTONE FACIES

Description: The Muddy Siltstone Facies is a homogeneous mixture of clay and silt (Fig. 4.1). The mottled and structureless appearance of the facies is due to bioturbation. The sediment has been so thoroughly churned, and the silt-clay mixture provides so little colour contrast that it is difficult to identify specific trace fossils. *Terebellina* is readily identifiable in many wells, and in well 2-21-38-25W4 (4780′) a burrowing bivalve (3 cm in length) was observed.

In places, faint horizontal layering is represented by remnants of delicately laminated silt and very fine-grained sand. Generally only those silty laminae which are thicker than one centimetre are preserved; presumably those which are thinner are more readily destroyed by organisms. Typical 1-cm beds have sharp, flat bases and burrowed tops. Their interiors seem to be structureless, but parallel flattish to undulatory laminations can be seen in slabbed cores. Bentonitic silt layers have also been thoroughly mixed-in and are often present only as smears on crude parting planes.

Facies 1 dominates the lowermost 10-15 metres of the Viking and is found throughout the study area at this position. In the Gilby area, Raddysh (1986), has divided the equivalent facies into the Homogeneous Dark Muddy Siltstone Facies and the Muddy Siltstone Facies on the basis of approximate clay and silt contents.

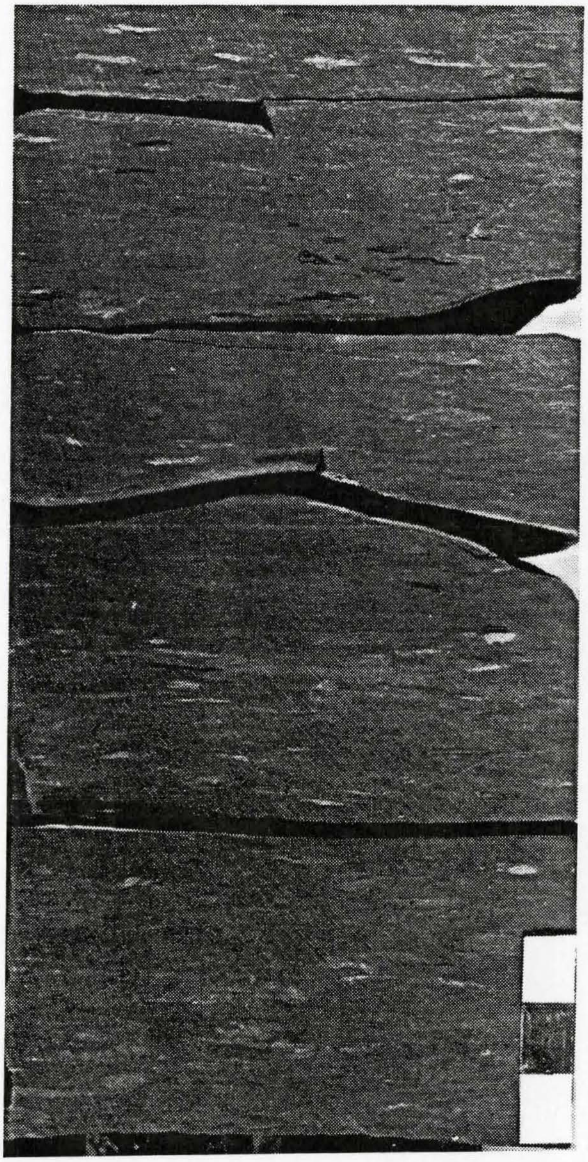


Figure 4.1 **Facies 1: MUDDY SILTSTONE FACIES**

Note the thoroughly stirred appearance and faint horizontal lamination characteristic of this facies.

Well 14-5-38-24W4 Depth 4414 feet Scale bar 3cm long

Preliminary Interpretation: On the basis of the very fine grain sizes, the intensity of bioturbation, and the absence of angle-of-repose cross-lamination, it is most likely that the depositional setting was offshore, well below fairweather wave base. The undulatory nature of the silty laminae suggests deposition from suspension under the influence of storm waves weakly feeling bottom. During fairweather, the sediment was subject to vigourous biological reworking (in an otherwise quiet environment) which destroyed those silty laminae thinner than 1-2 cm.

Facies 2: PALE SILTSTONE FACIES

Description: This facies is a structureless mixture of clay and silt (Fig 4.2). The pale colour is a reflection of the increased proportion of silt and the presence of very fine-grained sand as compared to the Muddy Siltstone Facies. Colour contrast between clay and very fine-grained sand serves to highlight individual trace fossils. Terebellina, Asterosoma, Rhizocorallium (?), Helminthoida, Conichus conicus(?), Cylindrichnus and tiny "Chondrites-like pin-point traces" are visible. The dominant senses of burrowing are horizontal and diagonal; vertical burrows are very uncommon.

Laminae are typically 1-3 cm in thickness. Very few laminae are totally preserved due to the burrowing intensity. They resemble those of Facies 1, and have sharp bases, seemingly massive interiors, and burrowed tops. Within these laminae, subtle parallel laminations

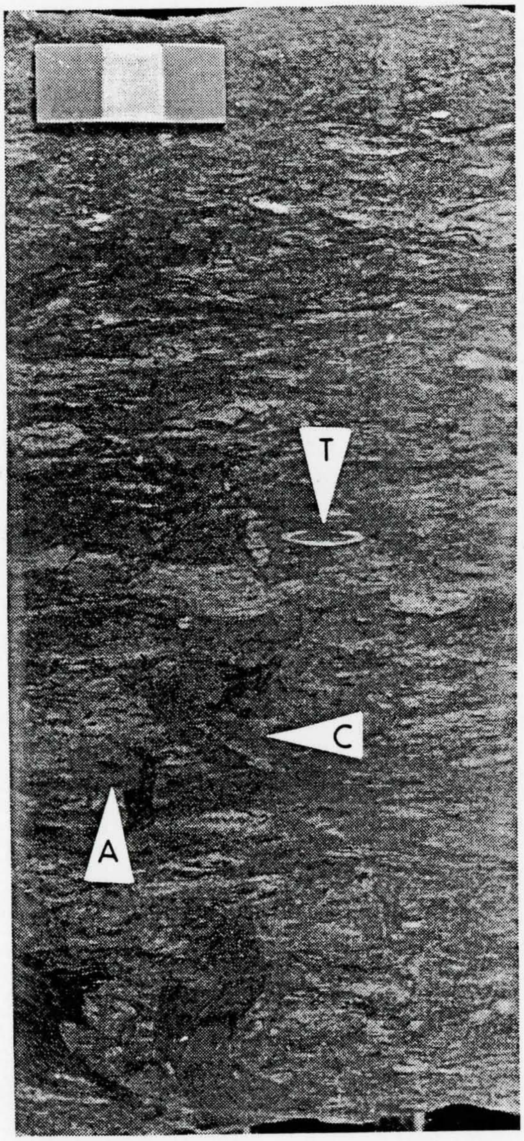


Figure 4.2 **Facies 2: PALE SILTSTONE FACIES**

There is only a faint suggestion of the original layering. The presence of very fine-grained sand in Facies 2 helps to highlight the trace fossils. Present in this photo are: Asterosoma (A), Terebellina (T) and Cylindrichnus(?)(C).

Well 10-25-36-24W4 Depth 4829 feet Scale bar 3cm long

which sweep across the width of the core can be seen on some slabbed surfaces.

Facies 2 occupies one stratigraphic position (above Facies 1) and attains a maximum thickness of 4-5 metres. It is usually only seen in off-field wells, especially southwest of Joffre.

Preliminary Interpretation: The depositional environment of this facies appears to be very similar to that of the Muddy Siltstone Facies. The intensity of the bioturbation suggests slow, continuous deposition probably below fairweather wave base. The main difference between the two facies is the increased proportion of silt and sand-sized material being deposited as Facies 2.

Facies 3: BIOTURBATED MUDDY SANDSTONE FACIES

Description: This facies is a thoroughly "shredded" mixture of approximately 75-90% very fine- and fine-grained sand, 25-10% mud, and trace amounts of glauconitic material (Fig.4.3). There is a diverse population of well-defined trace fossils including: *Terebellina*, *Asterosoma*, *Paleophycus*, *Rhizocorallium*, *Cylindrichnus*, and slender *Skolithos* burrows (several milli-metres in diameter).

Bedding is rarely intact. Preserved beds are seen in the upper half of the facies occurences. Individual beds are 2-5 cm in thickness; presumably thinner beds were totally shredded by biological activity. Most of the fine-

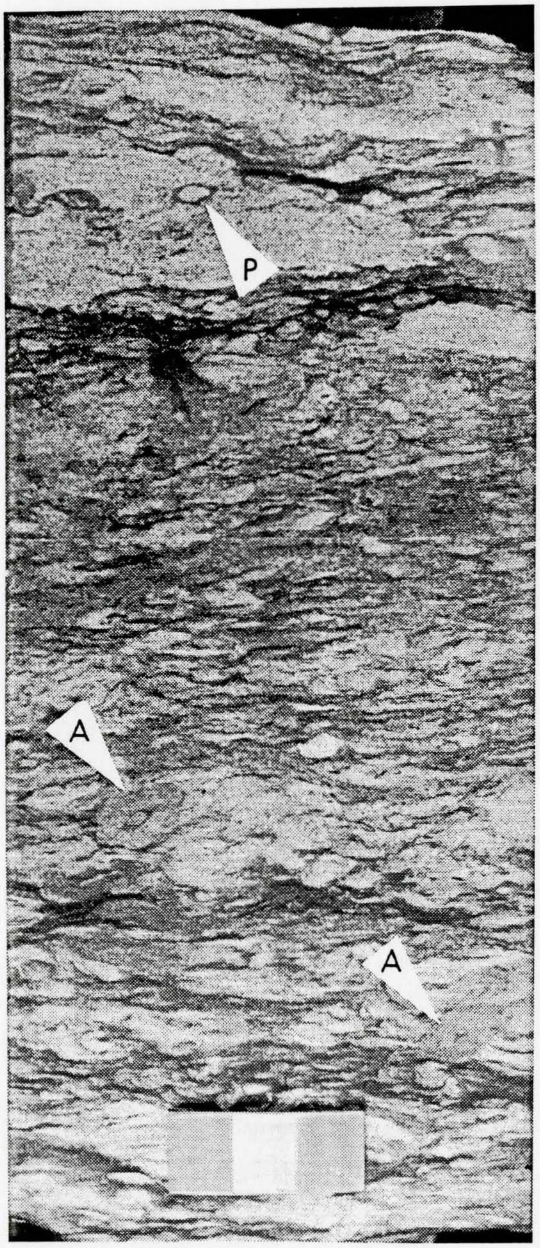


Figure 4.3 **Facies 3: BIOTURBATED MUDDY SANDSTONE FACIES**

This facies is dominated by biological sedimentary structures. The structureless remnant of a 2cm thick bed is shown at the top of this photo. Trace fossils present in this photo include Asterosoma (A), and Palaeophycus(?)(P).

Well 1-33-37-24W4 Depth 4658 feet Scale bar 3cm long

grained sand beds have disrupted bases and tops, and appear "fuzzy" and structureless inside. A few of these relict beds exhibit flat lamination or trough cross-lamination. Bedding foresets of the cross-laminations may dip as steeply as 12^{0}.

Sometimes three vertical trends are observed within this facies: i) the ratio of sand/mud increases upward;

ii) the average grain size of the sandy portion increases upward from very fine-grained to fine-grained;

iii) there is a tendency for bedding to be preserved in the upper portions of the facies.

The uppermost few centimetres of this facies may be sideritized. The siderite occurs in the matrix of the sandy sediment as a diffuse zone.

Facies 3 appears to occupy two main stratigraphic positions in the Viking and is seen in cores of both on-field and off-field wells. The base of the lowermost occurrence commonly features diffuse layers of scattered pebbles or granules (Figs.5.4, 5.10). These layers have been disaggregated by burrowing. Sometimes the pebbles are observed within discrete fine-grained sand laminae. The uppermost occurrence usually displays exceptional examples of <u>Terebellina</u>, and sometimes features prominent, large diameter (1cm) <u>Skolithos</u> burrows. The different stratigraphic positions of Facies 3 are emphasized in the discussion of facies sequences in Chapter 5.

Preliminary Interpretation: This facies was deposited in an environment which was almost continuously dominated by biological activity. The infrequently preserved examples of trough cross-lamination and flat lamination suggests that at times, the results of physical processes could be preserved at the sediment-water interface.

However, the vertical trends developed within this facies indicate that these environmental conditions were subtly changing, and that physical sedimentary structures were becoming increasingly preserved upward.

i) The upward increase in the sand/mud ratio might have resulted from higher depositional energies which prevented the clay particles from settling and accumulating.

ii) The upward increase in the sand grain size indicates a greater ability of the depositional currents to transport coarser sediment.

iii) The tendency for preservation of bedding structures in the upper portion of the facies also attests to the increasing significance of physical processes.

The first two vertical trends might also be explained by subtle changes in the nature of the source. It must be emphasized that these environmental changes were not significant enough to overcome the biological dominance of the system.

Facies 4: BURROWED-LAMINATED SANDSTONE/MUDSTONE FACIES

Description: This facies is composed of interlaminated mudstone, siltstone, and sandstone (Fig.4.4). Interlamination is developed on the centimetre scale, the sandy laminae ranging from 0.5 to 4cm in thickness. The grain sizes of these laminae vary from very fine-grained to fine-grained. The intensity of burrowing varies widely; the background may be non-burrowed, weakly burrowed, or extensively burrowed. Commonly, those intervals which are most "disrupted" contain laminae of the coarsest sediment (i.e.fine-grained sand). Trace fossils which occur in this facies include *Planolites*, *Terebellina*, and *Rhizocorallium*.

The character of the sand laminae varies immensely:

1. Laminae may have parallel upper and lower contacts, and contain subtly dipping internal lamination which sweeps across the width of the core. Slight divergences and truncations amongst the internal laminations impart a wavy appearance to these types of laminae. Typically these sand laminae have very sharp bases and tops. These laminae are composed of very fine-grained quartzose sand.
2. Lenticular laminae are also composed of very fine-grained quartzose sand. The lenticles contain dipping foresets which intersect asymptotically with the base of the lamina, as seen in ripple cross-lamination. These laminae also have sharply-defined bases and tops.

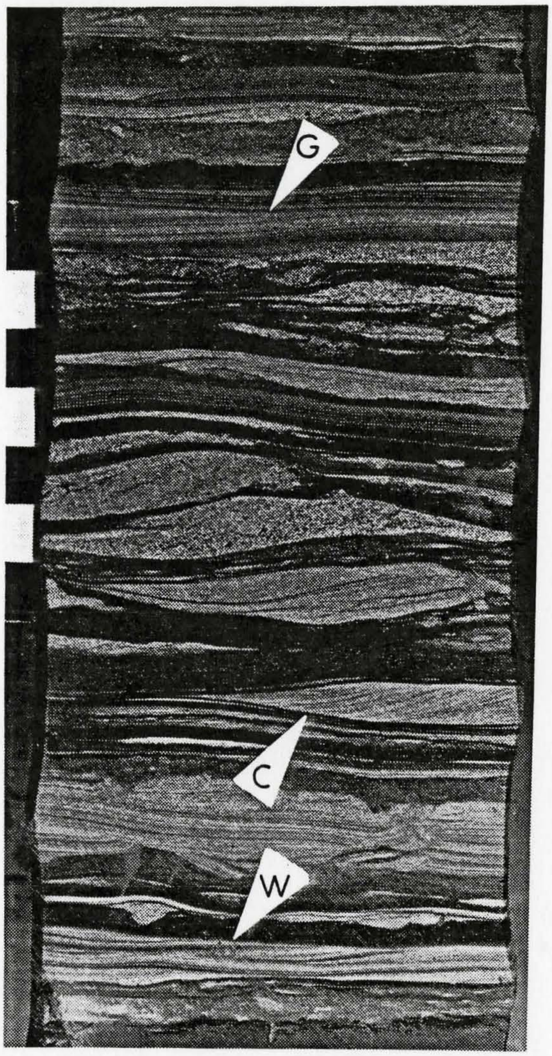


Figure 4.4 **Facies 4: BURROWED-LAMINATED SANDSTONE/MUDSTONE**

Alternating periods of rapid and slow deposition are indicated by the interlamination of sandstone and mudstone. The sandstone laminae most likely represent storm deposits. The sand laminae in this photo are wave rippled (W), current rippled (C), delicately colour-graded (G), and burrow-mottled. This interval is only weakly burrowed.

Well 3-31-36-22W4   Depth 4587 feet   Core is 8 cm wide

3. The slightly coarser, fine-grained laminae frequently have a more massive appearance and tend to be irregular in shape. This is chiefly due to burrowing which appears to be preferentially associated with these laminae. Sometimes tiny chert granules appear in these laminae.
4. Normally-graded laminae are also observed in this facies; basal layers containing fine-grained sand pass up into silt. Their interiors may appear to have an undulatory, wavy nature to them.
5. The most delicate laminae of all are the silt laminae. These appear as discontinuous streaks which drape the thicker laminae. Alternatively, they occur as continuous faintly colour-graded layers. The thickness of these laminae ranges from 1-5 mm. The preservation of these laminae is remarkable.

Facies 4 occupies several stratigraphic positions and is ubiquitous throughout the study area.

Preliminary Interpretation: In general, it seems the rate of deposition exceeded the rate of bioturbation for this facies. As mudstone laminae comprise approximately 50% by volume of the compacted sediment, the depositional water column likely contained a large amount of suspended clay. Such a turbid environment might have proven hostile to organisms thereby allowing the accumulating clay and silt layers to remain intact.

Episodic interruptions to this quiet environment are represented by the sandy laminae. These laminae most commonly feature wavy "bedding". The subordinate amounts of current ripples and graded beds may indicate that these were the primary structures which were partially reworked by oscillatory currents to become wavy laminae. The fine-grain sizes and delicate structures of the silty and sandy laminae suggest that the episodic currents which deposited them were relatively weak at this depth. Perhaps the energy of these depositional currents was being dampened by the large amount of suspended clay in the water column.

Deposition probably occurred below fairweather wave base, at a depth which storm waves could weakly "feel bottom". The storm waves appear to have been able to overprint some of the sandy laminae but were unable to scour deeply into the more cohesive mud laminae, thus preserving delicate laminae. The curious association of burrows and coarsest sediment (fine-grained sand) might hint that the burrowers and sand "arrived" simultaneously, as a storm deposit. After the storm's energy waned, and quiet turbid conditions returned, the foreign organisms may have failed to flourish in this potentially hostile environment.

Facies 5: GLAUCONITIC-SIDERITIC SANDSTONE FACIES

Description: This facies consists of alternating intervals of trough cross-bedded glauconitic sandstone and sideritized bioturbated muddy sandstone (Fig. 4.5 A,B). The crossbed sets are 3-6cm thick, although some may be as thick as 10-20cm. The crossbeds are composed of fine- to medium-grained, well-rounded quartzose sand grains. Glauconitic clay occurs as powdery clumps and distinctive coatings on some of the quartz grains. The relative abundance of glauconitic clay in this facies is noteworthy; this is the only facies in which it exceeds trace amounts. The curvature of some of the crossbed foresets is accentuated by glauconitic-micaceous layers. Foreset dips range from $10-25^{0}$.

The sideritized bioturbated muddy sandstone intervals comprise from 25-75% of the facies development. These intervals resemble Facies 3 (without siderite). One such interval, 3-5cm thick, contains a distinctive occurence of concentrically zoned, kaolinitic spheroids (Fig 4.5C) This particular horizon is traceable in core over four townships. There is a possibility that these spheroids, which often contain nuclei of glauconitic clay or quartz grains, may represent oolites which have been partially replaced by kaolinite.

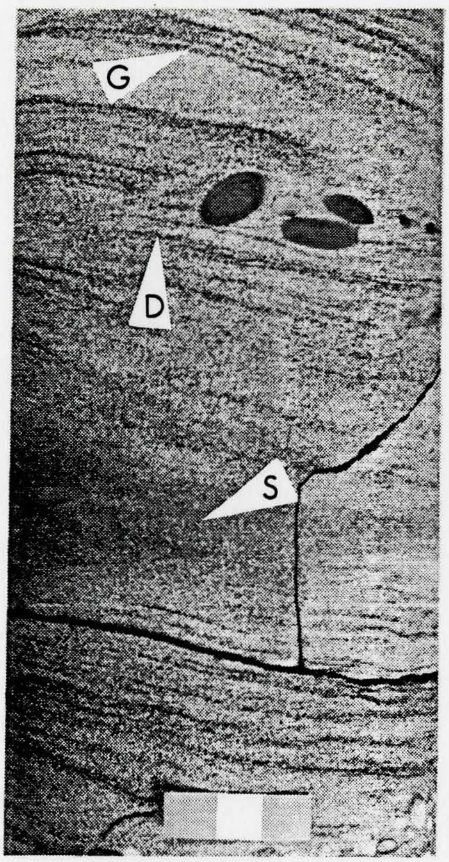
Sideritized mudstone laminae measuring less than 1cm to 6cm in thickness may drape the glauconitic crossbeds. Commonly these mudstone laminae are burrowed. The diameters of these burrows are typically 1cm, and the burrows have vertical as well as horizontal orientations. The vertical <u>Skolithos</u> burrows may extend over 10cm in length. They are filled with fine- to medium-grained sand (similar to the

Figure 4.5 **Facies 5: GLAUCONITIC-SIDERITIC SANDSTONE**

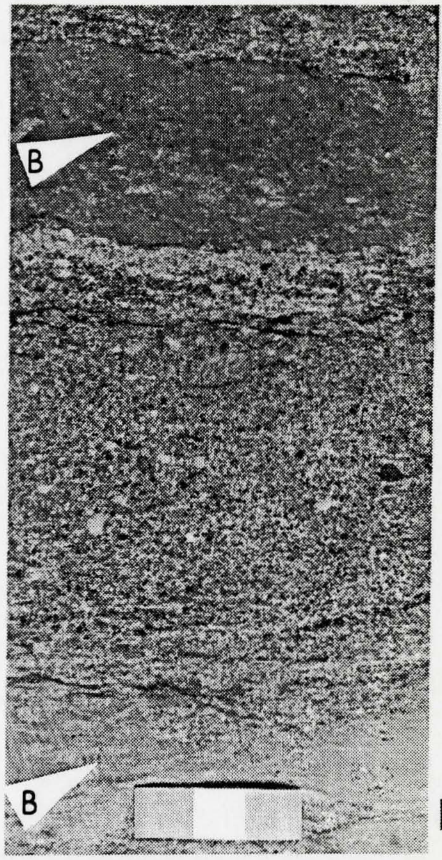
A Well 11-13-34-20W4, Depth 4024 feet, Scale bar 3cm long
This photo is a typical example of the cross-stratified intervals of Facies 5. Cross-stratification is emphasized by thin layers of glauconitic-micaceous material (G) which drape the foresets. A diffuse patch of siderite (S) marks the bounding surface between two crossbed sets. The discontinuity (D) within the micaceous laminae to the left of the sideritized mud clasts suggests that the clasts and surrounding pocket of sand may have been slumped into position. The largest sideritized clast has a dark outer rim, exhibiting zoning.

B Well 13-16-38-25W4, Depth 4798 feet, Scale bar 3cm long
The upper and lower beds in this photo are typical examples of the sideritized burrow-mottled (B) intervals of Facies 5. The burrows in these bioturbated zones are non-distinctive. The middle bed is anomalously poorly-sorted, containing a mixture of glauconitic clay, sand and granules.

C Well 16-23-38-26W4, Depth 5056 feet, Scale in cm
This is a close-up photo of one of the sideritized muddy sandstone intervals. This is the horizon bearing the whitish, irregular, kaolinitic spheroids, some of which appear concentrically zoned about a distinct nucleus. It is suggested that these bodies represent the altered remnants of oolitically-derived clasts.



A



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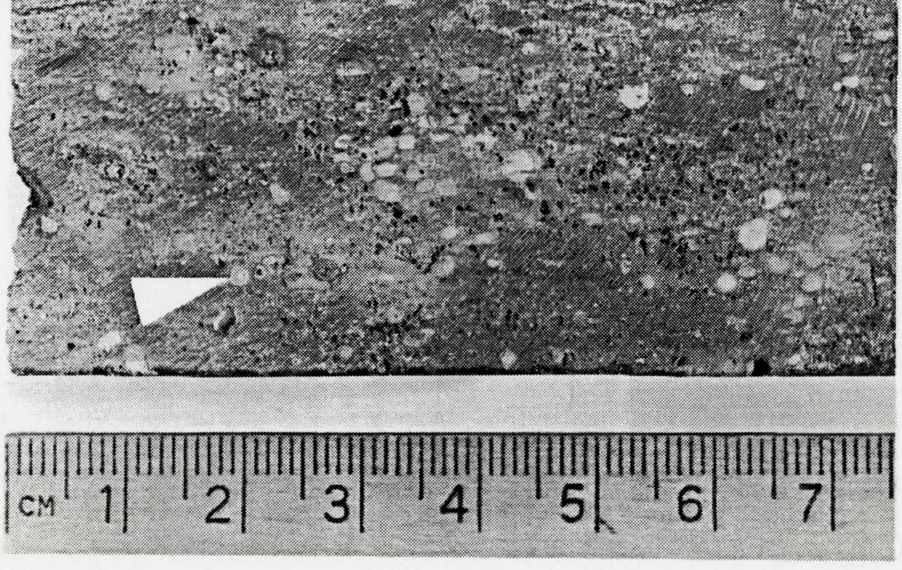


C

sand comprising the crossbeds). The burrow walls are unlined and the burrows do not contain spreiten. These burrows are distinctively larger and simpler in form than those of the finer-grained facies (Facies 1-4).

