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SEDIMENTOLOGY, ICHNOLOGY AND HIGH RESOLUTION ALLOSTRATIGRAPHY OF THE LOWER CRETACEOUS VIKING FORMATION, CENTRAL ALBERTA, CANADA

SEDIMENTOLOGY, ICHNOLOGY AND HIGH-RESOLUTION ALLOSTRATIGRAPHY OF THE LOWER CRETACEOUS VIKING FORMATION, CENTRAL ALBERTA, CANADA

By

JAMES ARTHUR BURTON, B.SC. (Hons.)

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ABSTRACT

The Lower Cretaceous (Upper Albian) Viking Formation of central Alberta contains numerous linear sandbodies and fewer large irregularly-shaped sandbodies. Most studies to date have focused on individual sandbodies, leaving their interrelationships largely unknown. Developing a high-resolution allostratigraphy for the Viking of central Alberta allows mapping of regional bounding discontinuities and the definition of distinct allomembers. Placement of the Viking hydrocarbon fields within this framework permits an understanding of the exact stratigraphic relationships of the various fields.

Examination of 120 cores and numerous well log correlations suggests the existence of four regionally mappable bounding discontinuities (BD1-4) which separate five distinct allomembers (I-V). Sandbodies within these allomembers were deposited in a variety of *sedimentologically* distinct environments. These include 'regional Viking' offshore to shoreface sandstones, prograding highstand shoreface sediments, transgressive incised shoreface sediments, and forced regressive, onlapping shoreface 'tongues'. The series of linear trending hydrocarbon fields from Joffre to Chain are also *stratigraphically* distinct. The sandbodies exist at five separate stratigraphic horizons and therefore are not all part of the same incised shoreface deposits.

The four regional bounding discontinuities are interpreted as transgressive surfaces of erosion formed by four separate drops and subsequent rises of relative sea level. These

fluctuations were greater than 30 m and each complete cycle occurred over roughly 375,000 years.

ACKNOWLEDGEMENTS

A sincere thank you must first go out to Roger Walker for his support, advice and incredible enthusiasm towards this project. His wealth of knowledge and experience (and of course his NSERC funding!) have provided me with the opportunity to expand my education exponentially these past few years. This work has also benefitted greatly from the input and encouragement of James MacEachern (SFU) who was always ready and willing to discuss the Viking!

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CHAPTER 1: INTRODUCTION

1.1 The Geological Problem

The Viking Formation of Central Alberta is an internally complex clastic wedge composed dominantly of marine sandstones and shales. Numerous long, narrow and linear sandbodies occur over much of central Alberta, with fewer large, irregularly shaped, sheet-like sandbodies in east-central Alberta. The relationship between linear and irregular shaped sandbodies is poorly understood and a high-resolution stratigraphy is needed to place all of the various sandbodies in their detailed stratigraphic context.

The linearity of Viking sandbody trends is strikingly apparent along the continuous and nearly straight series of hydrocarbon bearing fields, stretching from Gilby-Joffre through Mikwan, Fenn, Chain and southeastward towards the Saskatchewan border, a distance of over 300 km. Earlier interpretations placed the linear sandbodies as "offshore bars" (Koldijk, 1976; Leckie, 1986; Hein et al., 1986), but more recently they have been interpreted as incised shoreface deposits formed locally during changes of relative sea level (RSL) (Downing and Walker, 1988; Raddysh, 1988; McIntosh, 1995). Internal bounding discontinuities produced by fluctuations of RSL have been identified in many of these linear deposits.

The large irregularly-shaped Viking sandbodies have received little attention in comparison with their linear counterparts. In the study area, Provost and Hamilton Lake fields cover approximately 3,500 km^2 and 1,100 km^2 respectively. They represent large accumulations of sand which clearly demand investigation with respect to their stratigraphic positions relative to the linear Viking fields, and their depositional environments. Early studies interpreted them as accumulations of sand on submarine shoals (Lerand and Thompson, 1976), submerged deltas (Beaumont, 1984), or extensive offshore ridge and sheet deposits (Amajor and Lerbekmo, 1990a,b).

A high resolution stratigraphy must be developed to map out internal bounding discontinuities within the linear sandbodies and to trace these surfaces into the irregularly-shaped sandbodies. In this way individual sandbodies can be assigned to specific stratigraphic intervals and lateral and vertical facies relationships will be identified.

This research was initiated in an attempt to answer some of the questions and problems raised in the preceding paragraphs. The following goals were outlined at the beginning of work on this thesis:

1) To determine whether or not the linear sandbodies southeast of Joffre-Mikwan are a continuous part of the incised shoreface deposits identified at Joffre (Downing and Walker, 1988).

2) To determine if the bounding discontinuities identified at Joffre and Mikwan (Downing and Walker, 1988; McIntosh, 1995) are regionally mappable.

3) To understand the depositional environment of the large irregularly-shaped, sheet-like sandbodies to the northeast (i.e. Hamilton Lake-Provost), and their stratigraphic relationship to nearby linear sandbodies.