Mudstone rip-up clasts have also been sideritized; often these clasts have distinctive, dark (unaltered) rims which surround red-brown (sideritized) interiors.

Facies 5 occupies one stratigraphic position in the Viking at Joffre, where it does not exceed 3 metres in thickness.

Preliminary Interpretation: This facies exhibits fluctuations in the balance between the rates of sedimentation and bioturbation. Relatively strong currents have produced the glauconitic crossbeds and their associated rip-up clasts. The interbedding of erosively-based glauconitic cross-bedded sandstone intervals and (sideritized) bioturbated muddy sandstone intervals indicates alternating periods of rapid and slow deposition, very likely above fairweather wave base. The thin glauconitic micaceous layers which may occur in pairs draping the crossbed foresets, may represent mud couplets or tidal bundles (Allen, 1981). This is the only facies which features any suggestion of tidally-influenced deposition. Herring-bone cross stratification was not observed , therefore the depositional currents appear to have been dominantly unidirectional. The presence of mud drapes and intervals of bioturbated muddy sandstone suggests that the currents were episodic.

The oolitic horizon suggests a limited period of very shallow water with gently agitating currents. The zoned mudstone rip-up clasts were sideritized post-depositionally. The pervasive sideritization of this facies may be related to the availability of iron from the abundant glauconite. The timing of the distinctive Skolithos burrows is uncertain.

Facies 6: CROSS-BEDDED SANDSTONE FACIES

Description: The Cross-bedded Sandstone Facies is composed of well-sorted, fine-grained to medium-grained sand (Fig.4.6A). The grains are a mixture of white quartz and black chert, which lend the nickname "salt and pepper" to the sandstone. There is only a trace amount of glauconite present. The foresets are well-defined and have variable dips ranging from 10-25^{0}; sometimes there is a suggestion of upward steepening within one set. Sets are typically 4-7cm in thickness. There is no indication of bipolar orientation of the crossbed sets. In places, mud clasts are observed within the crossbedding.

Most commonly, the crossbed sets are stacked continuously upon each other, but they may occur interbedded with bioturbated sandstone. As in Facies 5, there are no distinctive burrows associated with the bioturbated intervals. In places vertical irregularities are observed within the cross-bedding (Fig. 4.6A); these may be related to either burrowing or compaction. Distinctive black mudstone laminae may also separate crossbed sets. These mudstone drapes are commonly less than 1cm in thickness, and may contain large-diameter, sand-filled burrows like those seen in similar mudstone laminae of the Glauconitic-Sideritic Sandstone Facies.

The average thickness of this facies at Joffre is 2 metres; it occurs mainly at one stratigraphic horizon in association with Facies 7 and 8. It may also be observed in cores of the Mikwan field and in wells directly to the southwest of Joffre's production limits (i.e.7-7-38-25W4).

Preliminary Interpretation: The rate of deposition far exceeded the rate of bioturbation in this facies. The depositional environment appears to have been dominated by unidirectional currents. The infrequent occurrences of mud drapes indicate few periods of quiescence. The almost continually shifting substrate probably restricted the establishment of a diverse biological community.

The paleoflow direction is not known. The preserved set thicknesses of 4-7cm may indicate that the original heights of the angle-of-repose sets could have been as great as 10-15cm. The facies was probably deposited above fairweather wave base.

Figure 4.6

A **Facies 6: CROSS-BEDDED SANDSTONE**

Well 8-12-39-27W4, Depth 4979 feet, Core is 8cm wide

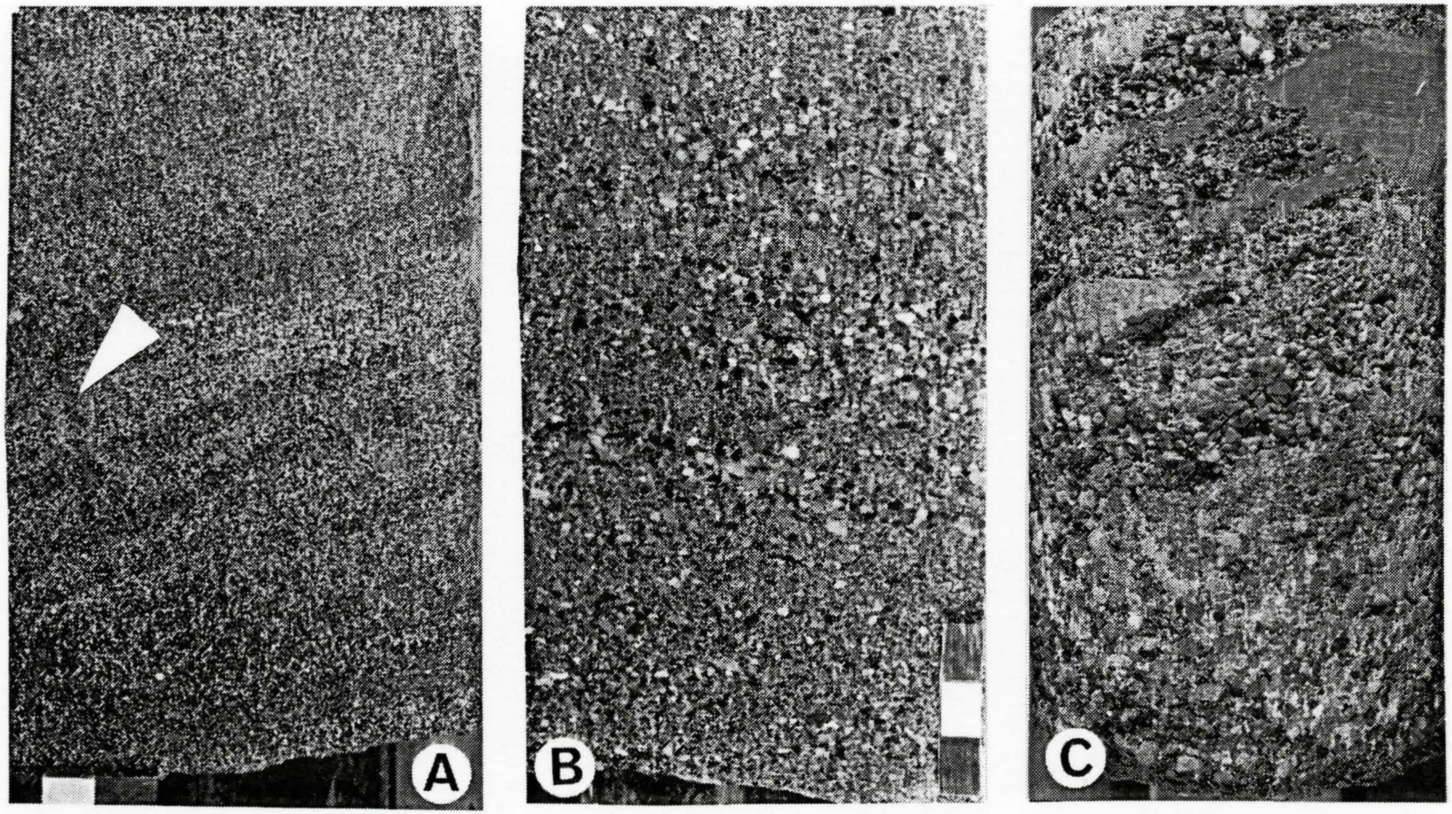
B **Facies 7: GRANULAR SANDSTONE**

Well 8-12-39-27W4, Depth 4972 feet, Core is 8cm wide

C **Facies 8: PEBBLY SANDSTONE**

Well 16-15-38-25W4, Depth 4806 feet, Core is 8cm wide

Discussion: Note the progressive addition of coarser granules from A to C. The fine- to medium-grained "salt and pepper" texture is common to all three facies. Inclined bedding can be readily defined and dips most steeply in the Cross-Bedded Sandstone Facies (Fig.4.6A). Bedding is usually more crudely defined and dips least steeply in the Pebbly Sandstone Facies. The vertical irregularity (arrow) in the left-central portion of photo A may represent a burrow.


A
B
C

Facies 7: GRANULAR SANDSTONE

Description: The Granular Sandstone Facies is a moderately sorted mixture of fine- to very coarse-grained sand (Fig. 4.6B). The fine- to medium-grained portion of the facies appears identical to the sand comprising the Cross-Bedded Sandstone Facies. The addition of very coarse granules as distinct laminae within the cross beds marks the difference between these two facies. The well-rounded, polymict granules are very colourful; granules are yellow, green, orange, black and white.

Overall, the facies exhibits a moderate degree of textural differentiation. Cross-stratification is most easily defined by granule-poor laminae, where foresets are as steep as 15^{0}. In places it is very difficult to distinguish set boundaries; estimates of set thickness vary from 4 to 20 cm. When plugged cores are matched together, it appears there is less than a 90^{0} variation in foreset dip direction.

Mudstone drapes are observed in places, and they separate crossbed sets which are 4-7cm in thickness. However, in some instances they are noticeably absent. Large (1cm) diameter vertical *Skolithos* and horizontal sand-filled burrows may be seen in the mudstone laminae.

The average thickness of this facies is 2 metres. The facies is observed to occur throughout the length and width of the Joffre field, and is not developed beyond the limit of Joffre's production. It typically overlies the Cross-Bedded Sandstone Facies.

Preliminary Interpretation: The depositional rate appears to have overwhelmed the rate of bioturbation. The depositional environment for this facies was probably dominated by fairweather unidirectional currents. The presence of very coarse granules may signify:

i) moderately strong currents; and/or

ii) access to a slightly coarser grained source.

Deposition by traction, producing a constantly shifting substrate, probably restricted faunal diversity.

Facies 8: PEBBLY SANDSTONE FACIES

Description: The Pebbly Sandstone Facies is a poorly sorted mixture of small pebbles (4-10mm), coarse and very coarse granules, and medium-grained sand (Fig. 4.6C). The finest grained portion of the facies is again the same "salt and pepper" mixture of quartz and chert grains as was noted in the two previous cross-bedded facies (Facies 6 and 7). The pebbles and granules are rounded to well-rounded, slightly elongate, and polymictic in nature. The coarsest grained fraction occurs as discrete laminae and "pockets" within the cross bedding.

Bedding tends to be very crudely defined. Finer grained (pebble-poor) intervals may show low angle (less than 10^{0}) cross stratification. Commonly bedding appears massive, without any distinctive cross stratification. In two instances, the long axes of pebbles were noted to lie transverse to flow, indicating deposition by traction. Cross bed set thicknesses were not tabulated because bounding surfaces were often not recognizable. Mudstone rip-up clasts when present, were often sideritized.

The facies ranges in thickness from a thin horizon (10cm) to 3 metres in thickness. It is observed only within Joffre's production limits. It is best developed in the northwest portion of Joffre, becoming less significant towards the southeastern end of the field.

Preliminary Interpretation: As was postulated for Facies 6 and 7, the Pebbly Sandstone Facies was probably deposited above fairweather wave base. The setting was dominated by physical processes which prevented diverse faunal communities from establishing themselves.

The similarity of the polymictic pebbles and granules, and the common "salt and pepper" matrix suggest that Facies 6,7 and 8 were receiving sediment from the same source.

Facies 9: "MIXED" FACIES

Description: The "Mixed" Facies is named for the intriguing variety of textures and structures it contains. Grain sizes range from clay-sized material through to small pebbles (3-5mm); physical sedimentary structures include cross-stratification, massive bedding, parallel-undulatory (wavy) lamination, and mudstone drapes (Fig. 4.7). The facies can be broken down into a fine-grained background and a coarser grained episodic foreground.

The background consists of interlaminated mudstone and very fine-grained, quartzose sandstone, the laminae varying from less than 0.5 to 2cm in thickness. The sandy laminae display parallel-undulatory (wavy) lamination. Some of these laminae have a basal layer of granules, thus appearing to grade normally upward to their siltier tops. Background burrowing varies in its intensity; in places the laminae are perfectly preserved, but otherwise the sediment has been thoroughly churned.

The foreground sediment consists of massive fine pebbly sandstone beds and lenticles of cross-bedded fine- to coarse-grained, salt and pepper sandstone. The massive pebbly sand beds are approximately 2-5cm thick, and the crossbed lenticles are usually 3-10cm thick. Foresets within these lenticles may dip as much as 25^{0}.

The "Mixed" Facies tends to occur in the central to southeastern portions of Joffre, above the cross-stratified sandstones of Facies 6,7 and 8. It has a thin development at Joffre, often measuring less than 50cm in thickness.

Preliminary Interpretation: The variable textures of the "Mixed" Facies indicate significant energy fluctuations within the environment of deposition. The physical sedimentary structures show that depositional currents consisted of both oscillatory and unidirectional flows.

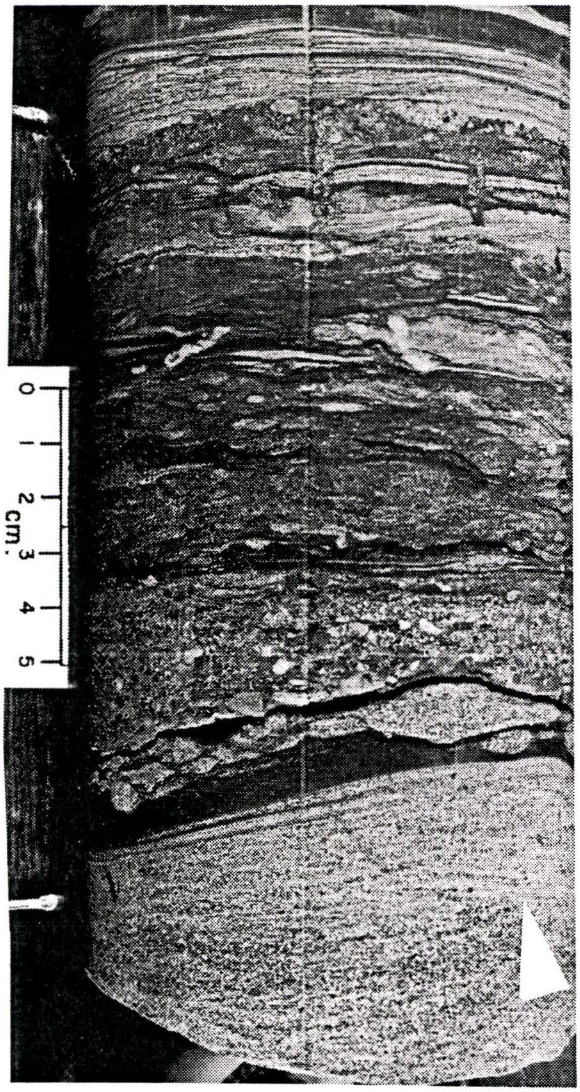


Figure 4.7 **Facies 9: "MIXED" FACIES**

Note the variety of grain sizes and sedimentary structures within this facies. Fine-grained sandy layers tend to exhibit wavy lamination, while the coarser grained sand layers appear massive or cross-laminated. Note also the variation of burrowing style and intensity.

The upper portion of the lowest crossbed shows evidence of wave reworking. Here, relatively delicate silt laminae highlight the parallel lamination which truncates (arrow) the more coarse-grained cross-stratified base.

Well 6-4-38-24W4 Depth 4554 feet Core is 8cm wide

It seems that weak oscillatory currents, probably related to storm waves, dominated background sedimentation; these currents deposited the very fine-grained, quartzose, wavy sand laminae. Deposition of mud from suspension occurred during the time between storms. Smothering rates of deposition from suspension may explain the non-burrowed intervals of sediment.

The background environmental setting appears to have been above storm wave base and at times possibly approached fairweather wave base. During these times unidirectional currents may have had the chance to erode, transport and deposit the coarser grained sediment. The primary cross-lamination of these coarser grained beds appears to have been reworked in part by waves.

Facies 10: HUMMOCKY-CROSS-STRATIFIED SANDSTONE FACIES

Description: This facies consists of interbedded black mudstone and plane parallel to low angle inclined laminated sandstone (Fig. 4.8). The sandstone is consistently very fine-grained. The thicknesses of the sandstone beds varies from 2 to 28cm. Sandstone beds have sharp basal contacts which exhibit scour and load features. Many beds contain low-angle divergences and truncations characteristic of hummocky cross-stratification (H.C.S.); the dips of which do not exceed 10^0 (Fig. 4.8A). Some of the beds appear to be horizontally laminated from the base to within 3 cm of the

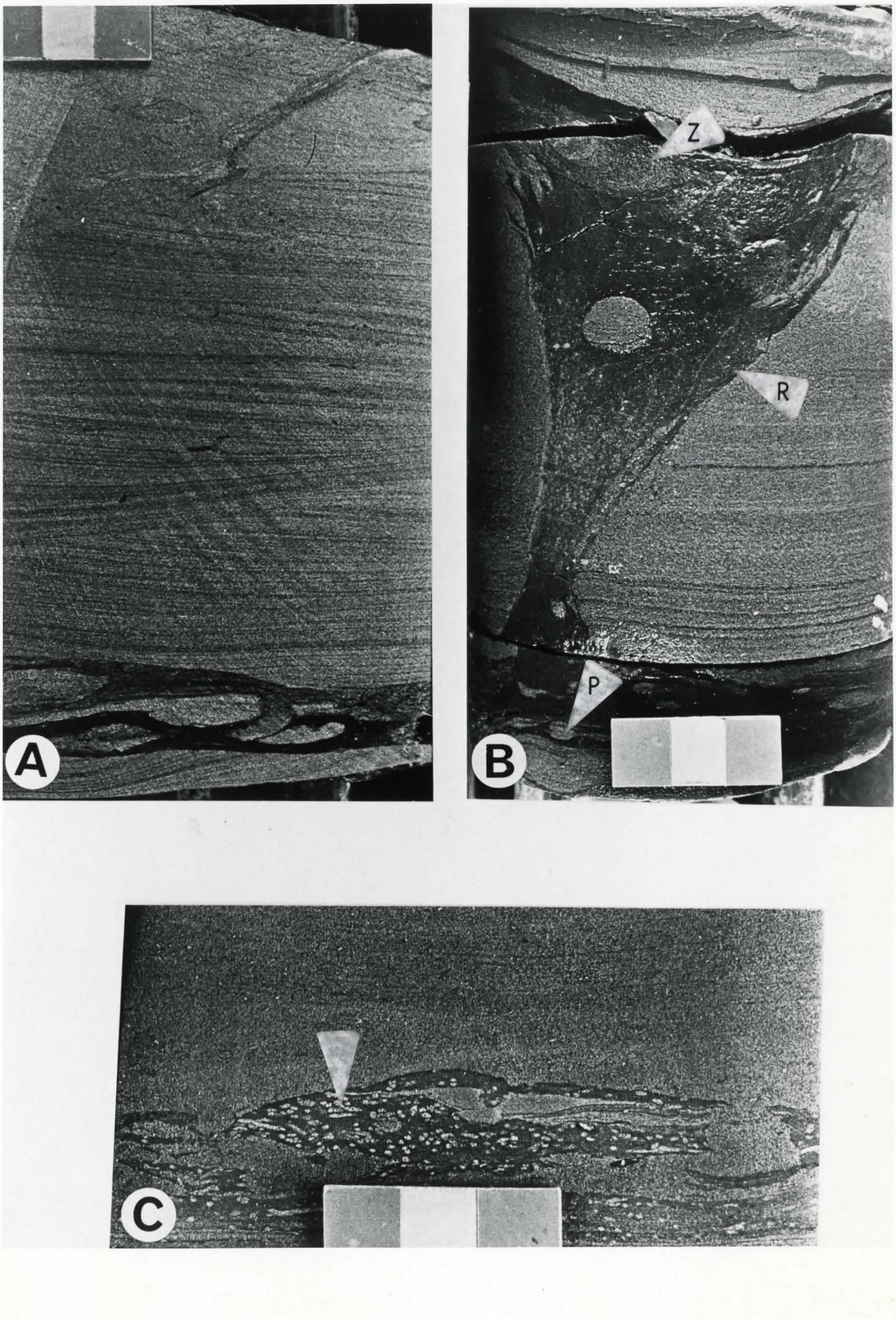
Figure 4.8 **Facies 10: HUMMOCKY CROSS-STRATIFIED SANDSTONE**

A) Hummocky cross-stratified bed composed of low-angle divergences and truncations. Well 10-25-36-24W4, 4784 feet

B) Plane parallel stratified bed featuring Rosselia (R), Planolites (P), and Zoophycus (Z).
Well 11-6-33-20W4 Depth 1198 metres

C) Chondrites (arrow)are plentiful in these irregularly-shaped burrowed mudstone lenses.
Well 2-9-34-18W4 Depth 1115 metres

Scale bar in all photos is 3 cm in length.


Z
R
P
A
B
C

top, whence the laminae begin to undulate. The upper contact of the beds is sharp, lenticular, and sometimes scoured. In places, non-sideritized rip-up clasts are incorporated in the wavy laminations.

Black mudstone drapes are usually 1-3cm in thickness. Burrows occur within the mudstone laminae, rarely are the interiors of the sandstone beds disrupted. Trace fossils which are observed include: Zoophycus, Rosselia, Planolites, and Chondrites (Fig. 4.8B,C).

The Hummocky-Cross-Stratified Sandstone Facies is seen in wells which lie approximately 25km to the southwest of the Joffre-Mikwan-Fenn trend. The facies is not present within any of these three fields, nor beyond their northeastern margins. The facies thickness progressively decreases from 4 metres (14-7-36-27W4), to zero at the southwestern margin of Joffre. Thus the facies development has a wedge-like shape, thinning towards the northeast parallel to the trend of the fields, and disappearing southwest of the fields.

Preliminary Interpretation: Hummocky cross-stratification suggests that the depositional environment of this facies was affected by oscillatory currents. Each sandstone bed probably records a waning storm event. The sharp basal contacts of these sandstone beds indicates their sudden emplacements. The development of plane parallel lamination within some of the beds attests to high shear stresses at the sediment-water interface. The transformation of unidirectional to oscillatory flow is indicated by wave-rippled tops to these plane parallel laminated beds.

The abundance of hummocky cross-stratification and the absence of angle-of-repose bedding suggests a shelf or shallow marine setting at depths between fairweather wave base and storm wave base. The remarkably uniform grain size (very fine-grained) may suggest that the transporting currents had access to a well-sorted "sand reservoir".

Facies 11: BANDED GRAVEL FACIES

Description: The Banded Gravel Facies consists of alternating laminae of pebbly sand and finer-grained, laminated to burrowed siltstone (Fig. 4.9). As many as 15 bands may occur in succession (well 16-24-38-26W4, depth 5032 feet). The pebbly sand bands are typically 1-3cm thick and contain fine to medium-grained salt and pepper sand and well-rounded, randomly distributed pebbles. The thinnest bands are one pebble diameter in thickness. The pebbles are polymictic in nature.

The bases of the pebbly sand bands are usually sharp, and incised into the underlying mudstone. The tops of the bands are either sharply draped by mudstone or burrowed. The interiors of the pebbly sand bands are commonly structureless, but may show normal grading (Fig. 4.9A: lowermost pebble band). Angle-of-repose cross-stratification is absent. The bands may be either dominated by pebbles (clast-supported), or dominated by sand (matrix-supported).

Figure 4.9 **Facies 11: BANDED GRAVEL FACIES**

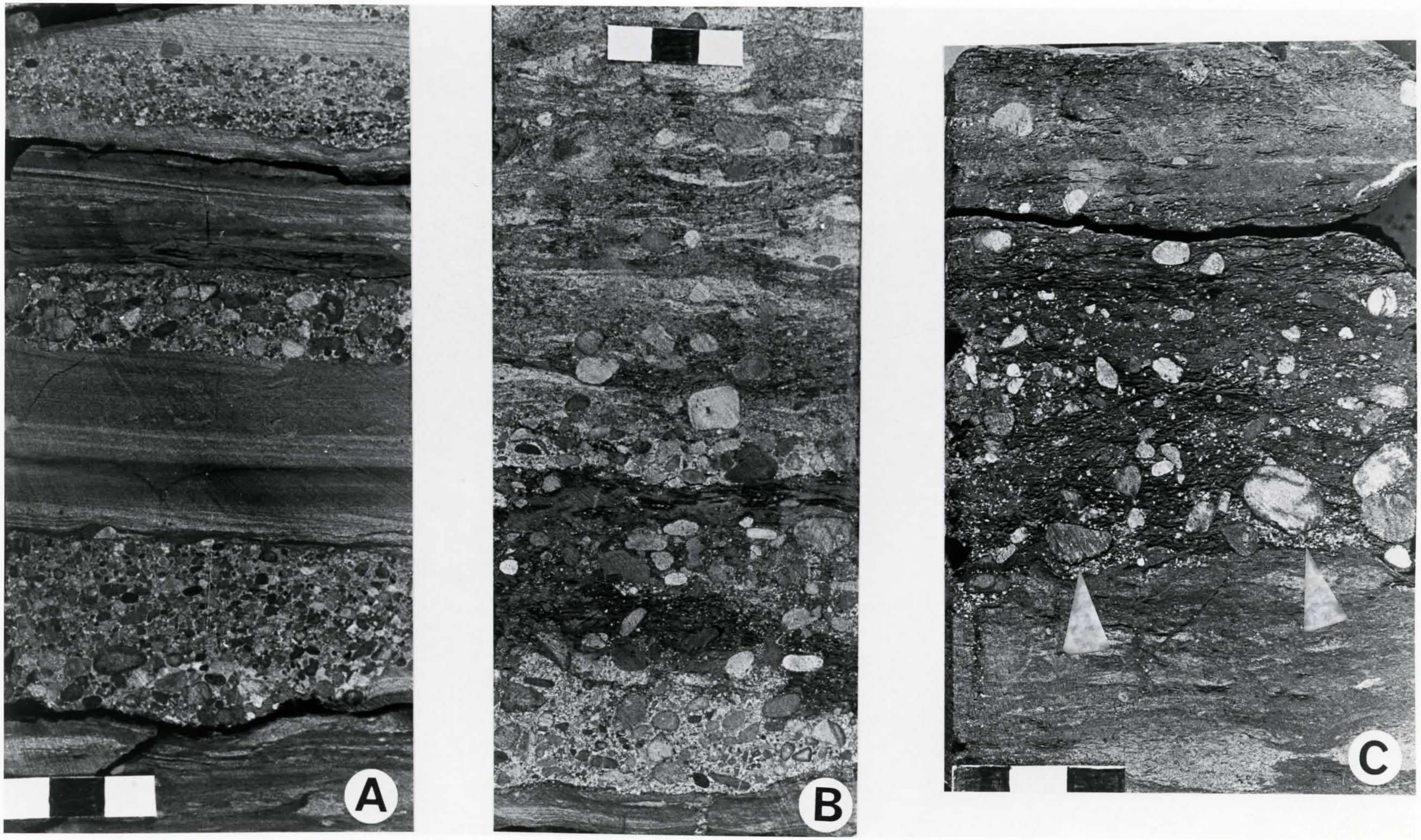
A) Well 9-20-39-27W4 Depth 5245 feet

B) Well 9-16-39-27W4 Depth 5112 feet

C) Well 16-14-38-25W4 Depth 4671 feet

Discussion: These cores are grouped together as the same facies, despite their apparent initial disimilarity. There is an increasing amount of biological activity from photo A to C which has progressively disaggregated the initially discrete bands of pebbly sand. Remnant "pockets" (arrows) of the sandy matrix can be seen in photo C. Sharp basal contacts can be seen in all the photos.

Scale bar in all photos is 3cm in length.


A
B
C

The background to these distinctive pebbly sand bands is variable and by definition belongs to a separate facies, usually Facies 3 or 4. Burrowing associated with the background facies sometimes disrupts these laminae and pebbly sand bands (Fig.4.9B), and vigourous bioturbation may completely homogenize both the muddy background and the pebbly sand bands, creating a gritty mixture of sand, mud and pebbles (Fig. 4.9C).

This facies is always less than 1 metre in thickness and tends to occur at several stratigraphic horizons.

Preliminary Interpretation: The depositional setting for each stratigraphic occurrence of Facies 11 varies according to the associated background facies. However, although the background conditions vary, Facies 11 is always very much coarser than its background sediment. Beds of facies 11 can be simplistically interpreted as the product of episodic, high energy erosive flows. They cannot be explained by in-situ winnowing due to their anomalous coarseness.

Facies 12: CONGLOMERATE FACIES

Description: The Conglomerate Facies is usually a clast-supported mixture of polymict pebbles and granules, medium-grained salt and pepper sand, and mud (Fig. 4.10). In places, a carbonate cement such as siderite, or less commonly calcite, may be present. Maximum pebble diameters vary from 20 to 35 millimetres. The pebbles are well-rounded and oblate in shape.

Figure 4.10 **Facies 12: CONGLOMERATE FACIES**

Typically the facies has a sharp, erosive base as shown in this photo (lower arrow). The erosive contact separating the conglomerate facies from the underlying sediment in this photo corresponds to the "E3" surface discussed in the next chapter. In places, siderite cement occurs in this facies, and calcite cement (middle arrow) occurs less commonly.

Well 7-1-37-24W4 Depth 4603 feet Core is 8cm wide

Bedding within the facies is crudely defined by horizontal alternations of sand-rich and cement-rich layers. Sometimes normal and inverse grading is recognized. Grading is expressed by changing pebble sizes, changes between clast-supported and matrix-supported networks, and the changing character of the matrix material. Normal grading was expressed in several cores by the upward progression from a clast-supported interval, to a sandy matrix-supported interval, to a muddy matrix-supported interval. In other instances, the facies appears structureless. Angle-of-repose cross-stratification was not recognized, nor are there any distinctive signs of burrowing.

The Conglomerate Facies usually has a sharply-defined, erosive base and sharply draped top. The uppermost few centimetres of the sediment directly beneath the conglomerate is commonly sideritized. The facies ranges from 5 to 50 cm in thickness and occurs at the top of the Viking throughout the study area.

Preliminary Interpretation: The Conglomerate Facies is interpreted as a "single-event" deposit. There are no intervening mudstone laminae to suggest that the conglomerate accumulated episodically. It is difficult to interpret the crudely-defined flattish bedding. The Conglomerate Facies possibly represents a lag deposit, emplaced and reworked(?) by wave action.

Facies 13: LOADED SANDSTONE FACIES

Description: This facies comprises beds of well-sorted fine-grained to medium-grained, salt and pepper sandstone, and very black, fissile shale (Figure 4.11) The sandstone beds vary from less than 1cm to 9cm in thickness.

The bases of the beds are sharp, and appear to be loaded into the shale interbeds. Sometimes lenses or "balls" of sandstone are observed to be completely encased in shale. In places, pebbles (3-12mm in diameter) may be seen at the base of the loaded sandstone beds. The interiors of these beds are commonly structureless. The tops of the sandstone beds are also sharp, appearing as flattish to undulatory surfaces which are draped by the overlying shale beds. The sequence of sandstone beds commonly thickens upward.

The shale interbeds are notably black and fissile, and are very similar in appearance to the shales of Facies 14. They range from 1 to 10 cm in thickness. Discrete burrows are scarcely seen in this facies, but where present, sand-filled horizontal burrows occur in the shale beds.

The Loaded Sandstone Facies is always less than 0.75m in thickness, and is usually less than 0.3 metres. The facies occurs randomly throughout the study area, but is restricted to one stratigraphic position, which is the upper contact of the Viking Formation.

Preliminary Interpretation: The black, clay-rich, fissile shale represents a deep water, low energy environment,

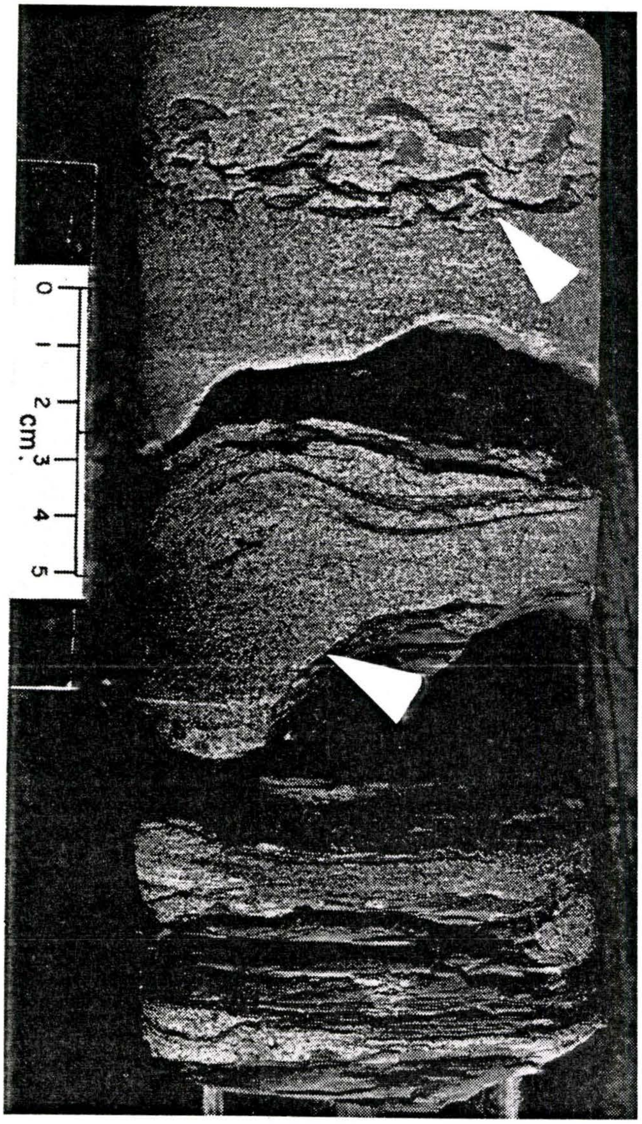


Figure 4.11 **Facies 13: LOADED SANDSTONE FACIES**

Note the excellent textural contrast between well-sorted sandstone beds and the very black fissile shale beds. The sharply rounded bases (lower arrow) of the loaded sandstone beds suggests their sudden and erosive emplacements onto an unconsolidated bottom. The interiors of the sandstone beds appear structureless, except for the mud rip-up clast horizon in the upper bed (upper arrow), and a few thin, continuous mud laminae close to the top of the middle bed. Well 5-22-38-25W4 Depth 4693 feet Core is 8cm wide perhaps below storm wave base. Very little silt-sized material was supplied to this setting. The sharp, loaded bases of the sandstone beds reflect the sudden emplacement of sand onto a relatively "soupy" substrate, thereby initiating synsedimentary deformation. The presence of mud clasts indicates that at least partially lithified substrate was scoured by and incorporated into the advancing sediment flow. Perhaps these sideritized mud clasts originated from sites of very early diagenesis shoreward of this setting. The transporting currents were likely storm-related and transported the sediment largely by suspension.

Facies 14: BLACK MUDSTONE FACIES

Description: This facies comprises a monotonous sequence of weakly burrowed, black, fissile mudstone (Figure 4.12). Core intervals with a high clay-to-silt ratio cleave into "poker chip-like" pieces, similarly, siltier intervals cleave into "hockey puck-like" fragments.

Overall, there is very little sand-sized material present. Periodically, delicate "pin-stripe" silt laminae (1-4mm thick) occur within the mudstone. These laminae have sharp bases and tops and may be lenticular in profile. Slightly thicker laminae (.5-2.0cm thick) are rare. These thicker laminae are composed of very fine-grained sand. The laminae may feature wavy laminations or cross-laminations, or alternatively they may appear structureless due to burrowing.

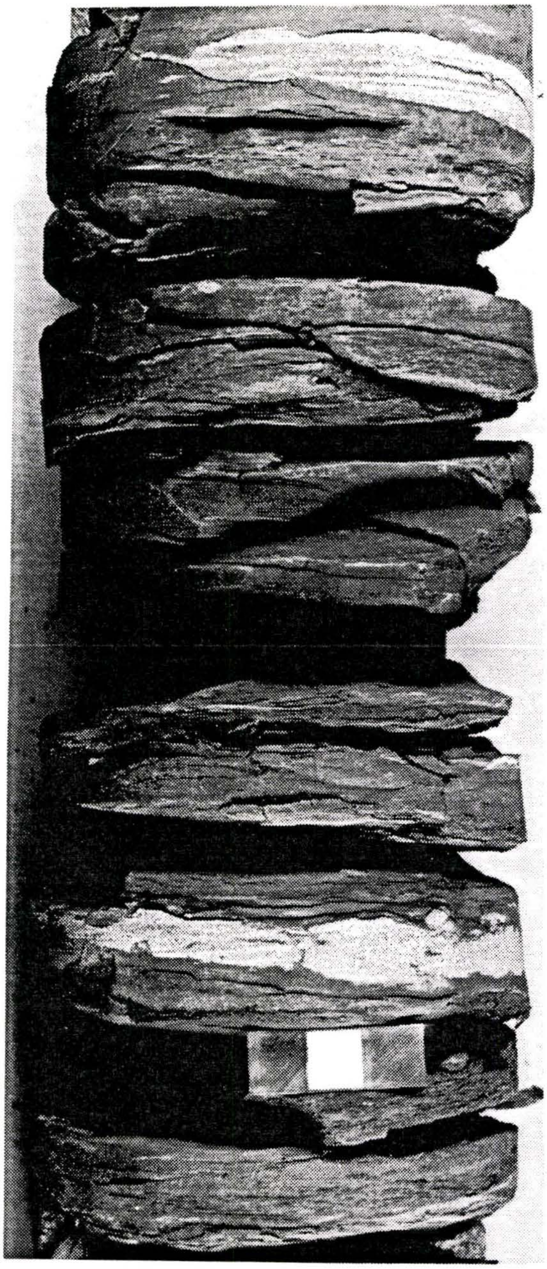


Figure 4.12 **Facies 14: BLACK MUDSTONE FACIES**

Note the fissile appearance of the mudstone. There are no distinctive burrows associated with this facies, and very few silty-sand laminae occur as well. The lowermost sandy lamina of this photo has been disrupted by burrowers. This core represents the uppermost stratigraphic occurence of this facies, it belongs to the Lloydminster Formation.

Well 8-12-39-27W4 Depth 4941 feet Scale bar 3cm long

Facies 14 has two distinctly different stratigraphic positions which are clearly expressed in the next chapter. Briefly, the lowermost occurrence is interbedded with the coarse, cross-stratified sandstones, while the uppermost occurrence blankets the Viking Formation and represents the Lloydminster Formation.

Preliminary Interpretation This facies represents deposition under very quiet conditions.

CHAPTER 5. DISTRIBUTION OF FACIES SEQUENCES

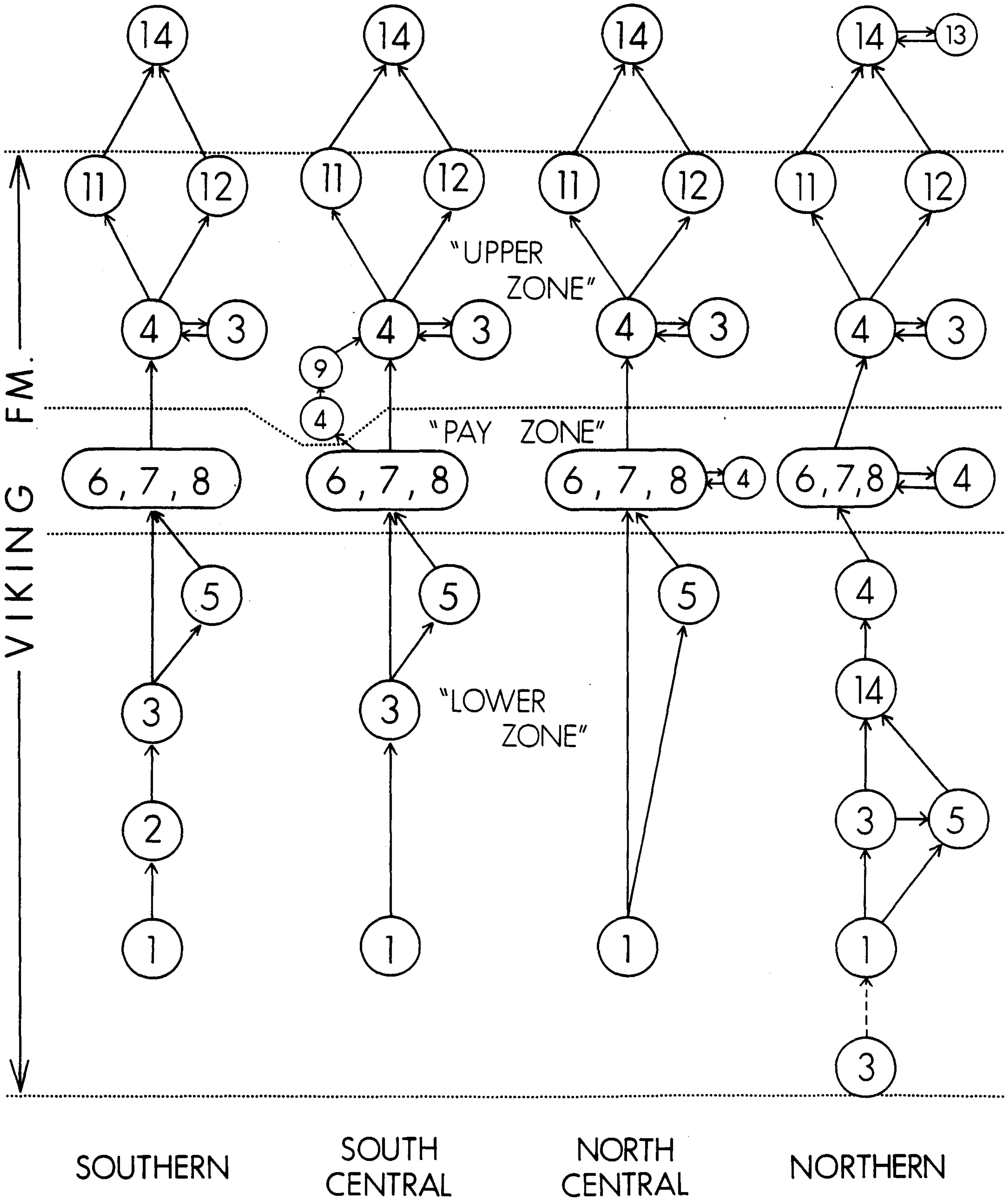
5.1. Introduction

The aim of this chapter is to present a summary of the distribution of the facies outlined in Chapter 4. The reader is here reminded that a schematic reference page for the facies is found in Appendix I.

In the first two sections of this Chapter (5.1, 5.2) the core data is simplified by establishing four groups of similar vertical facies sequences. In Section 5.3, the four types of Sequences are correlated using five paired core and log cross sections. Erosion surfaces documented in these cross sections help to explain the variations between the four sequence types. In the final part of this chapter the concepts of "genetically-similar Facies Packages" and "erosional Bounding Surfaces" are developed. The figures in this chapter are designed to highlight the close correspondence of textural observations between the cores and their accompanying resistivity logs.

Initially, the unwieldy data base of 100 cores and 14 facies was simplified, out of necessity, into four vertical facies sequences; within each sequence, the cores and logs were basically similar (Figure 5.1). The four sequences were found to group into "belts" oriented parallel to the length of the Joffre field (Figure 5.2), and their names were chosen to represent their geographical position with reference to the axis of Joffre.

Figure 5.1 The Vertical Facies Sequences at Joffre.



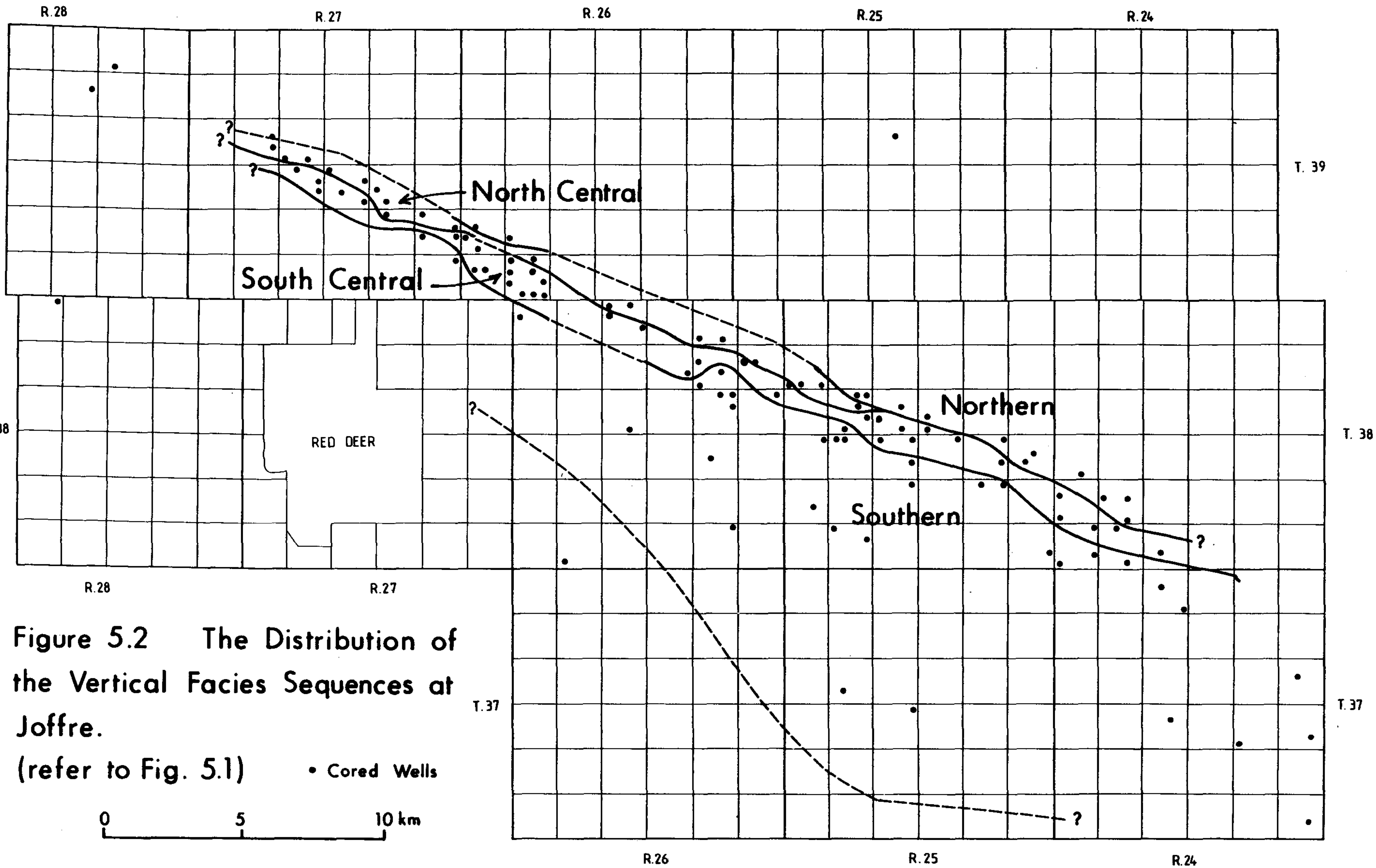


Figure 5.2 The Distribution of the Vertical Facies Sequences at Joffre.
(refer to Fig. 5.1)

The vertical facies sequences can be informally subdivided into 3 portions, (Fig. 5.1) herein referred to as "the upper zone", "the pay zone", and "the lower zone". These zones are named with respect to their stratigraphic position within the Viking Formation at Joffre and apply to this area of Chapter 5 only.

The "upper zone" is essentially the same in all four Sequences, and is generally dominated by Facies 4, although intervals of Facies 3 are observed also. Facies 4 is always capped with pebbly sediment of either Facies 11 or 12; the top of this coarse pebbly sediment marks the upper contact of the Viking Formation. The average thickness of the "upper zone" is approximately 7 metres. Several occurrences of Facies 9 at the base of this zone were noted in cores of the South Central Sequence (Fig. 5.1)

The "pay zone" occurs in the middle of the Viking Formation. It consists of Facies 6, 7 and 8, which are interbedded with each other in a variety of ways. In general, the "pay zone" facies succession tends to coarsen upward (i.e. 6-->7-->8); however, all three facies are not necessarily present in every well. In the North Central and the Northern Sequences, intervals of Facies 4 become more prominent. The average thickness of the "pay zone" is approximately 5 metres.

The most variation in vertical facies sequences occurs in the "lower zone" of each Sequence. It is this variation which serves to distinguish each of the four Sequence-types from its neighbour. The facies successions become simpler from the Southern, to South Central, to North Central Sequences:

1--->2--->3--->5 (Southern)

1--->3--->5 (South Central)

1--->5 (North Central).

Note that Facies 5 may be bypassed in the succession (Fig. 5.1). The "lower zone" of the Northern Sequence is more difficult to relate to its neighbours.

In all four of the type Sequences, the "lower zone" is overwhelmingly dominated by Facies 1. The average thickness of the "lower zone" is approximately 12 metres. With the exception of one well, all the Viking cores at Joffre end within 7 metres below the "pay zone". Thus, the base of the Viking Formation is seen in only one well (12-8-38-24W4), which belongs to the Northern Sequence. Facies 3 occurs at the base of the formation and is shown in Figure 5.1 as the initial facies of the "lower zone" in the Northern Sequence. The dashed line leading from Facies 3 to its successor (Facies 1) represents the assumption that it typically initiates the facies sequence of the "lower zone" in Northern-type wells. The character of the base of the Viking Formation in the rest of the type sequences is unknown.