1.2 The Study Area

The study area is located in central Alberta (Fig. 1.1) and covers 121 Townships or approximately 12,000 km^2. This area lies west of the 4th meridian between Ranges 6 - 25, and Townships 30 - 38. The Viking Formation within the study area is entirely in the subsurface, but has been extensively drilled owing to the numerous oil and gas reservoirs which produce from the Viking. This particular area was chosen because of its proximity to previously studied linear sandbodies (i.e. Joffre-Mikwan) and due to the proximity of these linear sandbodies to the larger irregularly-shaped Viking sandbodies.

1.3 Data Base and Methods

The data base consisted of suites of geophysical well logs from nearly 1500 boreholes. Cores from 120 wells were examined in detail. The locations of all data points are illustrated in Figure 1.2. The suite of well logs obtained from each well typically comprises both gamma ray and resistivity, but spontaneous potential and sonic well logs were commonly available. Gamma ray and resistivity were consistently utilized (where possible) to construct stratigraphic cross-sections and relate sedimentary facies to their well log patterns. The resolution of the log types varies considerably, depending on the age of the well.

Cores were examined in order to identify grain size, lithology, physical and biogenic sedimentary structures and trends within these properties. Recurring facies successions were identified and the contacts between differing facies were recorded in detail. All cores were photographed in their boxes and many detailed photographs of