It is important to realize that the most variation in the facies Sequences occurs stratigraphically below the "pay zone". The map in Figure 5.2 shows the systematic distribution of the four Sequences, and implies that the facies successions are mostly changing in a direction perpendicular to the strike of Joffre. Four of the five cross sections in Chapter 5.3 are oriented to show these across-the-field changes.

5.2. The Four Vertical Facies Sequences

A representative litholog and accompanying resistivity profile will be shown for each of the Sequences depicted in Figure 5.1. Three electric-log markers (LM1, LM2, and LM6) and one core and log marker (CLM3) are included in the diagram for reference to upcoming cross sections. These markers are defined at the beginning of Chapter 5.3. A brief discussion of each type of Sequence is intended to highlight specific facies contacts and trends.

Special emphasis is placed upon sedimentological "breaks" within the vertical facies sequences. The "breaks" are established at those facies contacts which feature:

i) rapid changes of grain size, and

ii) rapid changes of sedimentary structures. The fact that so many wells exhibit similar facies sequences suggests that common "break points" may lend themselves as markers for correlation of widespread, and sudden changes in the depositional environment.

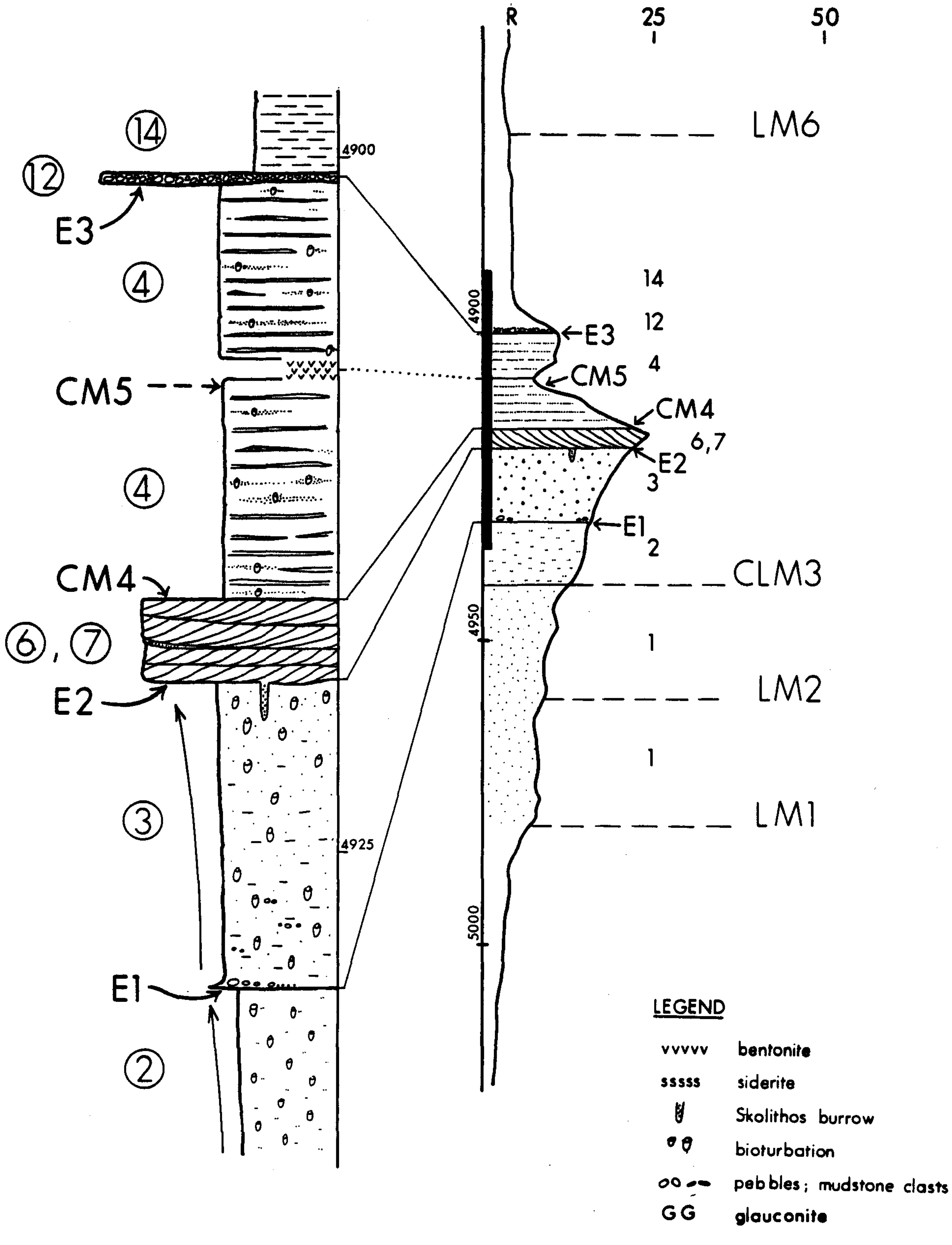
There are five main breaks common to all the Sequences, they are labeled E1, E2, CM4, CM5 and E3. Their names are derived from their appearances in the cross sections which follow. Three of the breaks have an erosive nature (E1, E2 and E3) as is proved in the cross sections. The other two have been named as core markers (CM4, CM5) and are numbered to fit into the overall suite of core and log markers. Thus, the CM4 marker overlies the CLM3 marker, which is turn overlies the LM2 marker and so on.

The Southern Vertical Facies Sequence (Figure 5.3)

There are 28 cored wells which exhibit this vertical facies sequence. These wells are found along the Southern flank of Joffre and can be mapped out as a "belt" (Fig. 5.2). The "belt" extends continuously (subject to well control) from the northwest end to the extreme southeast end of Joffre. Based on reconnaissance data, the belt appears to continue southeast, extending into the southern margin of the Mikwan field also. It can be extended off-field, into the southwest, as far as cored wells 16-16-37-25W4 and 6-20-37-25W4, which occur approximately 8 kilometres southwest of the Joffre field. Based upon well control, the Southern Sequence belt is the most extensive of the four defined.

There are five main sedimentological breaks in the Southern Vertical Facies Sequence (E1, E2, CM4, CM5, E3),these are indicated on Figure 5.3. Well 7-7-38-25W4 was chosen as the "Southern" representative because four of the five breaks could be clearly seen in the core and

Figure 5.3
An Example of the SOUTHERN Vertical Facies Sequence. 7-7-38-25W4



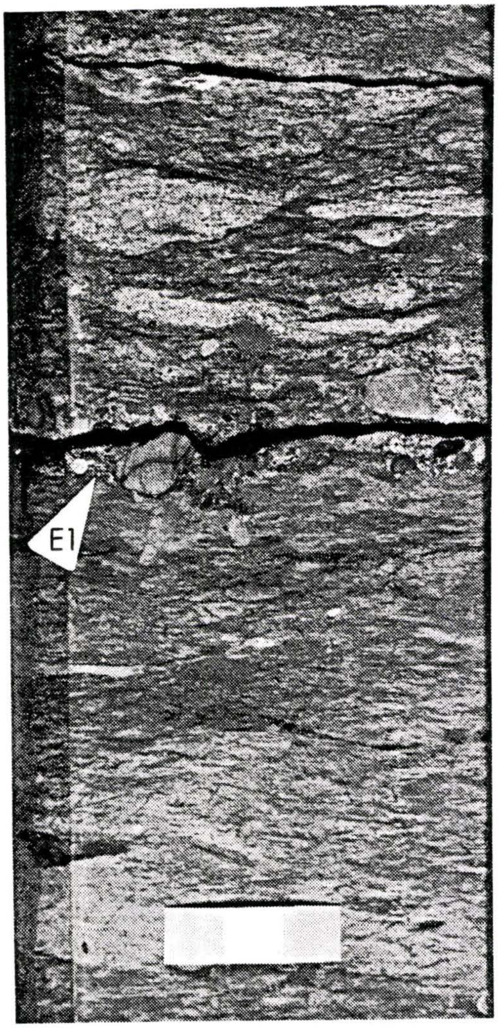


Figure 5.4 **E1 Break** Contact: Facies 2 / 3

The Facies 2-3 contact is easily recognized in this well. It is coincident with a burrowed layer of pebbly sand (arrow). Eighty percent of the Southern wells which are cored to this depth in the sequence exhibit coarse sediment at this facies contact or just slightly above it.

Well 7-7-38-25W4, Depth: 4931 feet Scale bar 3 cm long extrapolated to the resistivity log. The well also serves as a "data bridge" to tie-in with one of Reinson's core localities (Reinson et al., 1983; p.110).

As is commonly the case, only the upper half of the formation is cored. The main sedimentological breaks are discussed in ascending order.

E1. The first break is defined at a pebbly horizon (Fig. 5.4), which is either co-incident with, or slightly above the contact of Facies 2 and 3. Eighty percent of the southern cores feature a difuse layer of pebbles or grits at, or just above, this otherwise subtle facies contact. The subtlety of the contact is due to the similar bioturbation intensities of Facies 2 and 3, which creates the illusion of a continuously bioturbated sediment. Upon close examination, one can isolate a 5-10 cm zone of rapid grain size increase from very fine-grained sand within the Facies 2 siltstone to fine-grained sand of the overlying Facies 3 sandstone.

Granules and pebbles, whose diameters may exceed 1 cm, tend to be associated with a distinct layer of sand, approximately 1 cm in thickness. Pebbly sand laminae may recur several times within one metre above the Facies 2-3 contact. The scattered appearance of many of the pebble horizons is due to biological activity whereby the sandy component of the laminae is homogenized with the background sediment of Facies 3, leaving the pebbles and granules as a diffuse layer.

This bioturbated, yet distinct facies contact is recognized as a "break" because of the striking occurrence of pebbles and granules within it.

E2. The second sedimentological break in the Southern sequence occurs at the contact of Facies 3 and 6 (Fig.5.5). This break is more prominent and easier to recognize than the E1 break. It marks the transition from bioturbated fine-grained muddy sandstone (Facies 3) to cross-bedded medium-grained sandstone (Facies 6). Primarily, the E2 break is defined on the basis of:

a) an abrupt increase in grain size from the fine-grained quartzose sand to the medium-grained "salt and pepper" sand, and

b) a change from biogenic structures (below) to dominantly physical sedimentary structures (above).

There are two other (less typical) characteristics of this contact:

c) In 40% of the Southern-type wells which were cored to this depth in the Sequence, distinctive <u>Skolithos</u> burrows were observed to penetrate the top of Facies 3, extending down from the overlying facies (Fig.5.6).

d) In 20% of wells which were cored to this depth sideritization was observed to occur at or near the top of Facies 3.

Figure 5.5 **E2 Break** Contact: Facies 3 / 6

Note the "knife-sharp" break from bioturbated muddy sandstone (Facies 3) to cross-bedded "salt and pepper" sandstone (Facies 6) indicated by the arrow.

Well 16-2-38-26W4 Depth 1512.5 m Core 8 cm wide

Figure 5.6 **E2 Break** Contact: Facies 3 / 6

(Photo taken directly beneath contact) The Skolithos burrows are approximately 1 cm in diameter, occur in pairs (when seen in plan-view), and are filled with the medium-grained "salt and pepper" sand of Facies 6 which overlies the contact. The burrows may penetrate several decimetres into Facies 3.

Well 9-5-38-25 W4 Depth 1452.0 m Scale 3 cm long

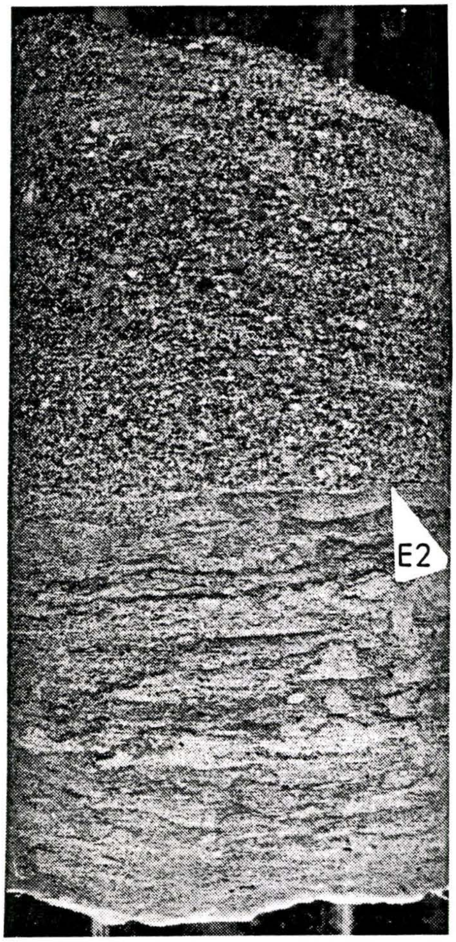


Figure 5.5

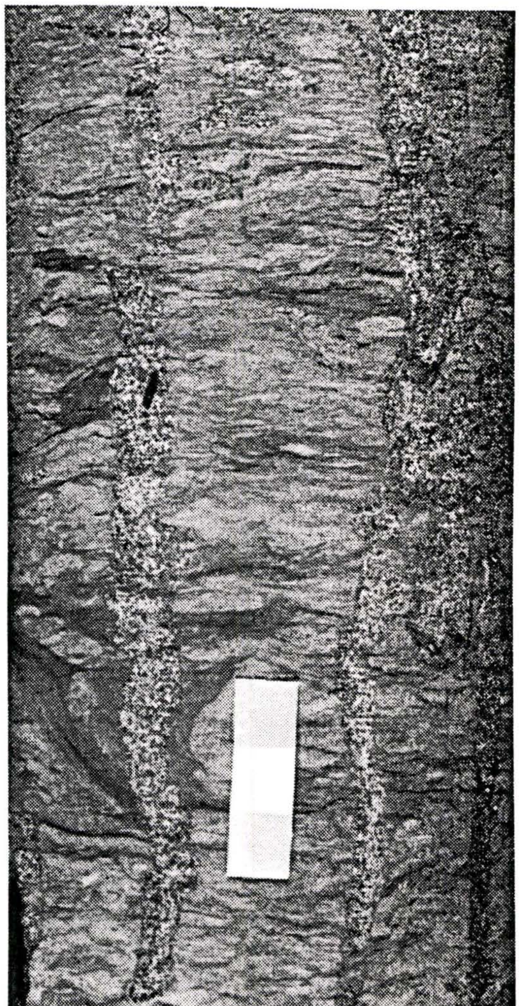


Figure 5.6

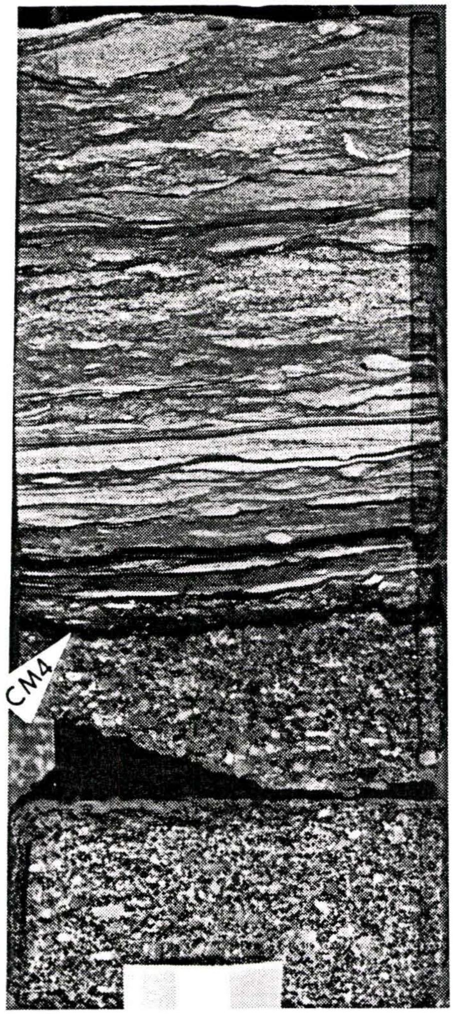


Figure 5.7 **CM4 Break** Contact: Facies 7 / 4

Note that at the sharp contact (arrowed), granular "salt-and-pepper" sandstone (Facies 7) appears "draped" by thinly-laminated mudstone and sandstone (Facies 4).

Well 5-12-39-27 W4 Depth 5008 feet Scale 3 cm long

CM4. The third sedimentological break occurs at the contact of the "salt and pepper" sandstones (Facies 6, 7 or 8) and the burrowed-laminated sandstones and shales (Facies 4). Figure 5.7 shows the abrupt decrease in grain size and sudden dominance of mudstone from Facies 7 to 4. The style of sediment accumulation has switched from deposition by traction (Facies 6,7 or 8) to deposition from suspension (Facies 4) with some wave influence. Biogenic sedimentary structures are much more common in Facies 4.

CM5. This sedimentological break is not as obvious as the previously defined breaks. In fact, this break is best seen in the other Sequence types, particularly at the northwest end of Joffre. It is discussed more fully under the South Central Vertical Facies Sequence.

Within the Southern-type wells, the CM5 break tends to occur <u>within one facies</u>, Facies 4. It is pin-pointed at the top of a rather intensely burrowed interval within Facies 4, in conjunction with a subtle decrease in grain size. Sometimes, anomalously coarse material is found at or slightly above this horizon.

In Figure 5.3, the CM5 break is positioned within Facies 4 above the top of a sideritized interval (15 cm thick), and below an unusually thick (25 cm) bentonitic shale horizon. This position approximately corresponds to a <u>subtle</u> decrease in both burrowing intensity and grain size. This well does not appear to have any coarse material draping the break.

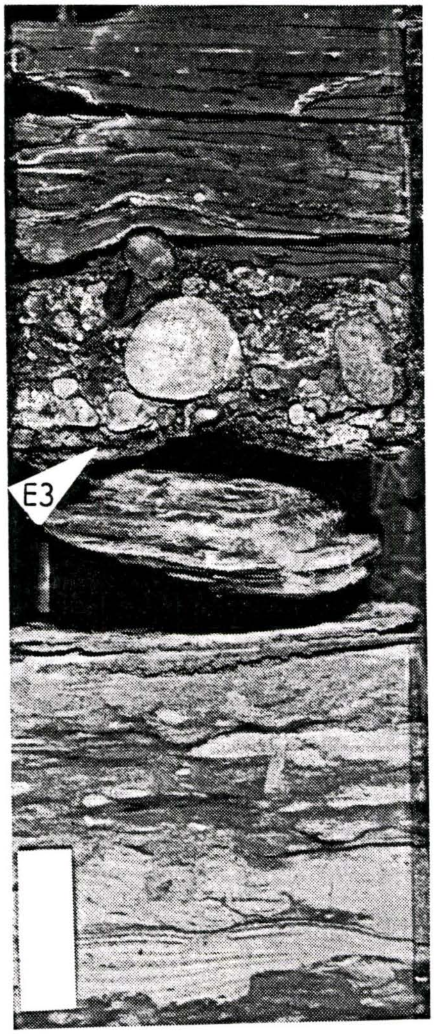


Figure 5.8 **E3 Break** Contact: Facies 4 /(11)/ 14

The contact of Facies 4 and 14 is marked by the lowermost layer (arrowed) in a series of pebbly sand "bands" of Facies 11 (Higher pebbly sand bands are not shown in this photo). This pebbly sand layer rests with a very sharp base on one of the bentonite horizons (below arrow) within Facies 4.

Well 5-12-39-27W4 Depth 5002 feet Scale 3 cm long

E5. The fifth, and final, sedimentological break occurs at the top of the formation (Figure 5.8). Basically, the break marks the junction of Facies 4 and 14. However, in 100% of the Southern-type wells which cored the top of the Viking, a thin development of an intervening facies occurs at this junction.

The intervening facies has a sharp base and top, and contains unusually coarse pebbly sediment representing either Facies 11 or 12 (Fig. 5.1). The diameter of these pebbles may exceed 2 centimetres. The pebbly facies ranges from 6 to 39 cm in thickness and may occur as one horizon (Facies 12) or as repetitive "pulses" (Facies 11).

The break is pin-pointed at the sharp base of the lowermost pebbly horizon which separates the interlaminated sandstone and mudstone (Facies 4) from the overlying mudstone (Facies 14). The pebbly mantle marks the point at which the sand-size fraction of the sediment disappears between Facies 4 (below) and 14 (above).

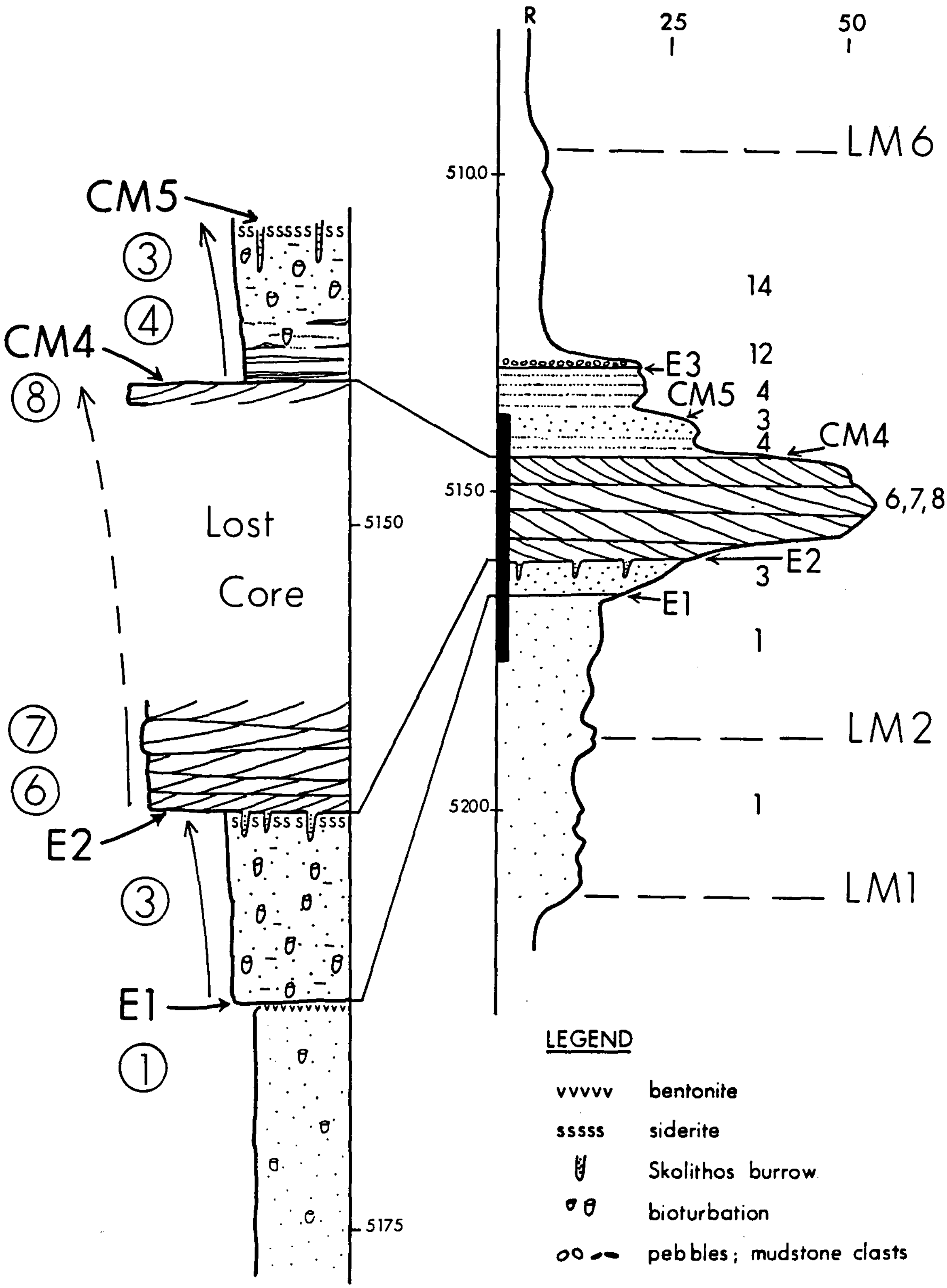
The South Central Vertical Facies Sequence (Figure 5.9)

In the Joffre vicinity, there are 38 cored wells which exhibit the South Central Vertical Facies Sequence. These wells occur closer to the axis of Joffre than do the Southern-type wells. Figure 5.2 shows the continuous extent of the "belt" of South-Central type wells. Several cores in the Mikwan area (T37 R23W4; southeast of Joffre) also exhibit the South Central Vertical Facies Sequence.