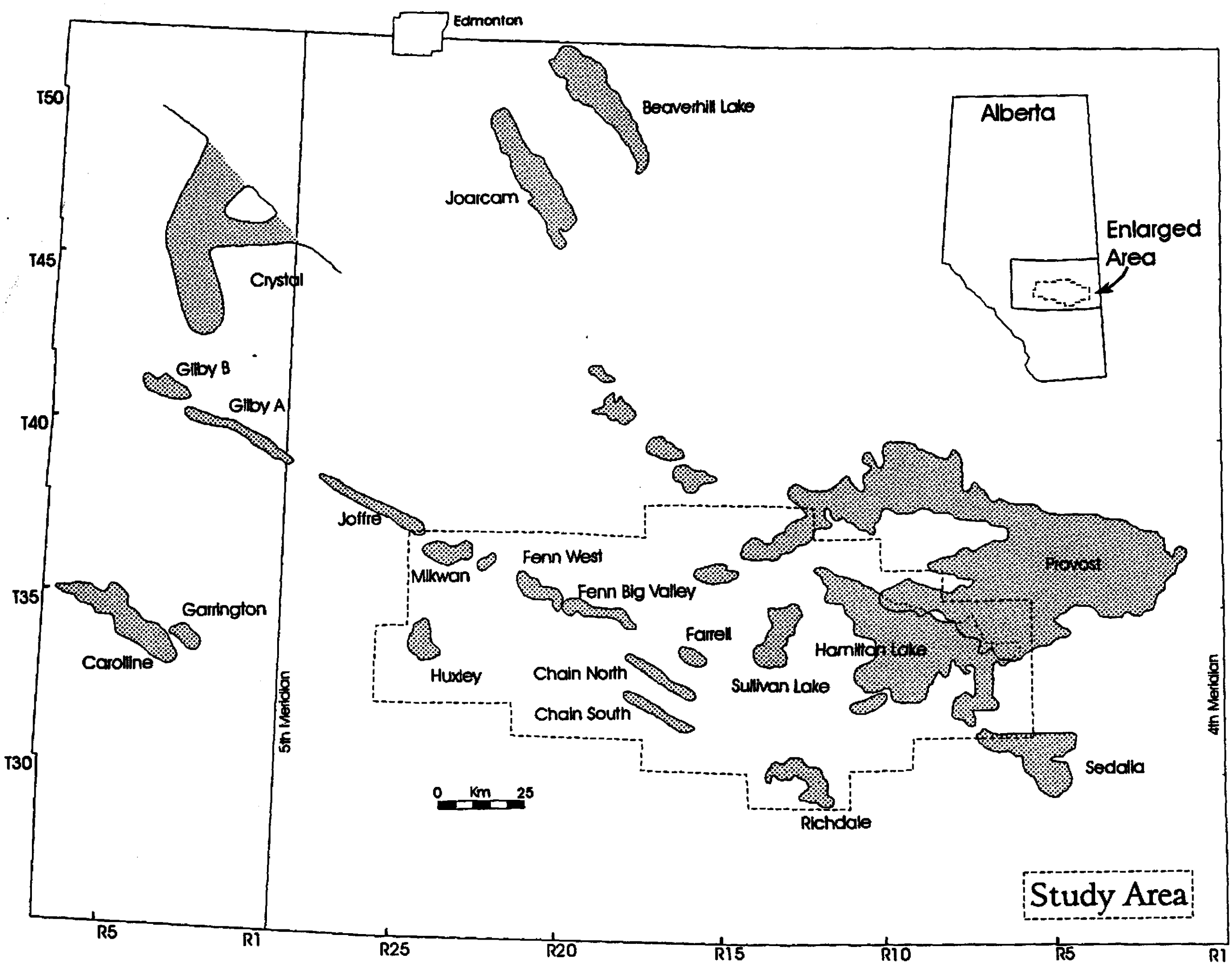
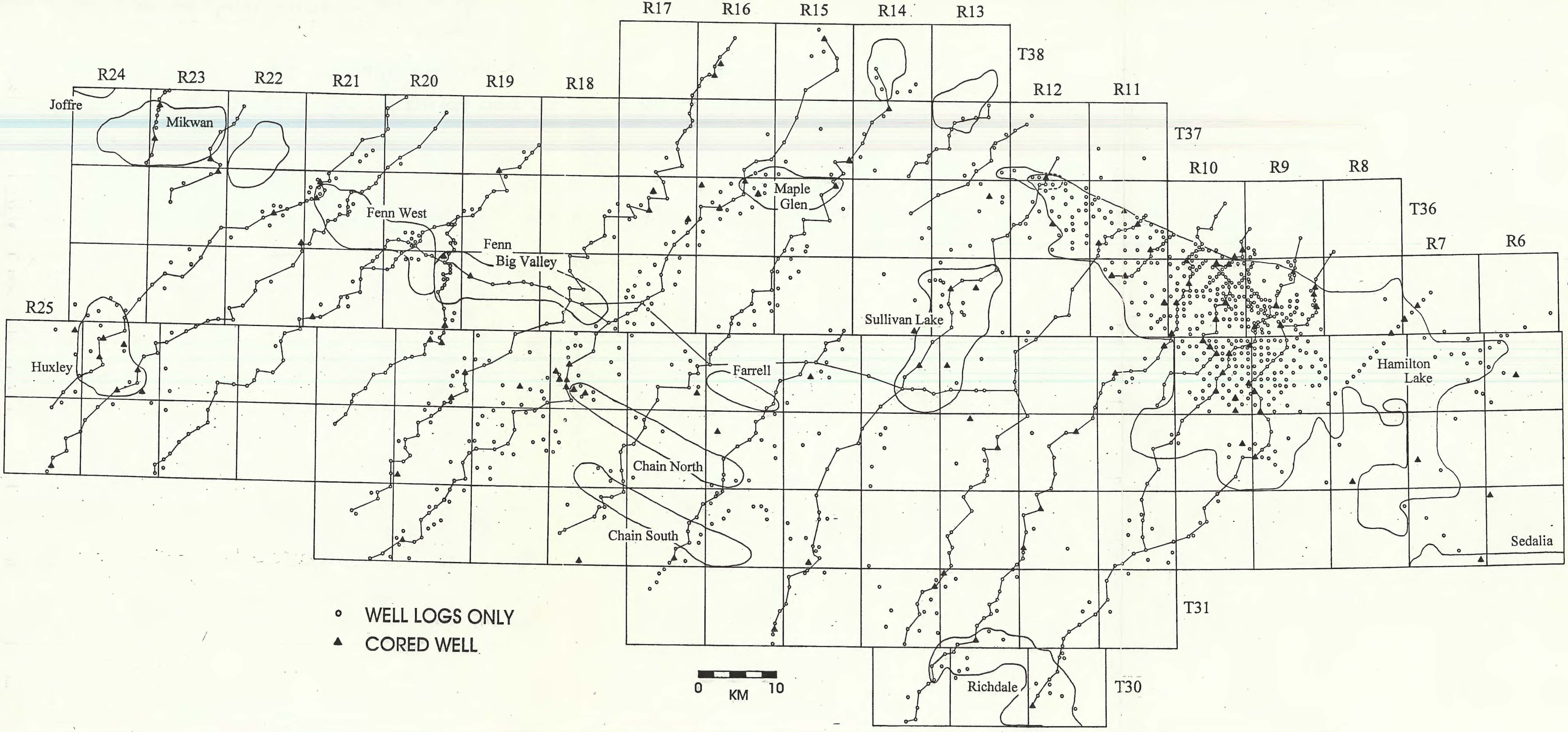


FIGURE 1.1 Location of the study area with respect to various Viking fields in central Alberta.

Figure 1.2 Location map showing well log and core data obtained for this study. Well logs were collected in 'swaths' along desired cross-section paths. Map also shows locations of working cross-sections used to develop the regional allostratigraphy. Viking hydrocarbon fields are outlined.



R17
R16
R15
R14
R13
T38
R24
R23
R22
R21
R20
R19
R18
R12
R11
Joffre
Mikwan
T37
R10
R9
R8
Maple
Glen
Fenn West
T36
Fenn
Big Valley
R7
R6
T35
R25
Sullivan Lake
Huxley
Farrell
Hamilton
Lake
T34
T33
Chain North
Chain South
T32
Sedalia
T31
WELL LOGS ONLY
CORED WELL
0
KM
10
Richdale
T30

important contacts, structures and typical facies were also taken. Grain size estimates were made using a Canstrat card, donated by Canadian Stratigraphic Services Ltd. Cores were examined at the Alberta Energy and Utilities Board (AEUB) Core Research Centre in Calgary, Alberta.