Figure 5.9

An Example of the SOUTH CENTRAL Vertical Facies Sequence

8 - 5 - 39 - 26W4



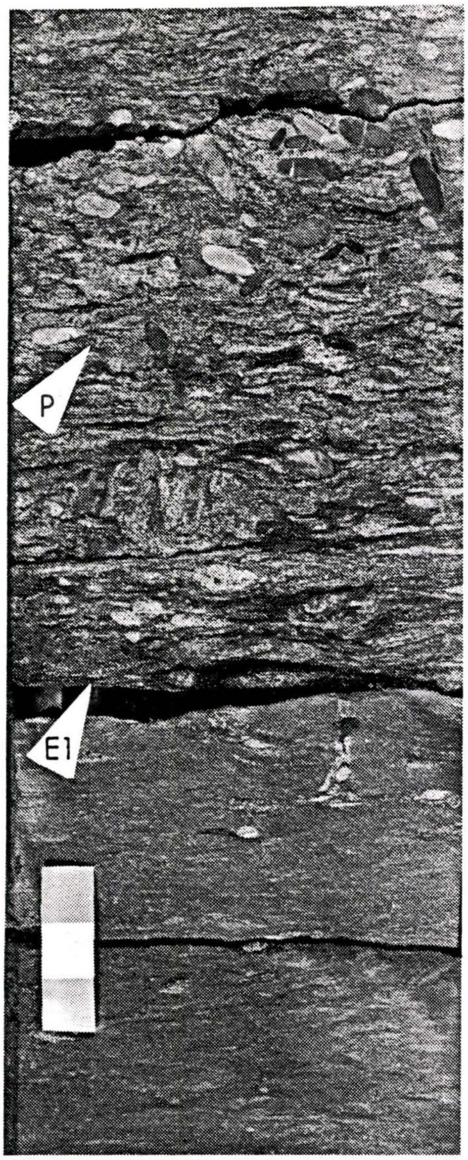


Figure 5.10 **E1 break** Contact: Facies 1 / 3

The Facies 1 / 3 contact is easily recognized (lower arrow) in this well despite its burrowed nature. There is a clear increase in grain size across the contact and a persistent association of pebbles at or slightly above it (upper arrow). Eighty-five percent of the South Central cores feature one or more diffuse pebble layers above this break.

Well 14-5-38-24W4 Depth 4410 feet Scale is 3cm long

The same five sedimentological breaks occur in this vertical facies sequence, they are indicated on Figure 5.9. Most of the breaks are virtually identical in character to their expressions in the Southern Sequence, and the reader will be referred to previous photos in the following discussion.

Despite the fact that well 8-5-39-26W4 is missing 3 metres (10′) of core, it was chosen to represent the South Central Vertical Facies Sequence because the existing core shows several of the sequence breaks, and the corresponding resistivity log shows the entire formation.

E1. In the South Central Sequence, E1 occurs at the burrowed, yet distinct contact of Facies 1 and 3. In 85% of the South Central cores, a diffuse pebble horizon was noted to occur at, or just above, this contact (Fig. 5.10). The Facies 1-3 contact is recognized as a break for two reasons:

a) there is a sharp increase in grain size from siltstone (Facies 1) to fine-grained sandstone (Facies 3),

b) there is a persistent occurrence of pebbles or granules directly above the contact (not seen in Figure 5.9).

Core and log correlations show that this break is equivalent to the E1 break despite the variation of the underlying sediment between the Southern and South Central Sequences. The cross sections which suggest this are presented in Section 5.3.

The sudden increase in grain size across E1, and the burrowed nature of it are very clearly expressed in the South Central wells because of the good textural contrast between Facies 1 and 3. Discrete, small burrows, filled with fine-grained sandstone (from Facies 3), can be seen in the siltstone a few centimetres below E1 in Figure 5.10.

E2. The expression of E2 in Southern and South Central wells is virtually identical. The reader is referred back to the previous E2 discussion (Southern Sequence) and also to Figures 5.5 and 5.6.

There are two slight variations to E2 in the South Central wells. Firstly, 40% of the cores featured glauconitic sandstone (Facies 5) directly above E2, but this was not seen in Southern cores. Secondly only 17% of the South Central cores feature Skolithos burrows penetrating E2, compared to 30% of the Southern wells.

CM4. As described under the Southern Sequence expression of CM4, this break marks the transition from cross-bedded "salt and pepper" sandstones (Facies 6, 7 or 8) to burrowed, laminated sandstones and shales (Facies 4). The reader is referred to Figure 5.7 for an example of its look-alike.

CM5. The fourth sedimentological break occurs at the contact of Facies 3 and 4. The CM5 break is defined by:

a) an abrupt decline in the intensity of burrowing, and

b) an abrupt decrease in grain size from fine- to medium-grained sandstone (Facies 3) to burrowed, laminated very fine-grained sandstone and mudstone (Facies 4).

Other sedimentological features associated with the CM5 break include:

c) unusually coarse sediment resting directly on or just above the Facies 3/4 contact (Figure 5.11) in slightly greater than 50% of the cores. The unusual grain sizes range from coarse-grained granules to 1 cm pebbles; generally the development of the unusually coarse sediment thickens and coarsens towards the northwest end of Joffre.

d) prominent Skolithos burrows penetrate Facies 3 but do not occur above the break in more than 60% of the cores. These Skolithos burrows are identical in dimension to those described for the E2 break and are likewise filled with fine-to medium-grained "salt and pepper" sandstone,

e) sideritization occurs at or near the top of Facies 3 in 25% of the cores examined.

f) a bentonitic shale horizon overlying the coarse sediment veneer described in item "c" above in approximately 50% of the cores. In several wells the bentonite is 30 centimetres in thickness,

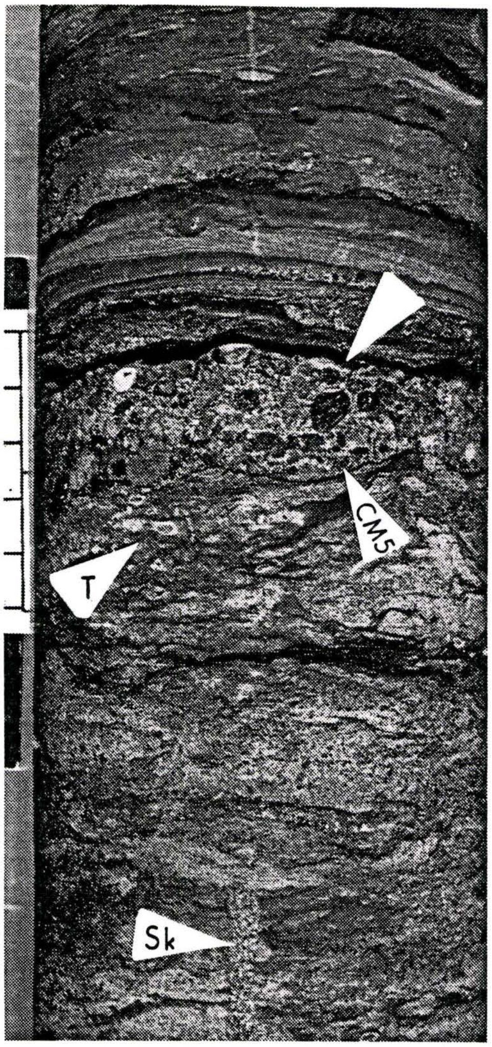


Figure 5.11 **CM5 Break** Contact: Facies 3/4

Fifty percent of the South Central cores feature a sharply-based pebble veneer (bracketed by arrows) directly above CM5. <u>Terebellina</u> (left arrow) is commonly seen in this upper occurrence of Facies 3. Part of a <u>Skolithos</u> burrow is shown by the lower arrow.

Well 12-26-38-26 W4 Depth 5058 feet Core is 8 cm wide which is an order of magnitude greater than the normally preserved thickness of bentonitic shale for the Joffre area.

The core point of well 8-5-89-26 (Fig. 5.9) is just slightly below the CM5 break, in Facies 3.

E3. The expression of E3 in South Central wells is identical in character to that of the Southern wells.

The North Central Vertical Facies Sequence (Figure 5.12)

There are 17 cored examples of this sequence, and most of the corresponding wells are located towards the northwest end of the Joffre. The North Central Sequence has only four main sedimentological breaks, because E1 does not occur here. Well 13-12-39-27 was chosen as the North Central representative because the four breaks could be clearly seen in the core. The 13-12 litholog is paired with the resistivity log of 11-12-39-27 (a neighbouring well) because 13-12 "bottoms out" at the base of the cored interval and 11-12 (being a deeper well) shows the complete formation.

E1. Core and log correlations suggest that the E1 break has been eroded in the North Central wells. This is shown in the cross sections which follow.

E2. In the North Central Sequence, E2 is the sharp contact between the underlying siltstone of Facies 1 and the coarse, cross-bedded sandstones of Facies 6, 7, or 8 (Fig. 5.13). Sometimes, the contact is burrowed as shown in

Figure 5.12

An Example of the NORTH CENTRAL Vertical Facies Sequence

13-12-39-27W4 / 11-12-39-27W4

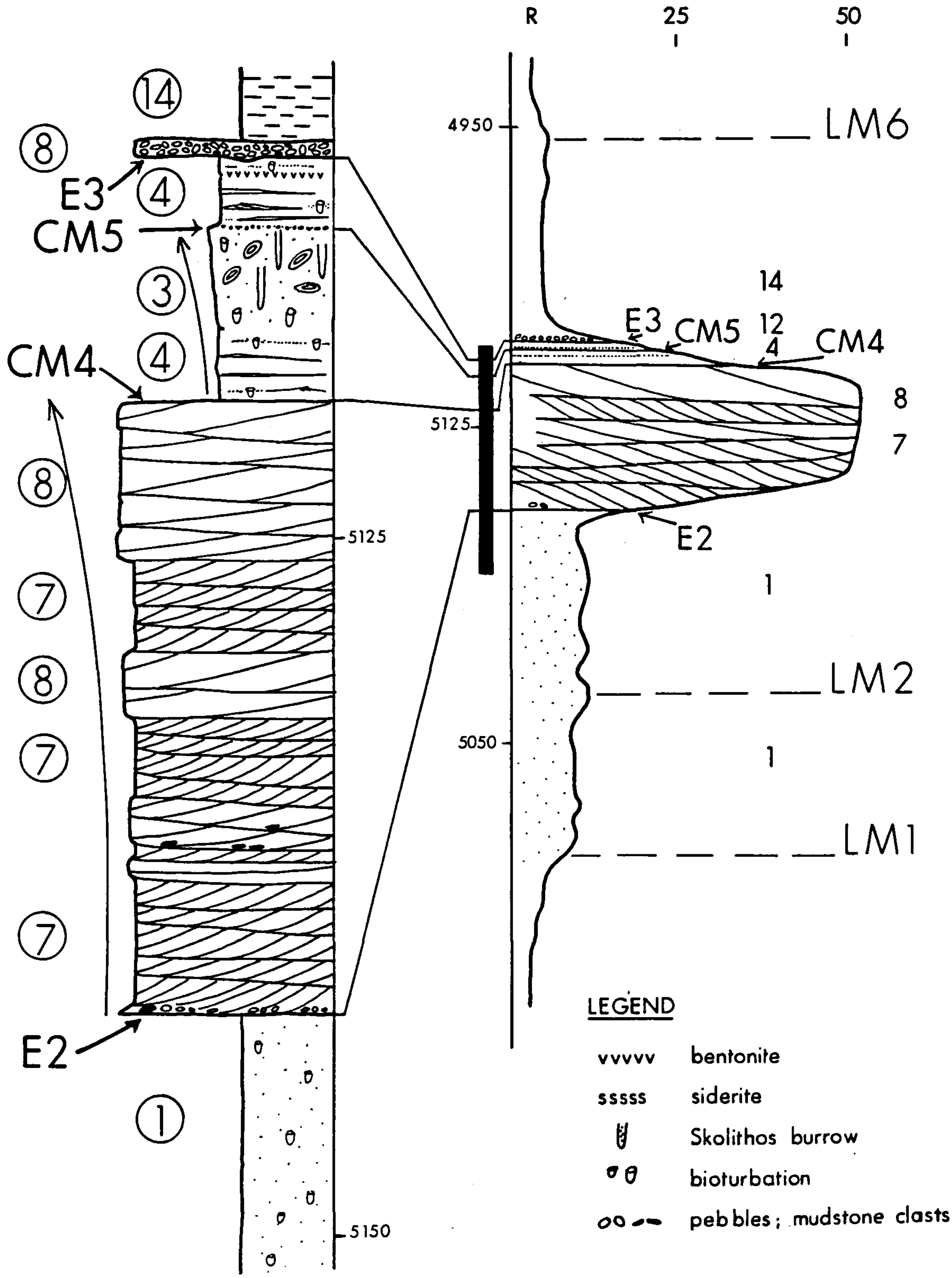


Figure 5.12

Figure 5.14. The North Central expression of the E2 break is characterized by:

a) a striking increase of grain size from siltstone to granular, (sometimes pebbly), medium-grained sandstone;

b) a change from dominantly biogenic structures (Facies 1) to dominantly physical structures (Facies 6, 7 or 8).

Other affiliated features of this E2 expression include:

c) a distinct basal accumulation of granules, pebbles, mudstone rip-up clasts or rarely glauconitic material in the "salt and pepper" sandstones overlying the break in more than 60% of the cores. In many cores, the long axis of the pebbles exceeds 20mm in length.

d) large diameter horizontal and vertical burrows which penetrate the E2 break and extend down into the siltstone facies (Figs.5.13 and 5.14) in 25% of the cores. These burrows are filled with coarse sediment from the facies above the break.

e) sideritization, which occurs at the top of the siltstone facies, directly beneath the break in just over 10% of the cores.

CM4. The nature of the CM4 break in North Central wells is identical to its occurences in the preceding Sequences.

CM5. The CM5 break is identical in nature to that of the South Central Sequence (Fig. 5.11).

Figure 5.13 **E2 Break** Contact: Facies 1 / 7

The E2 break is an easy pick as shown here by the knife sharp contact (upper arrow) which separates the two contrasting facies. Large (1cm diameter) horizontal burrows, (lower arrow) filled with granular sandstone, can be seen penetrating the underlying siltstone. The oval shape of the burrow diameter is attributed to sediment compaction.

Well 14-11-39-27W4 Depth 5161 feet Core is 8 cm wide

Figure 5.14 **E2 Break** Contact: Facies 1 / 7

An unusually rhythmic succession of very fine-grained sandstone laminae within Facies 1 is clearly cut by large diameter *Skolithos* burrows. The burrows are filled with granular sandstone and penetrate almost 20cm into the underlying siltstone in this well. The shredded appearance of the very fine-grained sandstone laminae is due to *Helminthoida* (arrow).

Well 9-15-39-27W4 Depth 5096 feet Core is 8 cm wide

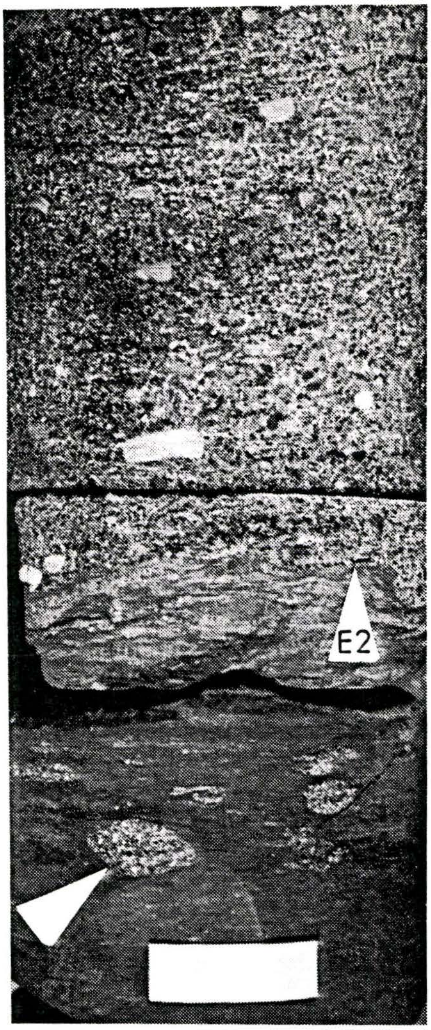
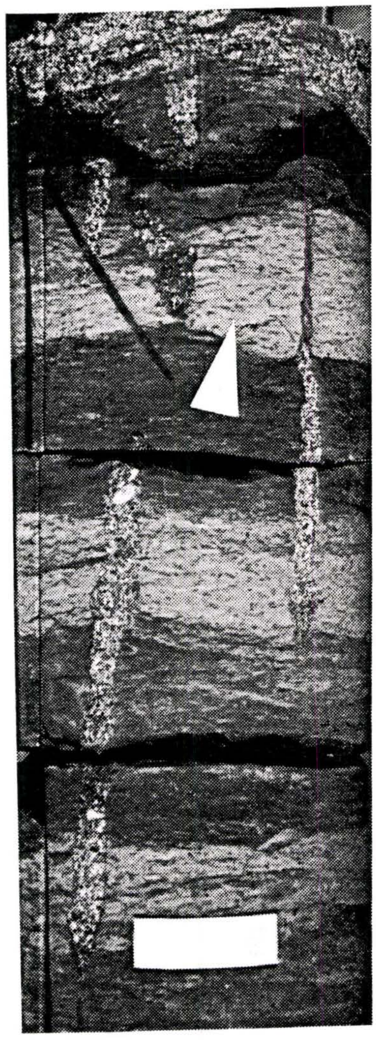


Figure 5.13

Figure 5.14



E3. The North Central expression of the E3 break is also identical to that of the preceding Sequences.

The Northern Vertical Facies Sequence (Figure 5.15)

There are twelve cored wells which exhibit the Northern Vertical Facies Sequence. These wells are found along the northeastern margin of Joffre. Well control is particularly sparse along this margin of the field, and the continuity of the group shown in Figure 5.2 is assumed.

Despite the disimilarity of the "Lower Zone" facies sequence (Fig. 5.1), all five sedimentological breaks can occur in the Northern-type wells, although typically E1 is absent. The disimilarity of the facies sequence is due to a lateral facies change of the sediment above the E2 break and below the CM4 break between the North Central and Northern wells. This lateral facies change is shown in the cross sections which follow.

E1. The E1 break is not always present in the Northern-type wells, it is seen in only two Northern cores. Core and log correlations suggest that the E1 break has been eroded in most of the Northern wells. Where it does occur, it is identical to the South Central expression of E1 (Fig. 5.10), that is, the sharp, burrowed contact between Facies 1 (below) and Facies 3 (above). At the 10-21 well (Fig. 5.15), four pebbles with an average diameter of 7 millimetres are observed at the base of Facies 3. No pebbles were noted at this contact in the other core which features this break.

Figure 5.15

An Example of the NORTHERN Vertical Facies Sequence

10-21-38-25W4

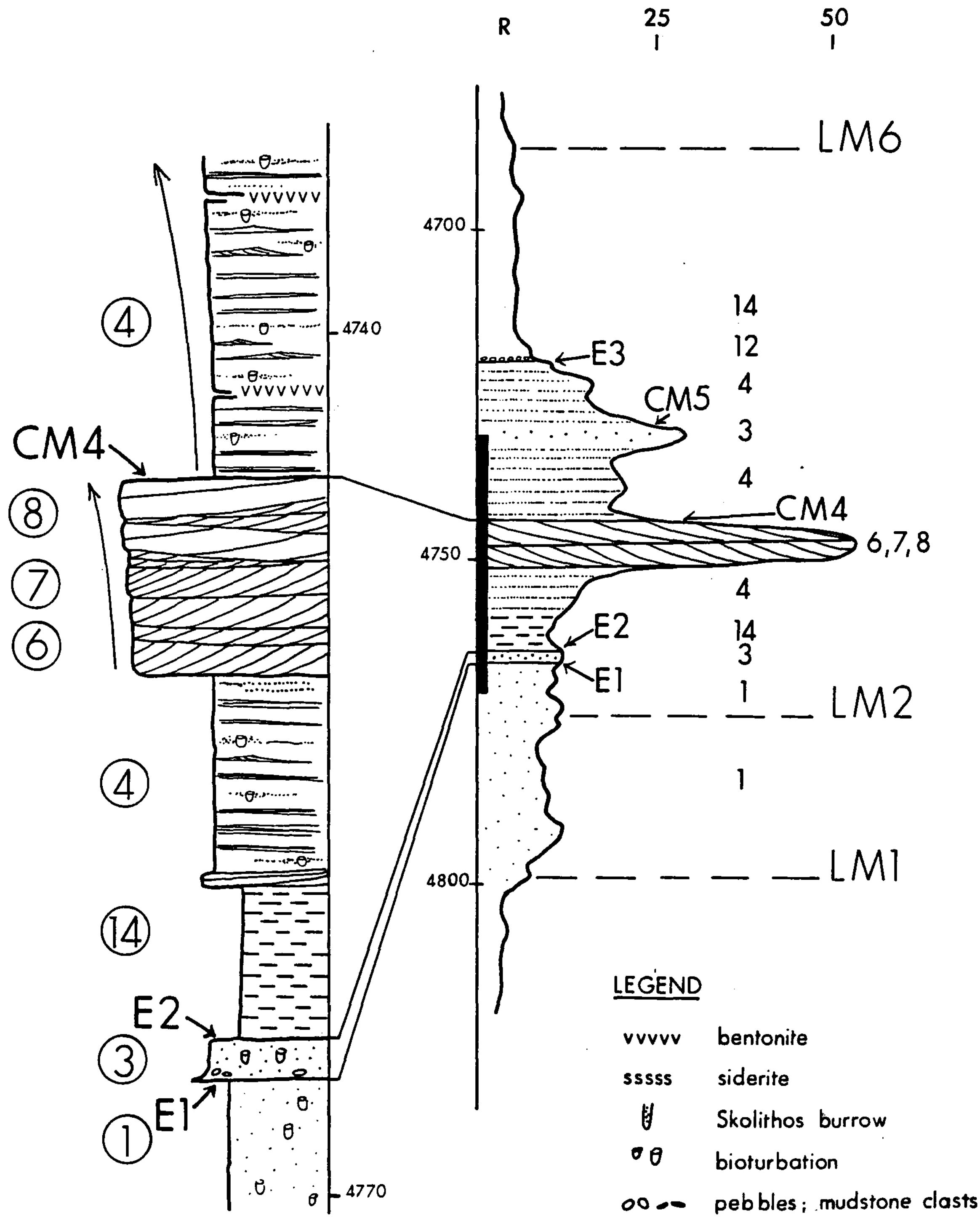


Fig. 5.15

E2. The E2 break is picked at the sharp contact between Facies 3 muddy sandstone (below) and Facies 14 shale (above) at well 10-21 (Fig. 5.15). In the three other Sequences, E2 was picked at the base of the cross-bedded sandstones, however, detailed correlations show that the cross-bedded sandstones interfinger northeastward with shales of Facies 14 and 4. Therefore, the basal contact of the shale in well 10-21 is equated to the basal contact of the cross-bedded sandstones, and is designated the E2 break.

Several of the Northern cores feature very glauconitic sandstone directly beneath Facies 14, in these instances E2 occurs below the glauconitic sandstone (Facies 5) as happens with many of the expressions of E2 shown by the other Sequences.

When Facies 3 and the E1 break have been eroded, E2 occurs at the sedimentological break between bioturbated siltstone (Facies 1) and overlying glauconitic, cross-bedded sandstone (Facies 5) or laminated shale (Facies 14), where Facies 5 is absent.

At this stratigraphic level, Facies 14 features a curious abundance of small (2mm), amber-coloured, lenticular bodies (Fig. 5.16). They have been identified as Leioshaeridaceae (Combaz, 1967; J. Wall, personal communication, 1986), although many of them bear a more striking resemblance to Lancettopsis lanceolata (Madler, 1968). The origin of these bodies is generally considered to have been vegetative, possibly they were algal cysts.

They have two distinct shapes, the most common one is lenticular (Fig. 5.16) with a distinct central furrow, the other shape is discoidal. These lenticular bodies have been observed at the base of the Shaftesbury Formation (Singh, 1971), which is equivalent to the Lloydminster Formation in northern Alberta. They have also been found stratigraphically higher, at the base of the Fish Scale sandstone (J. Wall, pers. comm., 1986). They appear to be useful locally at Joffre as a biostratigraphic marker along the northeastern margin of the field.

CM4 The CM4 break is placed at the contact of coarse cross-bedded sandstone (Facies 8), and burrowed, laminated sandstone and mudstone (Facies 4) in Figure 5.15. In some Northern-type wells, there are a couple of cross-bedded sandstones separated by correlatable intervals of shale (Facies 4 or 14). Here, the CM4 break is designated as the upper contact of the uppermost cross-bedded sandstone. The Northern expression of the CM4 break is identical to its character in the other Sequence types (Fig. 5.7).