1.4 Previous Work

Previous studies of the Viking Formation can essentially be divided into two categories: 1) those which imply a fixed sea level, and 2) those which assume fluctuations of relative sea level (RSL). Most of the early work done on the Viking assumed that the shoreline was southwest of the main sandbodies and that deposition occurred in an offshore environment. Interpretations ranged from deep water turbidites (Beach, 1956), to shelf sandstones affected by tidal currents (Evans, 1970; Amajor and Lerbekmo, 1990a, b) to storm deposits (Koldijk, 1976). Within the study area of this thesis, Amajor and Lerbekmo (1990) suggested that tidal currents were responsible for deposition of Hamilton Lake and Provost fields, 20 - 250 km from the paleo-shoreline.

The idea that fluctuations of RSL influenced deposition of Viking sandbodies may have been introduced by Lerand and Thompson (1976) who investigated the northwestern tip of Hamilton Lake field (Township 36, Range 12W4). They identified three thin sandstones separated by two thicker mudstone units. A variety of northeastward migrating coastal depositional environments was suggested, with several transgressive-regressive cycles producing the alternating sandstone and mudstone units. The sharp updip edge of the Hamilton Lake sand was thought to represent the edge of an original strand line.

Beaumont (1984) also incorporated a major drop of RSL to account for the large irregularly-shaped sandbodies. He looked at several cores from these large fields and came to the conclusion that they represented submerged deltaic deposits as suggested by their shape and by the presence of abundant coal clasts and plant fragments. During the ensuing transgression, sand was reworked into linear shelf sandbodies.

Hein et al. (1986) and Leckie (1986) studied the upper part of the Viking at Caroline and Garrington fields and interpreted them as deposits of a prograding shoreline during a lowering of RSL. A conglomeratic lag caps these deposits and represents the transgressive reworking of the shoreface.

Since 1986, numerous studies of the Viking have been carried out at McMaster University, describing the stratigraphy and sedimentology of various individual Viking sandbodies. Downing and Walker (1988) studied the linear Joffre sandbody and identified three erosional surfaces (E1-E3). The second one, E2, displayed a pronounced asymmetrical morphology. Coarse sediment above this asymmetric incision was interpreted to represent a remnant of a shoreface which developed at Joffre during a lowstand of sea level. Two other surfaces (CM4, CM5) were identified in core, but were not considered to be extensive erosion surfaces.

The identification of two valley incisions and fills at Crystal (Pattison and Walker, 1994) demands at least two major fluctuations of RSL of magnitude 30 - 50 m. This idea is supported by the identification of two stratigraphically-distinct lowstand shorelines at

Lindbrook and Beaverhill Lake (Walker and Wiseman, 1995).

Most of these studies have focused on individual sandbodies and a regional stratigraphy for the Viking did not emerge until 1991, when Boreen and Walker attempted a regional correlation of Viking deposits and developed a preliminary allostratigraphy.

1.5 Previous Work - Directed Reading

Summaries of past Viking Formation studies in other areas of the basin are provided in previous Viking theses written at McMaster University. Readers needing more information are directed to the following sources: Downing (1986), Power (1987), Boreen (1989), Davies (1990), Pattison (1991) and Hadley (1992).

1.6 Regional Allostratigraphy

Boreen and Walker (1991) were the first to propose an informal allostratigraphy (Fig. 1.3). It was based in the Willesden Green area but had wider implications. They suggested the existence of four bounding discontinuities (VE1-4) separating five allomembers (A-E). VE1 was not recognized as an erosion surface and therefore Allomembers A and B can be combined into a series of conformably stacked coarsening upward 'regional Viking' sediments. Allomember C consists of coarse grained valley fill sediments (Crystal and Willesden Green) above VE2, and transgressive shoreface deposits (Gilby and Joffre) above VE3a, b. Prograding storm-dominated shoreface deposits (Caroline and Garrington) above VE3 are defined as Allomember D, and transgressive deposits above VE4 are defined as Allomember E. This scheme, while effective for the

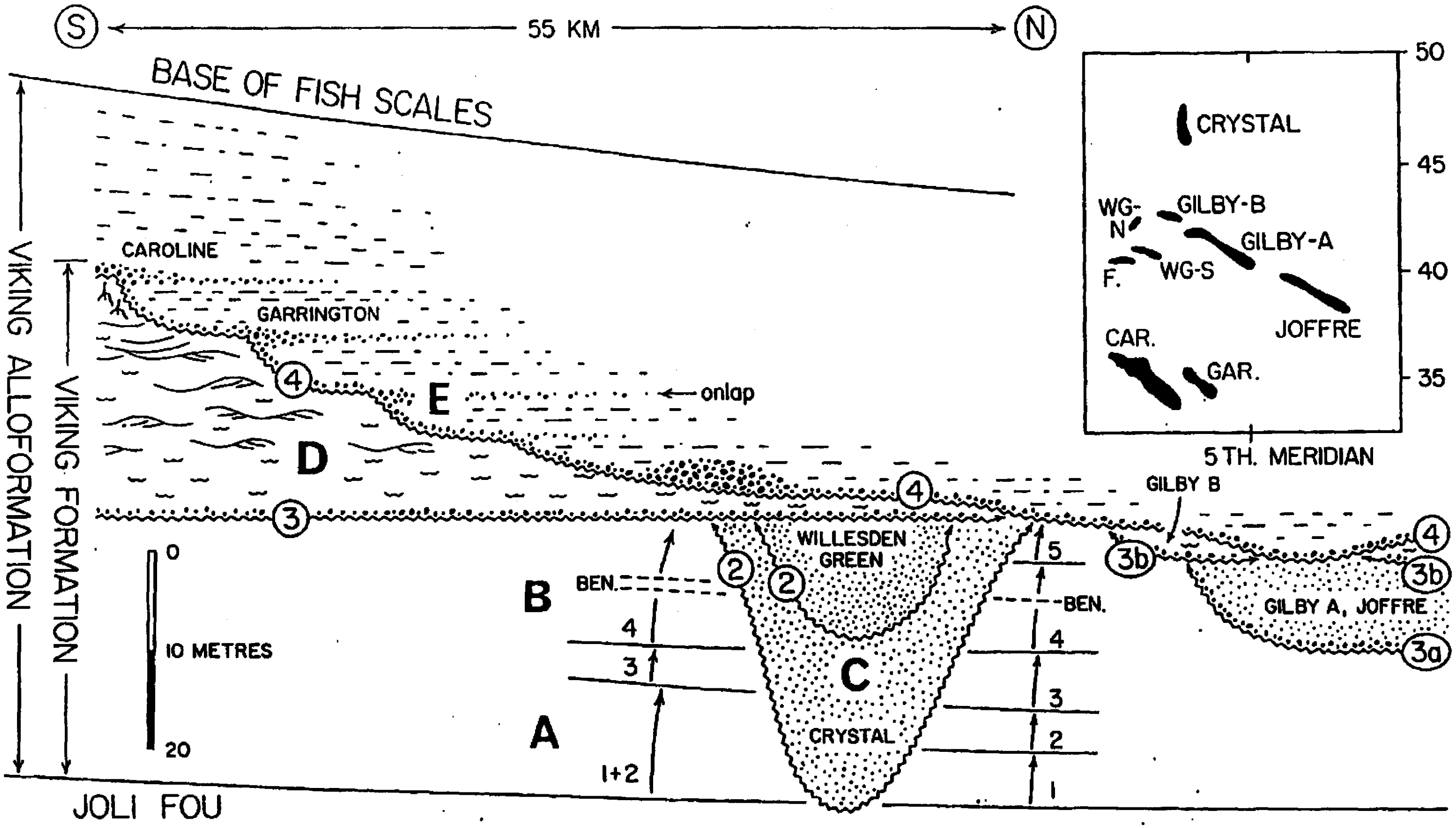


Figure 1.3 Summary of Viking allostratigraphy in the Caroline-Willesden Green area (after Boreen and Walker, 1991). (See text for details)

Ferrier and Willesden Green area, failed to account for two of Downing and Walker's (1988; Fig. 1.4) surfaces (E2 and CM4) which will be shown here to be extensive and mappable transgressive surfaces of erosion (TSEs).

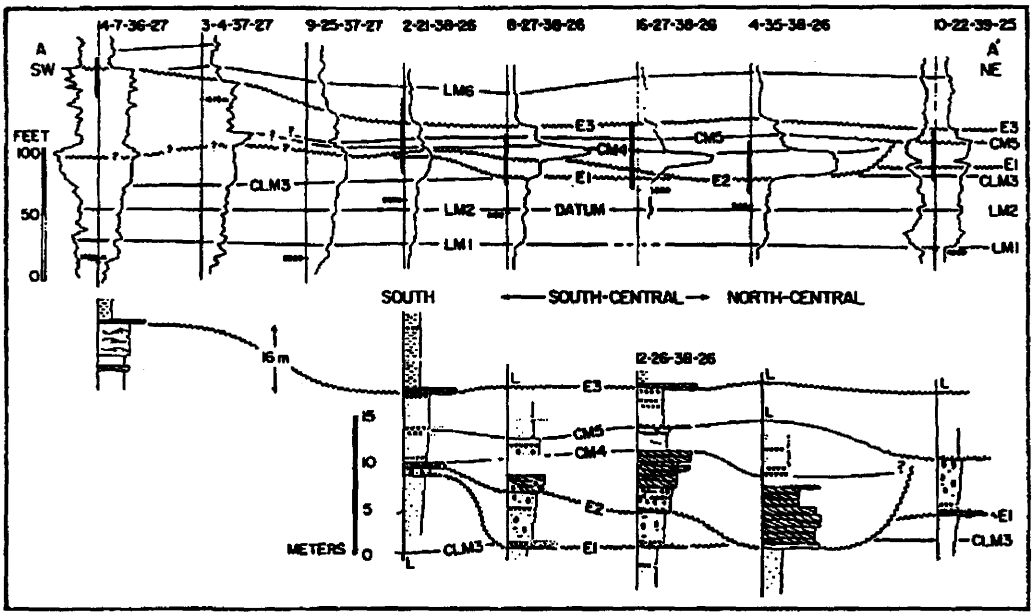


Figure 1.4 Stratigraphy and terminology used at Joffre (Downing and Walker, 1988).