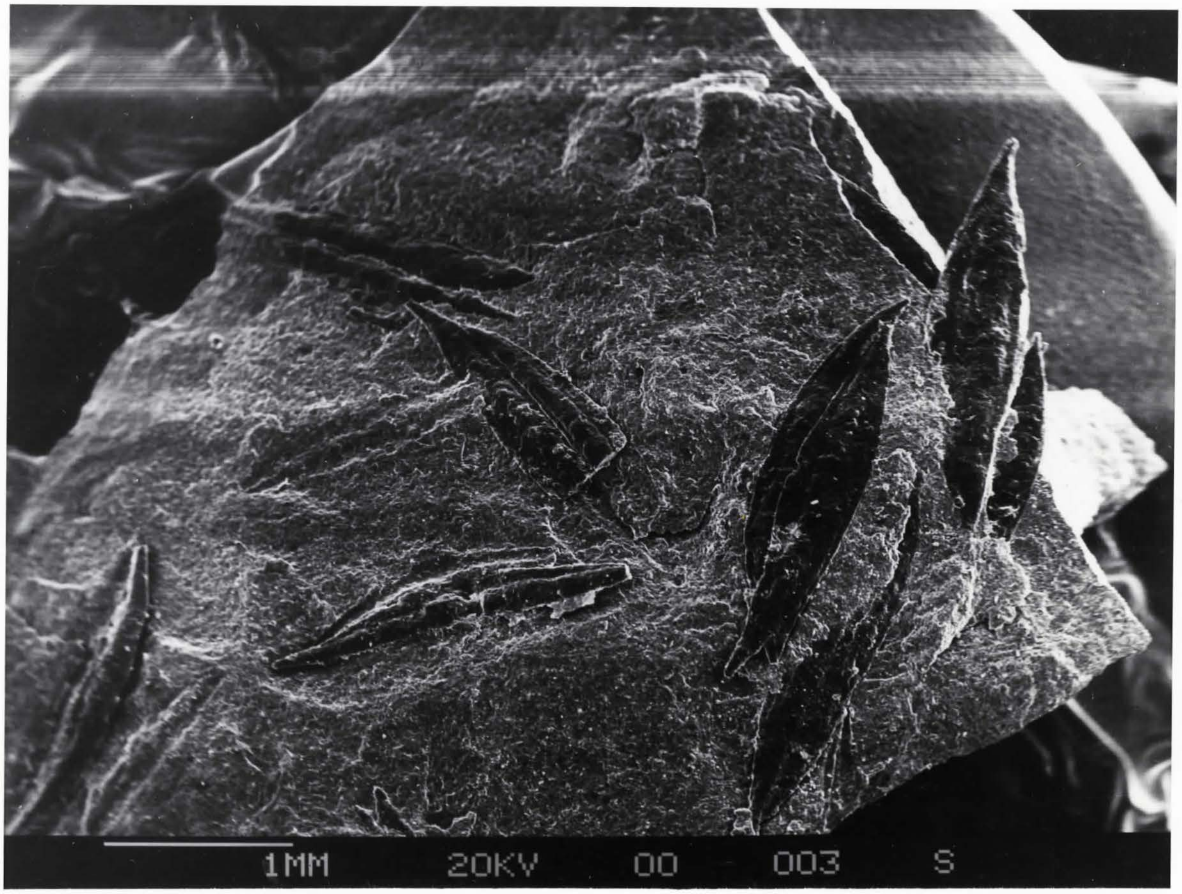
CM5 The CM5 break (not cored in 10-21, Fig. 5.15) is identical in appearance to the other CM5 breaks. The gritty contact between Facies 3 (below) and Facies 4 (above) is comparable to the photo in Figure 5.11.

E3. The nature of the pebbled contact between Facies 4 (below) and Facies 14 (above) is identical to the E3 expression in the other types of Sequences. Either Facies 11 or 12 mark the E3 contact as seen in Figures 5.8 and 4.10 respectively.

Figure 5.16 **Lenticular Bodies**

These bodies are up to six times larger, but are otherwise very similar in appearance to Lancettopsis lanceolata (Madler, 1968). They are found on parting planes within Facies 14 (above E2) in Northern wells. This photo was taken using a scanning electron microscope.

Well 10-21-38-25W4M Depth 4763 feet Scale bar 1 mm long


1MM 20KV 00 003 S

5.3. Log and Core Cross Sections

The locations of the cross sections are shown in Figure 2.1. Cored intervals are shown as the black vertical bars positioned along the axes of the log profiles. Where they exist, gamma ray profiles are paired with resistivity logs. Reference depths shown for wells of the log cross sections are given in feet, as originally recorded by the logging companies. The core lithologs are scaled in metres and are presented in an expanded vertical scale relative to the log cross sections. The facies numbers are indicated adjacent to the core lithologs. Correlation lines which intersect the litholog axes beyond the core limits are labelled with an "L" to indicate they are based on log picks. Both core and log sections are hung on the LM2 datum (defined below).

The **LM2 marker** is best seen in microcaliper resistivity logs, it is a sharp double peak representing two relatively resistive horizons separated by a thin conductive "layer". In regular resistivity logs, the marker appears as a comparatively distinct "bump" in the log profile, sometimes featuring a cleft in the middle of it. The LM2 pick is made at this clefted midpoint on the bump. It is cored in well 11-7-39-26 (Fig. 5.20) where it appears that the cleft is bentonitic. Justification for using LM2 as the datum is given at the end of the discussion of cross section A-A′.

The **LM1 marker** is defined using resistivity logs, as the mid-point of the first major increase in resistivity at the base of the Viking. This pick is more difficult to make southwest of Joffre because the log character of the base of the formation changes (Fig. 5.16).

The **CLM3 marker** is taken at the midpoint of the transitional contact between Facies 1 and 2. In resistivity logs, the pick is made at the base of the smooth interval of elevated resistivity readings.

The **LM6 marker** is chosen as the uppermost of a pair of subtle resistivity "blips" which occur in shale of the Lloydminster Formation.

The log markers defined above are essentially parallel to each other, "boxing-in" the main development of sandbodies, as will be seen in the following cross sections. The core markers and erosion surfaces are described in the following cross section discussions.

All of the cross sections are presented together at the end of the chapter.

Cross Section A-A" (Figure 5.17)

This cross section is oriented perpendicular to the strike of Joffre, and is positioned to include data from two of the most remote off-field core locations (Figure 2.1). This cross section illustrates the way on-field wells of different facies sequences (Southern, South Central, North Central and Northern; Fig. 5.1) correlate with each other, and with off-field wells. The on-field wells (2-21, 8-27, 16-27/12-26, and 4-35) represent three of the four types of vertical facies Sequences described in Section 5.2.

The best available cores were selected to demonstrate correlation between the Southern, South Central and North Central Vertical Facies Sequences (Fig. 5.1). Unfortunately, there are no cores to represent the Northern Sequence in this area.

The core from well 12-26 is paired with the resistivity log from well 16-27 because there is no core available for 16-27, and the 12-26 resistivity log does not extend to the LM2 datum. Comparison of the existing portion of the 12-26 log with the 16-27 log shows close similarities in the shape of the log profile. I assume that the facies sequences of the neighbouring wells are thus very similar in succession and thickness.

The main development of the Viking sandbodies occurs between the LM2 and LM6 markers. Core data is used to simplify correlations amongst these sandbodies because of the variable nature of the log profiles. The correlations shown are established by linking the facies sequence "breaks" presented in Section 5.2.

To establish the fundamental ideas behind these correlations, consider the distribution of the lowermost occurrence of Facies 3. The base of Facies 3 is of specific interest here. A pebbly horizon occurs at or very close to the base of Facies 3 in wells of the Southern and South Central Sequences (2-21, 8-27 and 12-26). Several indications of erosion at the base of Facies 3 emerge when this contact (E1) is correlated:

i) the base of Facies 3 changes its stratigraphic position, dropping towards the LM2 datum from well 2-21 to 12-26;

ii) Facies 2 thins toward the northeast (from 2-21) and is cut-out before well 8-27;

iii) the CLM3 marker has also been truncated before well 8-27.

I conclude that the E1 surface is erosive because it is the only reasonable explanation for these observations. A lateral facies change between Facies 2 and 3 is the other option to explain these observations, but it is unlikely because of the obvious continuity of the pebble horizon and overlying bentonitic deposit.

The pebbly horizon at the base of Facies 3 mantles this erosion surface. This contact is interpreted in detail later (Chapter 6.2). The erosional nature of the E1 surface is thus symbolized by a wiggly line (Fig. 5.17).

The E1 surface is absent in well 4-35, but reappears northeast of Joffre in well 10-22. At well 10-22, as seen in wells 8-27 and 12-26, E1 is mantled by a pebbly interval which is in turn overlain by a bentonitic horizon. The E1 surface can, therefore, be correlated to extend 10 kilometres beyond the northeastern margin of Joffre. On the other hand, due to lack of core control, E1 is not traceable southwestward beyond well 2-21.

The E1 surface can therefore be mapped over 14 kilometres perpendicular to the strike of Joffre, although it appears to be eroded at the northeastern margin of the field. The maximum erosional relief as seen in this cross section is 6 metres between 2-21 and 8-27. The actual slope of E1 between these wells is 0.11 degrees.

The upper contact of Facies 3, the E2 break, is also interpreted as an erosion surface following the same logic as presented for E1. Evidence for the erosive nature of E2 is listed as follows:

i) the contact between Facies 3 and the overlying coarse-grained sediment (Facies 5,6,7,8 or 9) drops stratigraphically from 2-21 to 4-35, where it is interpreted to rise beyond the northeastern margin of Joffre, toward 10-22;

ii) the underlying sediment (Facies 3) thins toward the northeast and is completely cut out before well 4-35, the North Central well;

iii) the E1 surface has also been truncated before well 4-35 but reappears northeast of Joffre in well 10-22, where the E2 surface rises.

Once again, erosion associated with the E2 surface is the only logical explanation for these observations. The erosive nature of E2 explains variations in the distribution and thickness of Facies 3.

The E2 surface is not seen in well 10-22 as discussed later. Due to lack of core control southwest of well 2-21, the surface cannot be confidently traced southwest, beyond this point,in the log cross section.

The maximum relief of E2 (as seen in this section) is 5.5 metres between well 2-21 and 4-35; the actual slope is 0.08 degrees.

There is no suggestion of erosion associated with the CM4 marker. The coarse-grained sediments of Facies 5,6,7,8 or 9 appear to be sharply yet conformably draped by the mudstones of Facies 4. The changing stratigraphic position of CM4 is attributed to variations in the depositional thickness of the coarse sediment underlying it. The coarse sediment between E2 and CM4 thins both toward the southwest (2-21) and the northeast (better displayed in Figure 5.20. The CM4 marker is extended southwestward into wells 9-25, 3-4 and 14-7 without core control.

The character of the CM5 surface is somewhat variable at Joffre. It is delineated as the sharp contact between the uppermost occurence of Facies 3 and Facies 4. Sometimes the upper few centimetres of Facies 3 are sideritized, as seen in well 2-21. Mostly there is a gritty veneer which mantles Facies 3, as shown in wells 8-27 and 12-26. Although the CM5 surface locally truncates large (1 cm) diameter <u>Skolithos</u> burrows (12-26), it does not appear to truncate markers nor change its stratigraphic position amongst wells 2-21, 8-27, 12-26 and 4-35. It is thus depicted as a "conformable" contact within the limits of the Joffre field.

However, at well 10-22 the CM5 surface, recognized by the pebbly mantle at the Facies 3 and 4 contact and associated truncated <u>Skolithos</u> burrows, appears to have cut out E2. The conformable nature of the CM5 marker has changed laterally to become erosive. It will be suggested in Chapter 5.4 of this thesis that CM5 may correlate with the scour surface which underlies the coarse sediment at Gilby. The CM5 marker is not extended southwestward beyond well 2-21 due to lack of core control.

The erosional nature of E3 is best demonstrated by the southwesternmost wells of the log cross section. A similar line of reasoning to that used to justify erosion at E1 and E2 is used again to demonstrate erosion associated with E3:

i) the sharp contact between Facies 4 and 14 and its associated pebbly mantle drops stratigraphically 16 metres between 14-7 and 2-21 (sloping 0.04^0);

ii) Facies 10 (14-7) appears to have been truncated before well 3-4;

iii) an unnamed marker below E3 (shown in wells 14-7 and 3-4) is truncated by E3 before the 9-25 well.

In the immediate vicinity of Joffre, there does not appear to be significant down-cutting associated with the erosion surface. The sharp base of the pebbly sediment which mantles E3 does display local scour features, but the surface does not change its stratigraphic position appreciably. In total, the E3 surface can be mapped over 30 kilometres perpendicular to the strike of Joffre in this cross section.

The LM2 marker has been used as the datum for cross sections because it is below the erosion surfaces, and emphasizes their downcutting when it is taken to be originally horizontal.

Cross Section B-B′ (Figure 5.18)

This section is oriented parallel to the strike of Joffre. South Central wells were preferentially used to standardize the data along the length of the field. Two cored wells from the Mikwan field (wells 10-2, 10-8) were added for comparison along strike.

There are two pairs of core and log substitutions. The core of well 2-5 is paired with the log of well 3-5 because the existing log for 2-5 is too short to tie into the cross section. Although well 8-27 is cored (Fig. 5.17), the log of well 8-27 is paired with core from well 12-26 because the 12-26 core is continuous from above E3 to below E1.

Due to the strike-parallel orientation of this section, and the simultaneous restriction to South Central wells, the down-cutting nature of E1 and E2 cannot be shown. Instead, the erosion surfaces, core markers and enclosed sandstone are essentially parallel thoughout the length of Joffre. There is an undulation in the overall parallelism at 4-22 because this well is located on the northeast side of the South Central Belt. Aside from this, the main sand development can be traced continuously at one stratigraphic horizon (between the E2 and CM4 markers) from one end of Joffre to the other. This conflicts with Amajor′s depiction of "four relatively thin, isochronous sand units" which overlap one another towards the northwest (Amajor, 1986, his figure 6).

The characters of the erosion surfaces and core markers are the same as those in the South Central wells of cross section A-A'.

As seen in section A-A', the E1 surface occurs at the contact of Facies 1 and 3. The pebbly mantle to this surface can be traced over the entire length of Joffre becoming slightly thicker in the Mikwan area (wells 10-2 and 10-8).

The E2 surface, occurring at the contact of Facies 3 with overlying Facies 5 or 6, can also traced throughout the length of Joffre. It can be seen in this section that glauconitic sediment (Facies 5) occurs in the sandstone overlying E2 in wells 12-26, 4-22 and 6-4.

The CM4 marker is again defined as the top of the cross-bedded sandstone of Facies 6, 7, 8 or 9. Lateral facies variation amongst the E2-CM4 interval becomes evident in this section. The occurence of Facies 4 interbedded with Facies 5,6,7 or 8, in wells 4-22 and 6-4 is a function of facies changes in the southwest-northeast direction across Joffre, this is shown and discussed in the D-D' cross section (Fig. 5.20).

The CM5 marker can be recognized throughout Joffre as the sometimes gritty contact between Facies 3 and 4. Finally, the pebbled E3 surface, occurring at the Facies 4 and 14 contact, can likewise be traced throughout Joffre.

Cross Section C-C′ (Figure 5.19)

Cross section C-C′ is oriented perpendicular to the strike of Joffre. It is positioned at the northwest end of Joffre, closest to the Gilby field. The two cores included in the section belong to the South Central and North Central Sequences. The log of well 1-21 has been paired with the core of well 2-21 because the existing log for well 2-21 is too short to tie into the cross section.

The section is correlated using the same principles as were discussed in detail for the A-A′ section (Fig. 5.17). Once again, E1 occurs as the pebbled contact which caps Facies 1 and underlies Facies 3, as is typical in the South Central Sequence. It is difficult to establish the erosive nature of E1 in this cross section, due to the restricted amount of core available across the northwest end of Joffre.

As seen in the South Central and North Central wells of section A-A′ (Fig. 5.17), E2 overlies Facies 3 and Facies 1 respectively. The erosive nature of E2 can be established through the following observations:

i) the base of the coarse sediment (Facies 6,7) drops down towards LM2 in the northeast direction from well 16-7 to wells 1/2-21;

ii) Facies 3 is cut-out between wells 14-16 and 1/2-21;

iii) The E1 horizon has also been truncated between the same wells, and possibly again towards the southwest, between wells 16-7 and 14-16. The E2 surface is extended into the non-cored 11-22 well by analogy with 11-7-39-26 of section D-D′ (Figure 5.20). The maximum relief of the E2 surface as seen between wells 16-7 and 11-22 is 4.6 metres.

As seen in previous cross sections, the CM4 surface occurs at the sedimentological break between cross-bedded, coarse-grained sediment (Facies 6,7 or 8), and the overlying burrowed, laminated shale of Facies 4. The bulging profile of the CM4 marker between wells 14-16 and 1/2-21 reflects the on-field thickening of coarse sediment. Often the North Central wells feature the thickest accumulations of coarse sediment between the E2 and CM4 markers. Correlation of the CM4 surface between wells 1-21 and 11-22 is carried out by assuming that the 11-22 well is similar to Northern-type wells on the basis of the shaley appearance of its gamma log between 5138 and 5142 feet.

As before, the CM5 surface appears as the sharp, pebbled contact between the uppermost occurence of Facies 3 and the overlying Facies 4. The log section indicates parallelism between the CM4 and CM5 markers.

As in the previous cross sections, E3 is established at the sharp base of the pebbly deposit (Facies 11 in core 14-16), which separates underlying laminated sandstone and shale (Facies 4) from overlying shale (Facies 14). Compared to the pronounced change in stratigraphic position exhibited by E3 southwest of Joffre, in section A-A′ (Fig. 5.17), there is little change in the position of E3 in this section. This is consistent with the attitude of E3 in the immediate vicinity of Joffre as shown by all cross sections.

Cross Section D-D′ (Figure 5.20)

This section is also oriented perpendicular to the strike of Joffre, and is positioned midway between the A-A′ and C-C′ cross sections. There is one pair of core and log substitutions. Core of well 5-7 is paired with the log of well 6-7 because the 5-7 log is too short to tie into the cross section. The existing portion of the 5-7 log compares closely with the 6-7 log, supporting their pairing. This cross section is correlated in a similar fashion to the two previous strike-perpendicular cross sections. However, this cross section introduces the Northern Sequence, represented by well 11-7, into the established correlation scheme.

As is typical of its expression in Southern and South Central wells, the E1 "break" overlies Facies 2 or Facies 1 respectively, and underlies Facies 3. Pebbles are noted to occur at the base of Facies 3 in only the 5-7 core. The base of Facies 3 drops down in the northeast direction, cutting out Facies 2 between the Southern (16-1) and South Central (5-7) wells, and truncating the CLM3 marker between the same wells. E1 is not present in the 11-7 well. Deeper scour (E1?) is inferred northeast of 11-7 because of the marked difference in the shapes of the resistivity logs.

The nature of E2 in the Southern and South Central wells is also consistent with its previous appearances, namely that it occurs above Facies 3, and below the coarse sediment of Facies 6 or 7. The expression of E2 in 11-7, the Northern well, is very different to the other types of wells. The difference in the appearance of E2 is attributed to a lateral facies change of the sediment overlying it. In well 5-7, there are 7 continuous metres of coarse sediment. This sediment splits and thins laterally into two 2-metre thick intervals of coarse sediment separated by Facies 14 mudstone at well 11-7. The interfingering nature of the sandstone and shale is shown in the pair of cross sections by a dotted line. This "fingering out" of the coarse sediment occurs over a distance of only 0.4 km in this cross section.

The erosive nature of E2 is established by observing:

i) its 10m stratigraphic drop towards the northeast, (the slope of E2 between wells 16-1 and 11-7 is 0.41 degrees),

ii) the thinning and subsequent truncation of Facies 3 between wells 5-7 and 11-7, and

iii) the truncation of E1 between the same wells.

The upward doming of the CM4 and CM5 markers accentuates compaction around the significantly thick accumulation of coarse sediment. This section crosscuts the field very close to the thickest deposit of coarse sediment at Joffre.

Erosion on the E3 surface can be established on the basis of three observations:

i) although E3 does not appear to drop stratigraphically as shown in this section, E3 and CM5 converge at 5-7.

ii) Facies 4 (below E3), thins to a minimum at 5-7.

iii) the upper bentonite in 16-1 has been truncated before well 5-7.

It is interesting to note that E3 erosion can be detected in the area above the thickest accumulation of coarse sediment. However, only 2 metres of Facies 4 have been removed between wells 16-1 and 5-7.

Cross Section E-E´ (Figure 5.21)

This section is also oriented perpendicular to the strike of Joffre. It is positioned at the southeast end of Joffre, closest to the Mikwan field. There are several cored examples of the Southern Sequence, and one of each of the South Central and Northern Sequences. The section is hung on the LM2 datum, as the other sections have been, except when it appears the LM2 marker has been eroded inwell 12-8. This well is positioned by using the LM1 marker as a bridge from well 1-7. The core of well 8-6 is paired with the log of well 11-6 because the existing log for 8-6 is too short to tie in with the section.

The natures of the E1 and E2 surfaces are consistent with their expressions in the previous sections. The E3 surface has not been cored in any of the wells.

E1 overlies Facies 2 in the Southern wells, and Facies 1 in the South Central wells, as seen before. In addition to pebbles, coalified wood fragments are observed to mantle E1 in wells 8-1 and 16-6. The evidence for E1 erosion is as follows:

i) the base of Facies 3 drops stratigraphically 4 metres between wells 16-16 and 16-6;

ii) Facies 2 thins and is eliminated between wells 8-6 and 16-6; and

iii) the CLM3 marker is truncated between wells 8-6 and 16-6. E1 does not occur in 12-8, the Northern well.

The appearance of E2 in core changes from the distal Southern well (16-16), to the on-field Southern wells (8-1 and 8-6) and South Central well (16-6), to the Northern well (12-8). The different appearances of E2 mostly result from lateral facies changes in the overlying sediments. Facies 3 occurs beneath E2 in all wells except the Northern well (12-8), where Facies 1 underlies E2. In well 16-16, interlaminated granular sandstone and shale overlie E2, and this is labeled 7/11 in the 16-16 litholog. The most common context of E2 is displayed in wells 8-1, 8-6 and 16-6, where E2 is overlain by coarse sediment of Facies 6,7 or 8. In the Northern well (12-8), E2 is pin-pointed at the relatively sharp base of poorly-sorted, very glauconitic sandstone. A similar deposit of glauconitic sand was not featured in the Northern well of the previous cross section (D-D′, Fig. 5.20), although the previous cross section did show a similar fingering of coarse sediment and shale between the South Central and Northern wells. The erosive nature of E2 can be established from the following observations:

i) E2 drops stratigraphically 12 metres toward the northeast, especially between 16-6 and 12-8,

ii) Facies 3 thins subtly, and is truncated between 1-7 (log pick) and 12-8,

iii) the E1 surface and LM2 marker are truncated. This section shows the greatest amount of downcutting associated with E2 in that even the LM2 marker is eroded. Between wells 16-6 and 12-8, the E2 scour slopes relatively steeply to the northeast at 0.35 degrees.

The convergence of CM4 and E2 at well 16-16 is a reflection of the southwesterly thinning of the coarse sediment above E2.

There are no characteristic grits or pebbles associated with the CM5 marker in the two cores which penetrated the marker. Unfortunately, the E3 surface is above the core points of each well, however, the logs reveal a subtle convergence in the northeast between E3 and CM5 which might be attributed to E3 erosion.

5.4 Facies Packages and their Bounding Surfaces

The five widespread core markers (E1,E2,CM4,CM5 and E3), are considered as bounding surfaces to the facies groups between them. The fact that they have been recognized as significant breaks, common to all four vertical facies sequences, suggests that they represent widespread, and sudden changes in depositional environments. These five bounding surfaces, three of which are obviously erosive, segregate the sediments into four packages with other packages below E1 and above E3. It follows that a localized event stratigraphy may be set up at Joffre, such that the depositional history of the formation here can be unravelled one package at a time.

The six distinct facies packages bounded by these five surfaces, are identified by the letters "A","B","C","D","E" and "F". In four of the five packages, the sediments within them coarsen-upward, but it is emphasized that the packages are defined by the bounding surfaces, not the sediments within the packages.

Each package is usually less than 5 metres in thickness, although package A can occupy the lowermost 15 m of the formation. Therefore, five metres of down-cutting, typically seen with the lower two bounding surfaces (E1 and E2), can be significant enough to remove an entire package.

The distinct textures and geometry of each package are characterized below. The discussion proceeds from the earliest-deposited package, Package A. Brief comments about the nature of their bounding surfaces are included for the sake of continuity, although these surfaces have already been described in Sections 5.2 and 5.3.

Package A

Package A comprises the bioturbated siltstones of Facies 1 and 2 below bounding surface E1.. The coarsening-upward sequence from Facies 1 to 2 consists of an increasing proportion of very fine-grained sand amongst the background siltstone. It is preserved in the Southern Sequence wells. There are no signs of lateral facies changes occurring in this package. The dominance of silt-sized material, and common degree of bioturbation indicates slow, continuous deposition in a quiet, probably offshore environment where the rate of bioturbation appears to equal or exceed the rate of deposition. The base of the package is considered to be flat at Joffre, and is defined by the log marker LM1. The maximum preserved thickness of Package A is 20 m, it is seen in wells which lie southwest of Joffre.

Bounding Surface E1

Despite its burrowed nature, the E1 scour surface can be recognized by the closely associated pebble horizons. The coarseness of these granules, pebbles and coalified wood fragments is very foreign to the fine-grained background sediment. The coarse mantle to E1 varies from single and multiple, one centimetre thick, burrowed pebbly horizons, to a much less common, one metre thick, cross-stratified pebbly sandstone accumulation as seen in wells 10-2-37-23 (Figure 5.18) and 13-16-38-25 (not shown in thesis).

In general, the morphology of the E1 surface appears in cross sections to be a broad scour centred just slightly to the northeast of Joffre. In the immediate vicinity of Joffre, the E1 scour slopes northeastward at about 0.1^{0}. On the basis of several working cross sections, without core control, it seems that the greatest depth of E1(?) scour is found in a zone trending parallel to Joffre, approximately 4 km northeast of the field. In this zone, the unusual log profiles suggest that a scour surface has almost reached the base of the formation. Well 11-17-39-26 (cross section D-D´, Fig.5.20), shows the speculative correlation which leads to the suspicion of maximum E1 erosion northeast of Joffre. The maximum relief of the E1 scour in the immediate vicinity of Joffre is much less by comparison, being approximately 5 metres.

Package B

Package B is bounded below by E1, and above by E2. Within the package, there is a coarsening-upward grain size trend developed within the fine-grained sandstones of Facies 3. There are no lateral facies changes. The bioturbated appearance of the facies suggests slow, continuous deposition in an environment similar to that of Package A, where the rate of bioturbation equals or exceeds the rate of deposition. The textures of Packages B and A resemble each other, except for the distinct difference in grain sizes.

The pebbly layers which have been used to pin-point the E1 scour surface actually belong to Package B. The maximum preserved thickness of Package B is 5 metres, the sediments thin and disappear towards the northwest end and the northeast margin of Joffre.

Bounding Surface E2

E2 is the erosional surface which underlies the main sand development at Joffre. Cross sections suggest that E2 has an elongate scarp-like shape, trending parallel to Joffre´s axis. The overlying coarse sediment is banked up against this northeast-facing E2 scarp. The maximum erosional relief of E2 is 12 metres (Fig.5.21), which is more than sufficient to remove Package B as happens in the North Central wells and some of the Northern wells too. Generally, the E2 scour dips notheastward at less than 0.3^0 across the width of Joffre; however, E2 may dip as steeply as 0.4^0 along the extreme northeastern margin of Joffre (Fig.5.20).

Package C

Package C is bounded below by E2 and above by CM4. It comprises the cross-stratified sandstones of Facies 5,6,7,8 and 9, and interbedded intervals of Facies 14 and 4. The thickest accumulations of Package C are centred along the axis of Joffre, in the South Central and North Central wells. Commonly, glauconitic sandstone (Facies 5) directly overlies E2 in the South Central and Northern wells. On the whole, Package C tends to coarsen-upwards, Facies 5 and 6 tend to occur lowest in the Package, and Facies 7 and 8 tend to occur above them. The continuously coarse expression of Package C changes toward the northeast, becoming interbedded with Facies 14 and 4 (see Figs. 5.20, 5.21). The proposed facies change within Package C is substantiated by correlating Facies 14 (and its lenticular bodies), from Northern wells to North Central wells. Discrete tongues of cross-stratified sand thin and fine toward the northeast.

The average thickness of Package C is 3 metres, the maximum thickness is 7.5 metres, which occurs at well 6-7-39-26 (Cross section D-D´, Fig. 5.20). Package C thins rapidly southwest of Joffre to become a thin deposit of interlaminated gritty sand and shale (Figs. 5.17, 5.21).

Bounding Surface CM4

The CM4 bounding surface appears transgressive in nature. It separates the underlying coarse sediment from finer grained, laminated sand and shale (Facies 4) above.

Package D

Package D is defined by CM4 below, and CM5 above. Within the package, there is a coarsening-upward grain size trend from Facies 4 to Facies 3, accompanied by an increase in burrowing. Facies 3 features an abundance of *Terebellina* and large diameter *Skolithos* burrows at this stratigraphic horizon as compared to its appearance in Package B.

The depositional setting for Package D was probably above storm wave base, as suggested by the wavy laminated,very fine-grained sands and silts of Facies 4. The large proportion of well-preserved laminae of Facies 4 suggests that the rate of deposition exceeded the rate of bioturbation, although this balance appears to have shifted with time to favour a greater rate of bioturbation in Facies 3.

Bounding Surface CM5

The CM5 surface is a relatively subtle surface, it separates Facies 3 (below), from Facies 4 (above). It is recognized by its closely associated veneer of grits.

It is not obviously erosive at Joffre, although it may tie in with the erosion surface at Gilby which underlies the main development of coarse sediment there (Raddysh, 1986). There are three observations which suggest that CM5 may be a correlative conformity to the Gilby unconformity. Firstly, the abundance of Skolithos burrows directly below CM5 resembles the abundance of Skolithos burrows noted to occur below the Gilby unconformity (Raddysh, 1986). Secondly, the grits and granules which overlie CM5 at Joffre may be distal equivalents to the coarse sediment overlying the scour at Gilby. At well 4-21-39-27, at the northwestern end of Joffre, there is a pronounced increase in the coarseness and thickness of the overlying gritty veneer to CM5, thus suggesting that the CM5 veneer becomes more significant towards Gilby. The third observation in support of the correlation of CM5 and the Gilby unconformity is the equivalent stratigraphic position of both surfaces beneath the uppermost conglomeratic sediment (E3 at Joffre).

CM5 does appear erosive northeast of Joffre at well 10-22-39-25 (Cross section A-A′, Fig. 5.17), where it cuts out both CM4 and E2. It is identified at 10-22 by its associated Skolithos burrows, and pebbly veneer. Presumably, the bioturbated muddy sandstone CM5 rests on at this location is Package B, indicating that CM5 has cut out Packages D and C.

Package E

Package E is bounded below by CM5, and above by E3. It consists entirely of Facies 4 in the immediate vicinity of Joffre, but in the distant southwest, it may include the hummocky sandstones of Facies 10 (Fig. 5.17).

The gritty veneer used to help locate CM5 actually belongs to this package. In general, there is a slight coarsening of the gritty material laterally, towards the northwest end of Joffre, accompanied by an increasing number of gritty layers. Following the discussion of possible equivalence between CM5 and the Gilby scour, it is suggested that the gritty layers at the base of Package E are correlative with the coarse sediment at Gilby, although this is yet to be nailed down.

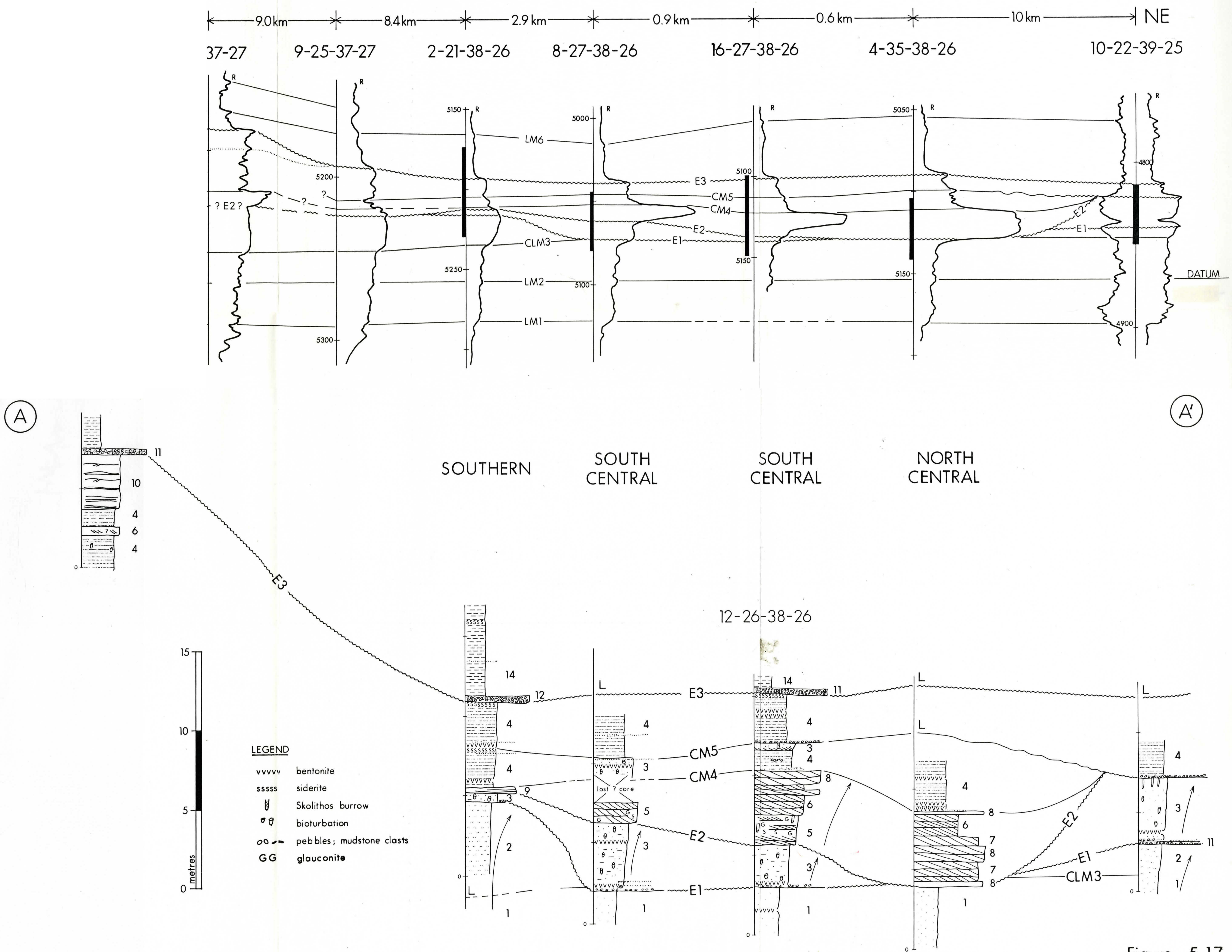
Bounding Surface E3

Bounding surface E3 is preserved as the sharp contact between Facies 4 and the overlying conglomeratic sediment of either Facies 11 or 12. It is mapped over an area of 1500 square kilometres in this study. The conglomeratic sediment which mantles it varies from 10 to 30 cm in thickness, and the maximum average pebble diameters exceed 20mm, this is the coarsest grained sediment seen at Joffre. Cross section A-A′ (Fig. 5.17), shows that most of the down-cutting associated with E3 occurs southwest of Joffre, the scour appears to be closely parallel to the underlying core markers in the direct vicinity of Joffre.

Package F

Package F is underlain by E3, its upper limit is not defined, it occurs somewhere in the Lloydminster Formation or perhaps it is even bounded by the Fish Scale sandstone. The basal sediments of Package F are the conglomeratic deposits of Facies 11 and 12 (which mantle E3), and the shales of Facies 14. Sometimes Facies 13 occurs above the conglomeratic deposits within Facies 14.

The depositional setting of Package F was probably offshore, in a quiet setting where the rate of bioturbation was equal to the rate of deposition. Very little sand was supplied to this environment, except for the sharply-based, loaded sandstone beds comprising Facies 13.



9.0 km
8.4 km
2.9 km
0.9 km
0.6 km
10 km
NE
37-27
9-25-37-27
2-21-38-26
8-27-38-26
16-27-38-26
4-35-38-26
10-22-39-25
LM6
E3
CM5
CM4
E2
E1
CLM3
LM2
LM1
? E2 ?
DATUM
A
A'
SOUTHERN
SOUTH CENTRAL
SOUTH CENTRAL
NORTH CENTRAL
12-26-38-26
lost ? core
metres
LEGEND
vvvvv bentonite
sssss siderite
Skolithos burrow
bioturbation
pebbles; mudstone clasts
GG glauconite

Figure 5.17

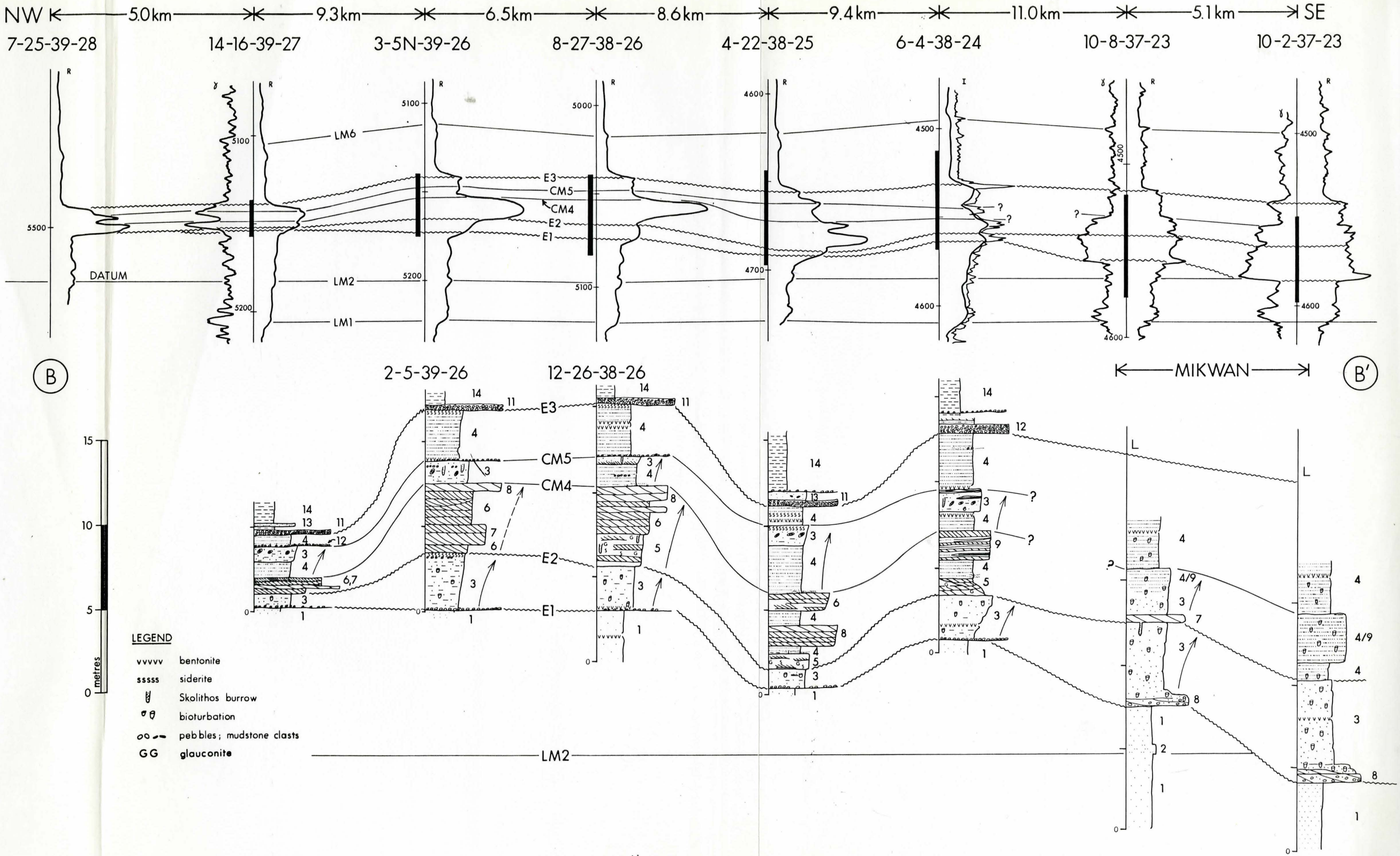
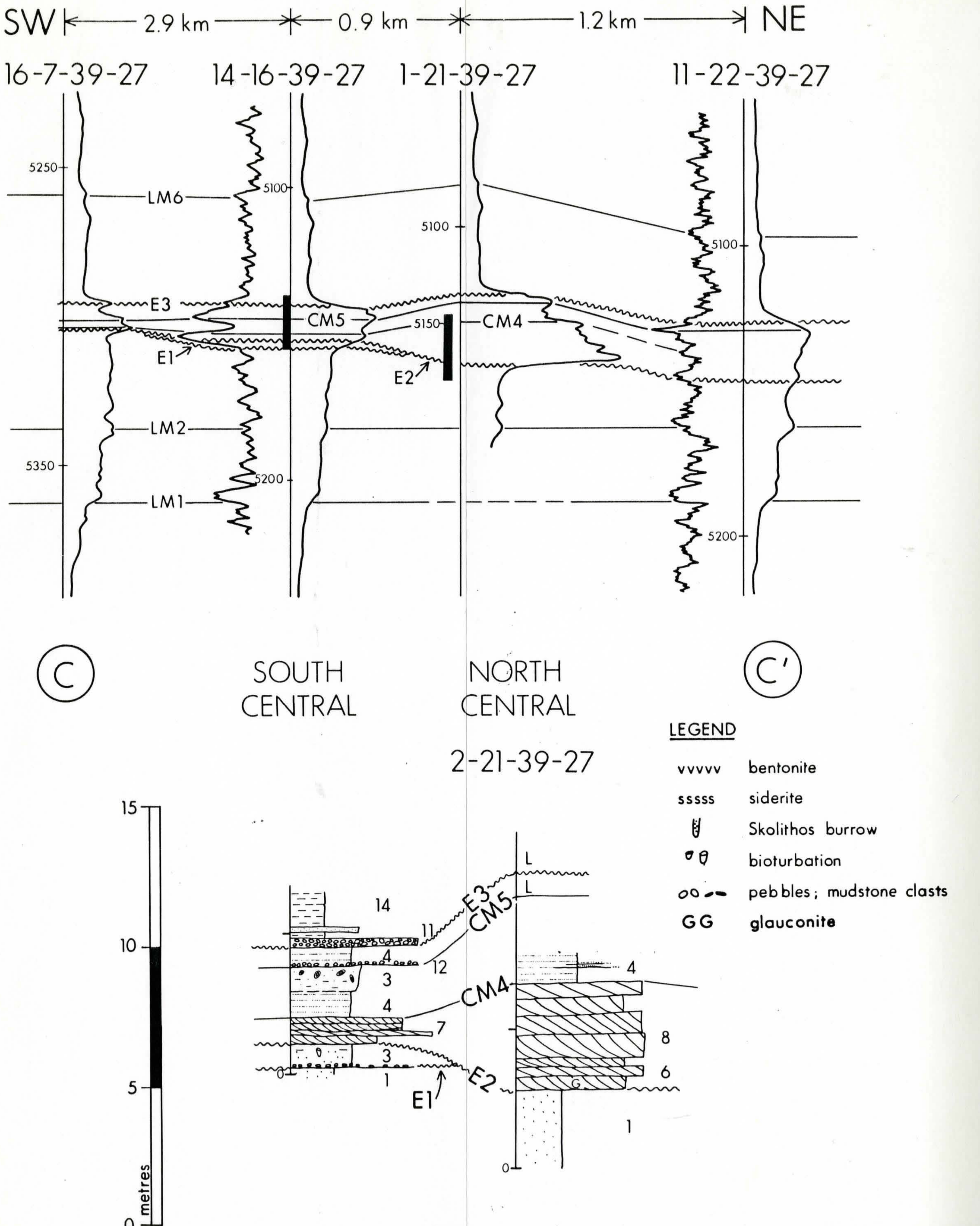

NW
5.0km
9.3km
6.5km
8.6km
9.4km
11.0km
5.1km
SE
7-25-39-28
14-16-39-27
3-5N-39-26
8-27-38-26
4-22-38-25
6-4-38-24
10-8-37-23
10-2-37-23
LM6
E3
CM5
CM4
E2
E1
DATUM
LM2
LM1
B
B'
2-5-39-26
12-26-38-26
MIKWAN
metres
LEGEND
vvvvv bentonite
sssss siderite
Skolithos burrow
bioturbation
pebbles; mudstone clasts
GG glauconite

Figure 5.18



SW
2.9 km
0.9 km
1.2 km
NE
16-7-39-27
14-16-39-27
1-21-39-27
11-22-39-27
5250
5350
5100
5200
5150
LM6
E3
CM5
CM4
E1
E2
LM2
LM1
C
SOUTH CENTRAL
NORTH CENTRAL
C'
2-21-39-27
LEGEND
vvvvv bentonite
sssss siderite
Skolithos burrow
bioturbation
pebbles; mudstone clasts
GG glauconite
metres
15
10
5
0

Figure 5.19

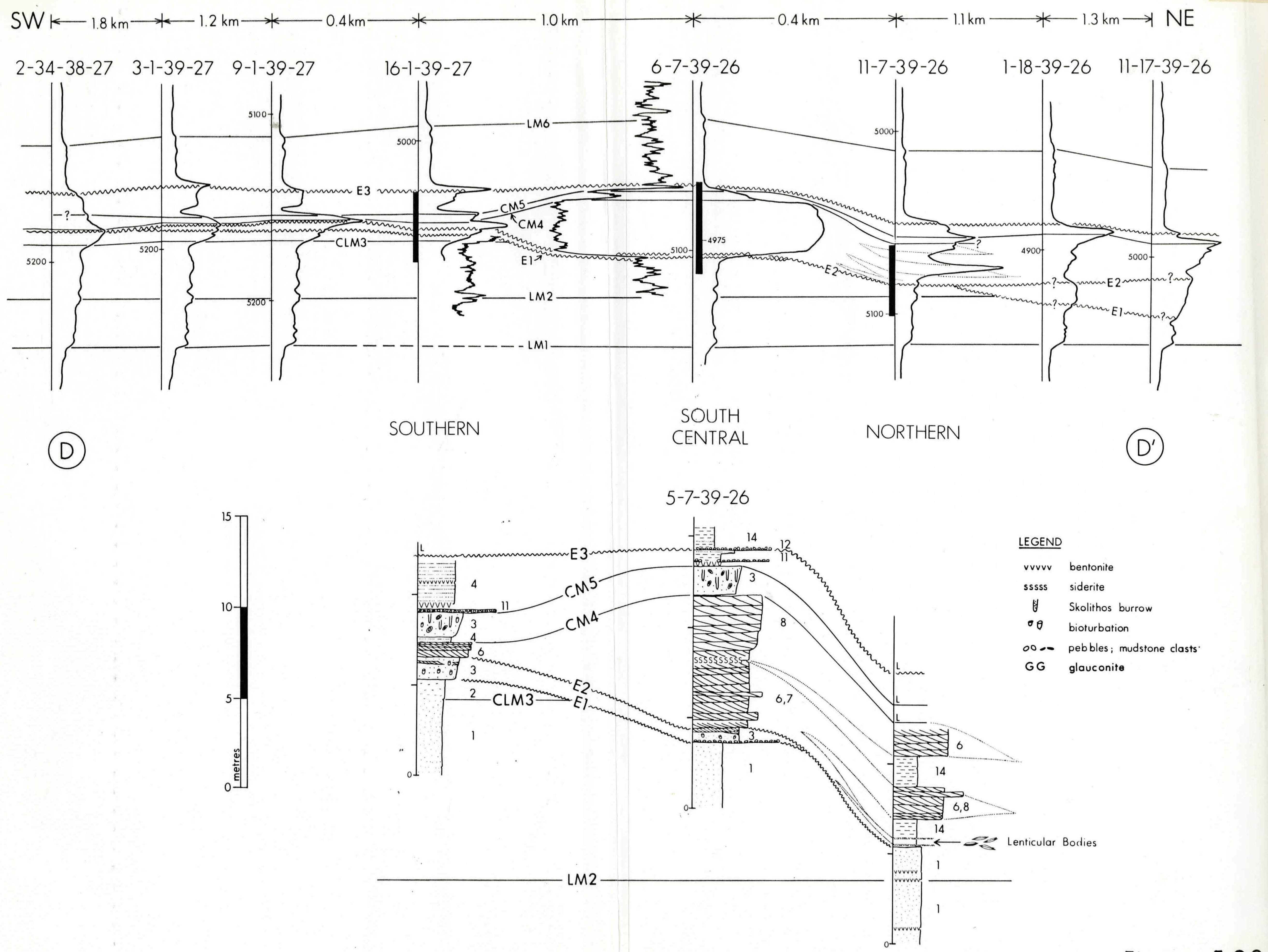

SW 1.8 km 1.2 km 0.4 km 1.0 km 0.4 km 1.1 km 1.3 km NE
2-34-38-27
3-1-39-27
9-1-39-27
16-1-39-27
6-7-39-26
11-7-39-26
1-18-39-26
11-17-39-26
LM6
E3
CM5
CM4
CLM3
E1
E2
LM2
LM1
SOUTHERN
SOUTH CENTRAL
NORTHERN
D
D'
5-7-39-26
metres
LEGEND
vvvvv bentonite
sssss siderite
Skolithos burrow
bioturbation
pebbles; mudstone clasts
GG glauconite
Lenticular Bodies