Leckie and Reinson (1993) also conducted a regional study of the Viking and identified two prograding cycles, separated by an unconformity. This interpretation suggests the possibility of two lowstands of sea level.

Pattison and Walker (1994) provided evidence that the valley fill at Crystal (Reinson et al., 1988) appears to consist of two separate incisions and fills, truncated by one TSE (VE3). They were unclear whether or not the first fill was truncated by a TSE and then subsequently removed by younger erosion surfaces (VE3, VE4). However, the presence of two separate valley fill events, prior to ravinement by VE3 and subsequently by VE4 suggests that there were in fact at least three major drops of RSL of the order 30 -

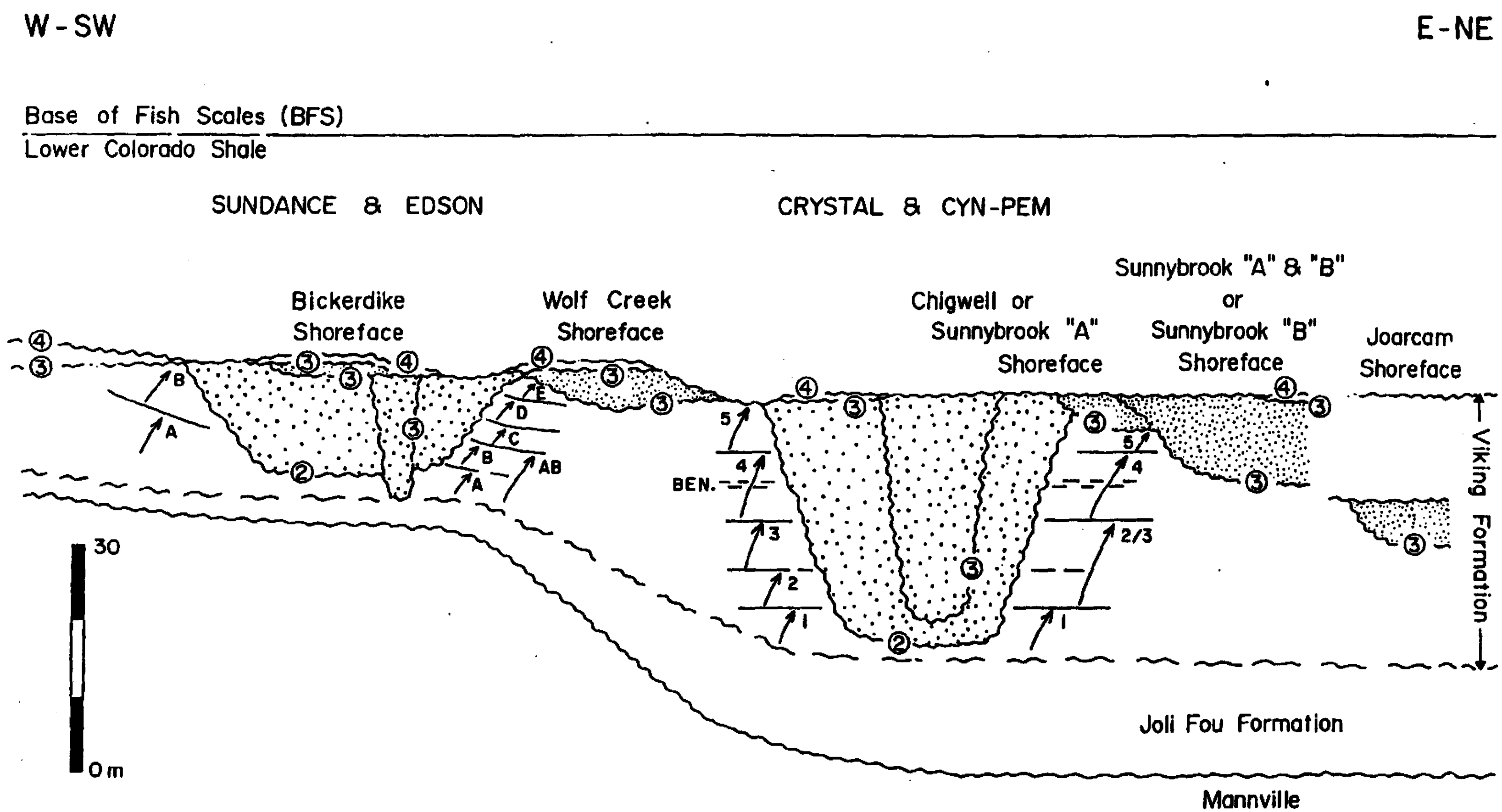


Figure 1.5 Summary of Viking allostratigraphy as modified by Pattison (1991). (See text for details)

50 m within the Viking Formation; valleys 1 and 2 at Crystal, and the drop immediately preceding TSE - VE4 (Pattison and Walker, 1994). A modified allostratigraphy was proposed (Pattison, 1991) in which the first lowstand incision was defined as VE2, and the second lowstand incision, plus the transgressive modification (ravinement surface) were defined as VE3 (Fig. 1.5). Later work by Walker and Wiseman (1995) substantiated claims of three major drops of RSL by identifying two separate lowstand shorelines (Lindbrook and Beaverhill Lake) stratigraphically below VE4.

McIntosh (1995) extended the work done at Joffre (Downing, 1986; Downing and Walker, 1988) into the Mikwan area and recognized two TSEs (CM4 and CM5; Fig. 1.4) above the main sandstone, but below VE4. This may have resolved Pattison and Walker's (1994) concern about the existence of a TSE originally truncating the first valley fill at Crystal. McIntosh (1995) proposed that CM4 was equivalent to the truncation of the first valley fill at Crystal and CM5 was equivalent to the truncation of the second valley fill at Crystal (VE3).

1.7 Updated Allostratigraphy

As a result of regional correlations within the study area, an updated allostratigraphy is proposed (Fig. 1.6). Four regional bounding discontinuities (BD1-4) are recognized within the Viking Alloformation which bound five allomembers (I-V).

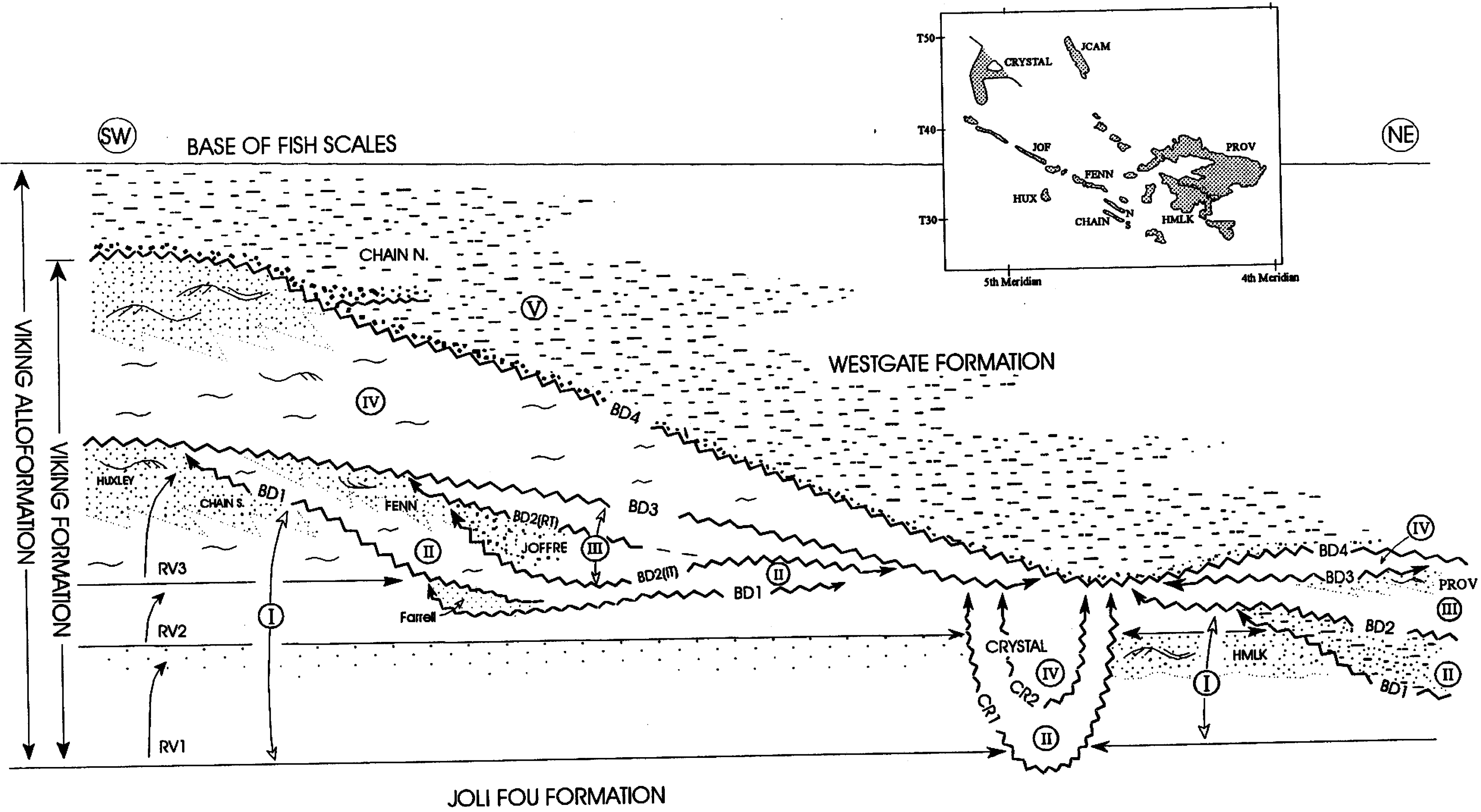
The base of the Viking Alloformation is commonly very gradational from the underlying Joli Fou shales. This presents a dilemma as to where to place the exact position of the base of the Viking Alloformation, since it must be a bounding discontinuity