Figure 5.20

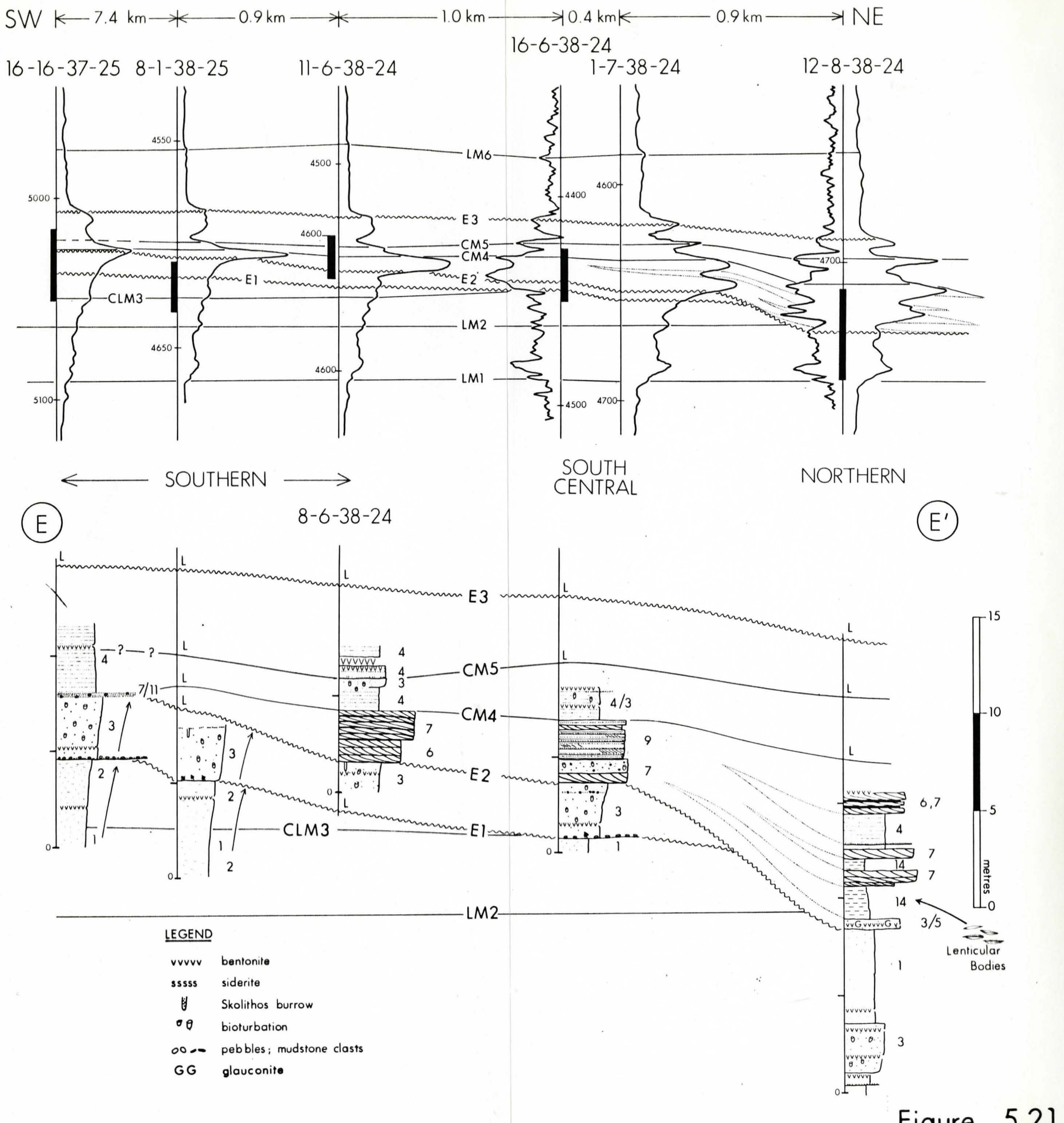

SW
7.4 km
0.9 km
1.0 km
0.4 km
0.9 km
NE
16-16-37-25
8-1-38-25
11-6-38-24
16-6-38-24
1-7-38-24
12-8-38-24
LM6
E3
CM5
CM4
E2
E1
CLM3
LM2
LM1
SOUTHERN
SOUTH CENTRAL
NORTHERN
E
8-6-38-24
E'
Lenticular Bodies
metres
LEGEND
vvvvv bentonite
sssss siderite
Skolithos burrow
bioturbation
pebbles; mudstone clasts
GG glauconite

Figure 5.21

CHAPTER 6. INTERPRETATION AND CONCLUSIONS

6.1. Introduction

The interpretations are built on specific observations from the cores and logs of Joffre, namely that:

i) there are at least three major erosional surfaces present at Joffre;

ii) there are six distinct packages of facies;

iii) there are overall grain size trends within the facies packages, and grain size breaks between packages.

Analysis of these features is directed towards solving

a) the origin of the erosional surfaces,

b) the nature of the depositional environments of the facies packages,

c) the history of changing depositional environments and fluctuating sea levels during Viking deposition.

6.2. Interpreting the Erosion surfaces

Erosion occurs when there is an increase in wave or current energy on the substrate. In the context of marine settings, erosion happens when relative sea level is lowered to the point that wave base is brought into contact with the substrate. Prior to a relative drop of sea level, the substrate would have been below wave base in a depositional setting , however in a shallower setting, it would become more susceptible to wave and current erosion

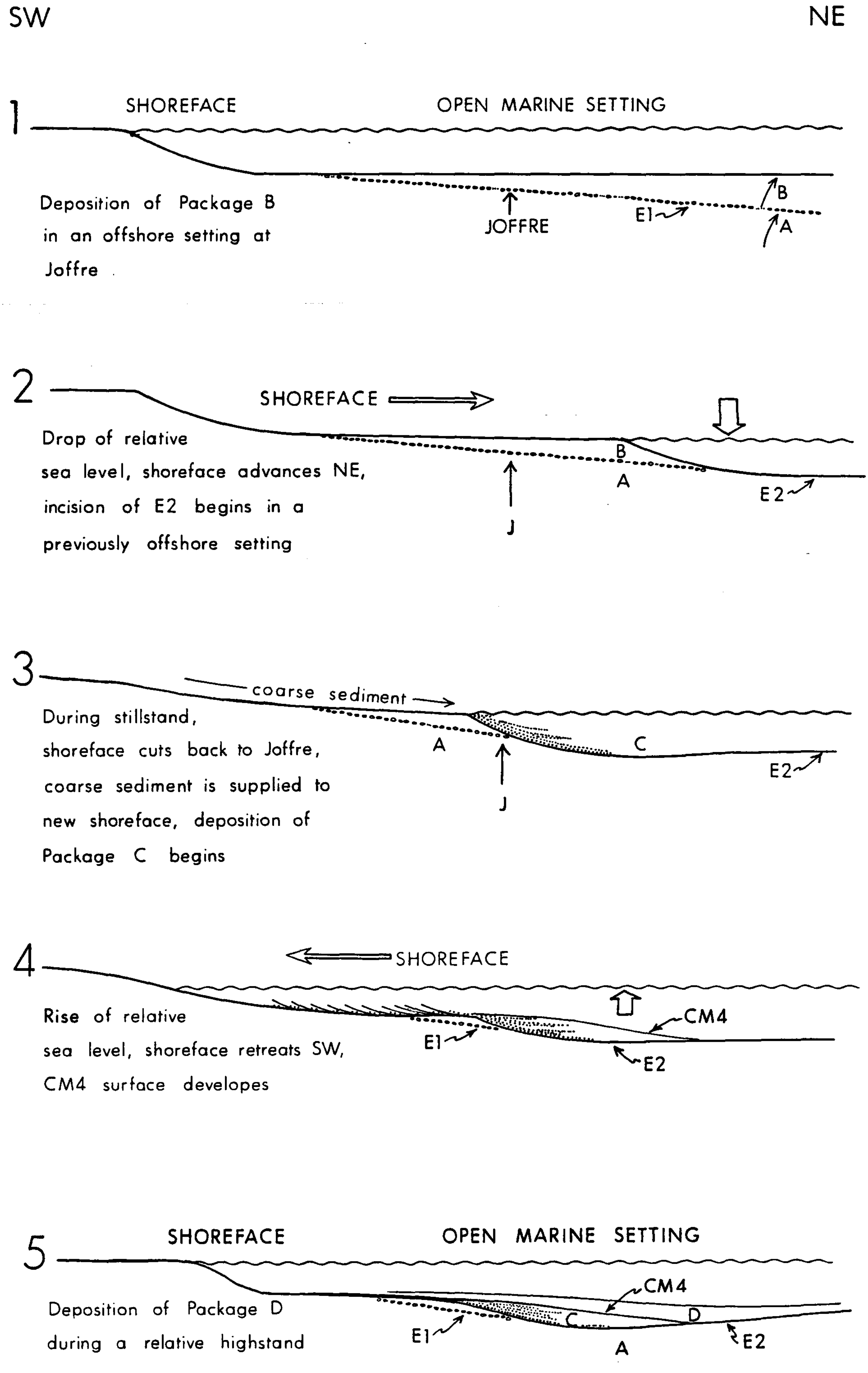
E2 The E2 scour surface is discussed first, because it underlies the main accumulation of coarse sediment (Package C). In the immediate vicinity of Joffre, the scour surface has a scarp-like shape, extending 30 km along the length of Joffre. The scarp plunges 12 metres towards the northeast, sloping at less than 0.3 degrees across the 2.5 kilometre width of Joffre. The economically important coarse sediment is banked-up against this scarp. The fact that the coarse sediment overlies the scour surface precludes any possibility for a genetic link between it and the underlying cleaning-upward sandstone of Package B. Northeast of Joffre the geometry of the E2 scour is undefined because of the lack of core data. The localized nature of the coarse sediment distribution has not encouraged drilling northeastward of the scarp.

Erosion of E2 can only have taken place in one of three settings: fully marine (offshore), fully subaerial, or some combination of both environments. The distinctive troughy shape of the scour creates problems for an offshore setting, because erosive currents or waves would somehow have to be focussed into the area of the present trough-like scour. There is no published account from recent shelf sediments of 5 m deep focussed erosion, over such an area. The contrasting appearances of the pre- and post-erosion sediments is striking. The depositional environment associated with the medium-grained to pebbly, cross-bedded sandstone of Package C appears markedly different to that of the bioturbated, fine-grained sandstone of Package B. This is a strong indicator of significant environmental change associated with the erosion surface. Erosion in an offshore setting seems to be an unlikely possibility for E2.

A subaerial setting might be feasible if the scarp shape of E2 were envisaged as one side of a northwest-oriented river valley. However, none of the sediment filling the "valley" has a fluvial character. The sediment directly overlying the scour is glauconitic and features *Skolithos* burrows, thus exhibiting a marine signature. To suggest that a former river valley was transgressed, transformed into an estuary, and that all signs of fluvial deposits were removed, is very unlikely. There is also no sign of former river valleys trending perpendicular to Joffre in the study area.

The process which best explains the shape of the scour and the character of the overlying sediment is a combination of marine and subaerial erosion, at or very close to a *shoreface*.

A major drop of relative sea level would significantly move the shoreline basinwards (northeastward), thereby localizing wave base scour in a previously offshore environment (Fig. 6.1). The northwest-oriented slope defined by the E2 surface can be compared to the toe of the newly formed shoreface. The scarp would represent the steeper middle shoreface. The coarse, cross-bedded texture of the sediment overlying the scour can then be explained by middle and lower shoreface processes.



SW
NE
1
SHOREFACE
OPEN MARINE SETTING
Deposition of Package B in an offshore setting at Joffre
JOFFRE
E1
B
A
2
SHOREFACE
Drop of relative sea level, shoreface advances NE, incision of E2 begins in a previously offshore setting
B
A
J
E2
3
coarse sediment
During stillstand, shoreface cuts back to Joffre, coarse sediment is supplied to new shoreface, deposition of Package C begins
A
C
J
E2
4
SHOREFACE
Rise of relative sea level, shoreface retreats SW, CM4 surface developes
CM4
E1
E2
5
SHOREFACE
OPEN MARINE SETTING
Deposition of Package D during a relative highstand
CM4
C
D
E1
A
E2

A marine setting can also account for the interfingering of glauconitic, cross-bedded sandstone and marine shale on the seaward side of the E2 trough, and explains the prominent Skolithos burrows which may penetrate the E2 surface. Erosion of E2 in a shoreface setting is also supported by the fact that the alternative settings do not explain the observations. Overall, the shoreface erosional setting solves problems of sediment transport and particularly sediment focussing in the previously postulated open shelf environment of Joffre.

A schematic summary of the local geological history associated with E2 is presented in Figure 6.1. Initially, deposition of Package B sediment occurred in an offshore setting, as suggested by the bioturbated nature of the muddy sandstone facies. The coarsening-upward grain size trend within Package B sediment is interpreted to indicate overall basin aggradation.

A drop of relative sea level (Stage 2, Fig.6.1) caused the shoreline to advance northeastward, beyond Joffre. Accompanying the advancing shoreline is a lowering of wave base. The depositional setting is transformed into an erosional setting as the wave base scours into the substrate (Package B), shaping a new shoreface in this more basinward position. During stillstand, the shoreface would cut back southwestward, to the present position of Joffre. The scour surface described is the E2 surface, the shape of the scarp is interpreted to have been created through wave scour, and is interpreted to represent the steeper middle portion of the shoreface.

During the stillstand (Stage 3, Fig.6.1), coarse sediment was supplied to the Joffre area, in response to the drop in base level. Drainage systems would begin to incise into the flood plain, and an increased gradient of the feeder systems, would allow relatively coarse sediment to be carried out over newly-exposed flood plain to the new shoreline. Once the coarse sediment reached the shoreline, it would be transported alongshore by processes such as long shore drift and tidal currents. Thus deposition of Package C begins under very different environmental conditions than existed for deposition of Package B. Package C would have been deposited in a nearshore setting under the influence of waves and long shore drift. There is no conclusive evidence of tidal influence within the sediments of Package C. The Skolithos ichnofacies attests to the continuously shifting nature of the sediment (Frey and Pemberton, 1984). Presumably, the finer-grained fraction of sediment that comprised Package B is moved right through the nearshore system to be deposited further out on the shelf.

It is during the initial stages of the stillstand that the glauconitic material is believed to have formed, as it is incorporated in the basal sediment of Package C. There is a tendency for siderite to occur amongst the glauconitic sandstone (above E2), and less commonly in the muddy sandstone (below E2). The timing of sideritization is not understood. Possibly the sideritized sediment below E2 was exhumed during E2 erosion, and was sufficiently firm to prevent further down-cutting by E2. Raddysh (1986) notes that the sharply-based sandstone at Gilby may rest on sideritized siltstone, and that Skolithos burrows which penetrate the sharp contact and enter sideritized siltstone at Gilby are not themselves sideritized. She suggests that sideritized fine-grained sediment underlying the Gilby erosion surface represents firm ground developments.

Distinct pauses in the deposition of Package C are indicated by the tongues of black shale which interfinger with the cross-stratified sediment. The origin of these pauses is not understood.

A sharp rise in the relative sea level (Stage 4, Fig.6.1), and the associated lift of the wave base, caused the shoreface to begin to retreat away from Joffre. The retreating wave regime would have planed off the upper portion of the Joffre shoreface and beach, removing the evidence for the newly-created floodplain associated with the Joffre shoreface. In a similar fashion, the Holocene transgression has removed a swath of sediment 5-15 m thick (Kraft, 1971; Rampino and Saunders,1980).The transgressive surface is mantled by pebble layers reworked from the top of the Package C sediment as the beach and upper shoreface sediments were redistributed southwestward, following the direction of shoreline retreat. The transgressive surface corresponds to the CM4 marker. The transgression is believed to have begun suddenly because the lower 5 metres of the shoreface profile and the overlying coarse sediment are preserved in tact. Evidence for the former shoreface position is thus preserved in situ by the trangressive blanket of Package D (Stage 5).

E1 The interpretation of E1 is not as straight forward as E2. This is because the E1 surface does not appear to have a similarly pronounced shape, nor does it have an associated deposit of cross-stratified shoreface sediment overlying it, as was seen in E2. The coarse sediment which mantles E1 is oftentimes only one pebble diameter in thickness, rather than the 3 to 5 m of cross-stratified sandstone seen above E2. The E1 scour surface cuts into bioturbated marine siltstones (Package A), and is overlain by bioturbated marine sandstones (Package B). Even the scour surface itself is bioturbated, it seems at first glance, to record an entirely marine history

There are at least three circumstances which could produce the offshore appearance described above. Each circumstance relects a different amount of relative sea level fall, and hence a different proximity to shore.

The first possibility invokes a **minor drop of relative sea level,** such that the shoreline made only a very limited advance toward Joffre, and the study area was still significantly offshore. The broad scour might be attributed to a re-equilibrating shelf circulation system responding to the minor, but distinct drop in sea level. The pebbly horizons which occur above E1 might have been transported away from shore by storm deposits which were eroding newly-available coarse sediment supplied to the distant shoreline following the small drop in base level. The similar nature of the underlying and overlying sediment could indicate that environmental conditions had not been greatly altered.

The second possibility invokes a **significantly greater drop of relative sea level**, such that the shoreline advanced as far as Joffre, creating a similar shoreface to the E2 event described earlier. The obvious questions that this poses are "what happened to the coarse shoreface sediment expected to overlie E1, as happened with E2?" and "why is there no pronounced scarp-shape to the E1 surface?" There is no doubt that coarse sediment was available because there is at least a thin veneer of pebbles above E1.

Assuming the E1 shoreface had developed at Joffre, a slow start to the E1 transgression could effectively rework the shoreface. Transgression of the E2 shoreface probably began suddenly, with a quick rise of relative sea level. This resulted in the preservation of the lower portion of the shoreface scarp, and the retention of a significant portion of the coarse shoreface sediment. Thus the lower part of the E2 shoreface was preserved intact, to be buried at sea. Alternatively, as hypothesized for E1, if the initiation of transgression is slow, there is a much greater chance the shoreface could be completely reworked. The pronounced shape of the original scour could be completely bevelled, and the sediment mantling the scour could easily be entrained by the retreating wave regime to be redistributed shoreward as a thin, continuous veneer. The intriguing one metre accumulations of pebbly sandstone which are rarely observed at the E1 horizon (10-2 and 10-8, Cross section B-B′, Fig. 5.17) may represent fortuitously preserved pockets of the original E1 shoreface. Certainly they occur stratigraphically deeper than their affiliated pebble horizons, and perhaps they were safely beyond wave base during the transgression. In this circumstance, the erosion associated with E1 would be caused by the slow erosional retreat of the shoreface.

The third possibility which could explain the nature of the E1 surface is a slight variation to the previous scenario. The third possibility invokes a **greater drop in sea level such that the shoreline advances beyond Joffre** to establish itself further basinward. Once again, the E1 surface is interpreted to represent the scour associated with the retreating shoreface, except this time the study area would have been behind the shoreface, in an area of newly-exposed flood plain. The rare occurences of cross-stratified pebbly sandstone might represent preserved remnants of the most deeply incised streams which would have cut across the emerging flood plain to keep pace with the rapidly advancing shoreline. The incision of these streams would have to have been deep enough to save them from transgressive-overprinting. In this instance, the sharp base of the cross-stratified deposit would be equated with erosion caused by a drop of relative sea level. All evidence of subaerial exposure would have been removed by the transgressive erosion, juxtaposing marine sediments of Package B overtop marine sediments of Package A. Presumably the underlying sediment was still appropriately unconsolidated for the burrowing organisms of Package B to homogenize the E1 surface and scramble the contact.

The local scope of this study cannot support one unique setting for the E1 surface, regional mapping of the erosional surface is the best way to determine its history.

E3 The E3 surface resembles the E1 surface in that both have diffusely shaped scours, and both are capped by relatively thin pebbly mantles as compared to Package C which overlies E2. E3 is certainly a widespread surface, and the relative coarseness of the pebbly sediment overlying it are intriguing. The same inability to precisely explain E1 applies to E3.

Perhaps the best analogue for E1 and E3 is the gravel veneer, which lies shoreward of the Carrot Creek shoreface (Bergman and Walker, 1986). A widespread veneer of pebbles has been mapped a great distance shoreward of the Carrot Creek shoreface (Plint et al., 1986). Bergman and Walker (1986) suggest that this veneer was deposited during the Carrot Creek Transgression "T5", by waves which were reworking the upper portion of the Carrot Creek shoreface.

By applying this analogy to the E1 and E3 surfaces, one conludes that the pebbly shorefaces which supplied the pebbles to each surface was located further seaward, towards the northeast. Regional mapping of the scour surfaces would prove or disprove this.

6.3 Conclusions

1. Deposition of the Viking at Joffre was controlled by fluctuations of relative sea level.

2. There are at least three erosional surfaces at Joffre (E1, E2, and E3), and each is capped by unusually coarse sediment. At Joffre the maximum depths of scour associated with the E1 and E2 erosion surfaces are 6 and 12 metres respectively. Southwest of Joffre, the E3 erosion surface exhibits 16 metres of erosion.

3. The E2 erosional surface displays the most pronounced morphology, it is a one-sided, northeastward-sloping surface dipping 0.3 degrees.

4. The coarse sediment of Package C, which overlies E2, is interpreted to represent the remnant of a shoreface which developed at Joffre during a lowstand.

5. The thinner, coarser veneers above E1 and E2 are more difficult to explain in such a localized study, possibly they represent transgressive lags associated with shorefaces further seaward (northeast) of Joffre.

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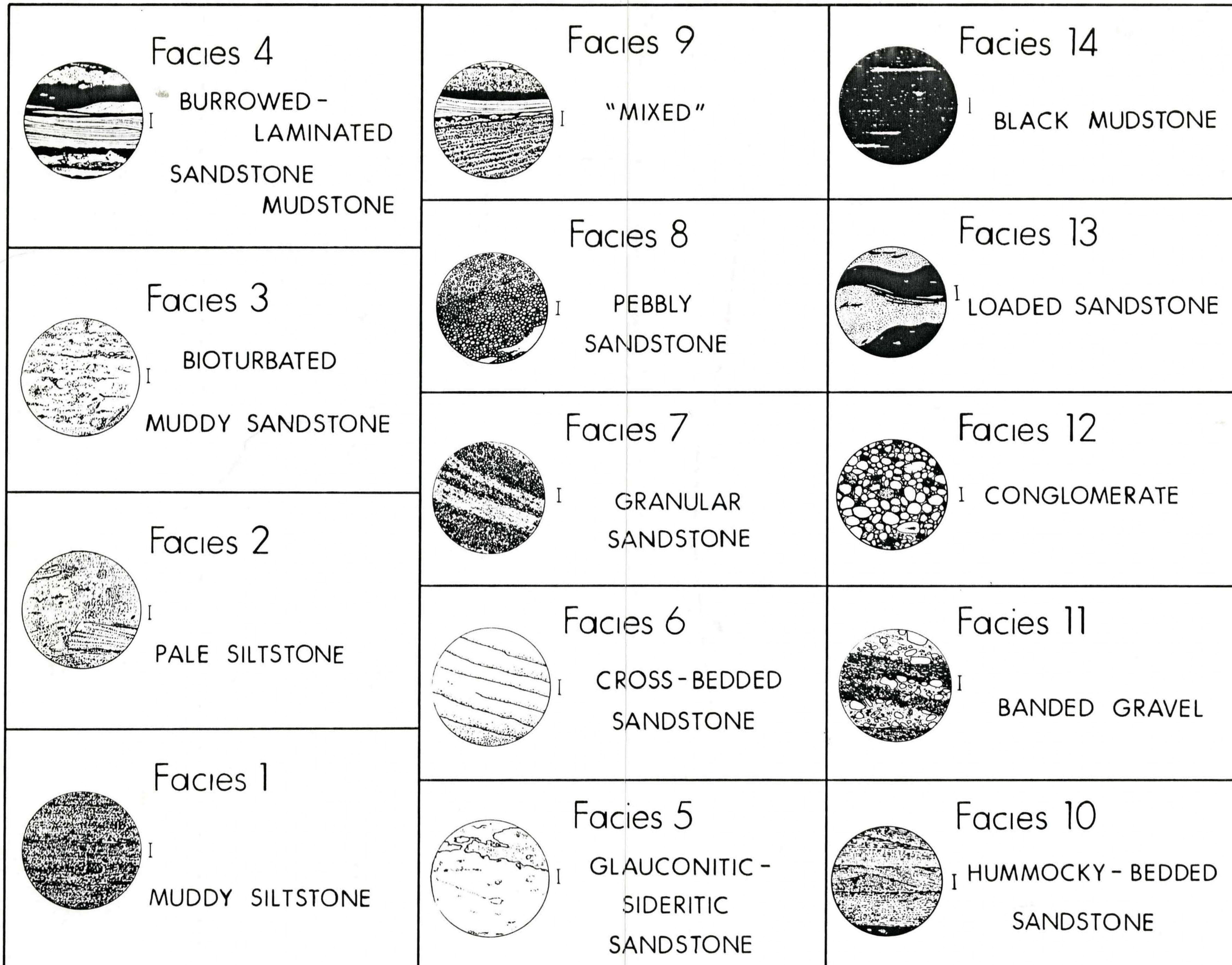
Appendix I



Viking Facies Scheme at Joffre   Sketches are based on slabbed cores. Bar scale: 1 cm