(NACSN, 1983). Therefore for this thesis, the Joli Fou Alloformation is defined from the top of the Mannville Group to the maximum flooding surface within the Joli Fou shales. This maximum flooding surface then also defines the base of the Viking Alloformation and Allomember I. Allomembers I, II, III and IV are bounded at their tops by BD1, BD2, BD3 and BD4 respectively, although commonly higher discontinuities have locally removed lower ones; for example BD3 rests directly on Allomember I at Huxley. Allomember V is bounded at its top by the Base of Fish Scales marker (BFS) which represents a condensed horizon.

The updated allostratigraphy for the Viking is presented in Figure 1.6. It is based upon correlations within the current study area, but the reader must be made aware that elsewhere in the basin, parts of this stratigraphy are possibly (even likely) erosively removed. Even within the study area, allomembers are commonly dissected by overlying erosion surfaces and in places entirely removed. The two valley incisions identified at Crystal (Pattison and Walker, 1994) have also been superimposed on Figure 1.6 due to their importance in the Viking stratigraphy.

Surfaces BD1 and BD2 are split into two surfaces each at Farrell and Joffre respectively. The lower surface is the initial transgressive (IT) surface, which is followed by a pause in transgression and some amount of shoreface progradation. The upper surface is formed during resumed transgression (RT), when usually the upper shoreface sediments are 'planed off'. Although there are two distinct discontinuities at these locations, they are only local and are considered part of the same overall transgression and therefore receive the same BD designation.

Figure 1.6 Updated Viking Allostratigraphy for central Alberta. Cross-section is oriented roughly SW-NE and shows stratigraphic relationships of various Viking fields from the inset illustration. Bounding discontinuities are labelled BD1 - 4 and allomembers are denoted by circled Roman Numerals I - V. The two valley incisions at Crystal (CR1, CR2; Pattison and Walker, 1991) are superimposed. No scale implied. See text for details.


SW
BASE OF FISH SCALES
NE
T50
T40
T30
CRYSTAL
JCAM
JOF
PROV
FENN
HUX
CHAIN
N
S
HMLK
5th Meridian
4th Meridian
VIKING ALLOFORMATION
VIKING FORMATION
CHAIN N.
V
WESTGATE FORMATION
IV
BD4
HUXLEY
CHAIN S.
BD1
FENN
BD3
BD2(RT)
JOFFRE
II
III
BD2(IT)
BD1
RV3
RV2
RV1
I
Farrell
CRYSTAL
CR1
CR2
II
IV
BD4
BD3
PROV
III
BD2
HMLK
BD1
II
I
IV
JOLI FOU FORMATION

The important modifications that are presented by this proposed allostratigraphy include 1) the recognition of four distinct, regional and erosional bounding discontinuities, 2) the recognition that 'regional Viking' successions (Allomember I) can develop important shoreface and offshore sandbodies, and 3) an understanding of the two key surfaces identified under the main sandbody at Joffre (Downing and Walker, 1988). Development of the proposed allostratigraphy is presented in detail in Chapter 6. Table 1 highlights the relationships of key surfaces from Downing and Walker (1988), Boreen and Walker (1991) and the current study.

Downing and Walker (1988)	Boreen and Walker (1991)	Current Study - Burton (1997)
E3	VE4	BD4
CM5	VE3b	BD3
CM4	?	BD2(RT)
E2	?	BD2(IT)
E1	VE3a	BD1

Table 1. Comparison of the terminologies between related papers. This table shows general correlations of terminology, but some of the correlations between Downing and Walker (1988) and Boreen and Walker (1991) are not exactly correct in light of our current understanding of BD surfaces.

CHAPTER 2: STRATIGRAPHY AND REGIONAL SETTING

2.1 Lithostratigraphy of the Viking Formation and Equivalents

The Viking Formation of central Alberta is Upper Albian in age and is part of the Lower Cretaceous Colorado Group (Fig. 2.1). It consists dominantly of marine sandstones and shales which rest stratigraphically above the Joli Fou Formation and below the Westgate Formation (Bloch et al., 1993).

2.1.1 The Joli Fou Formation

The Joli Fou is a unit of marine shales deposited over much of the Western Canada Sedimentary Basin following a major sea level rise that created the post Mannville unconformity. It represents the transgressive portion of the Kiowa-Skull Creek marine cycle (Caldwell, 1984). Joli Fou equivalents include the Lower Hasler Shale of northeastern British Columbia, part of the Bow Island Formation of southern Alberta, and in the United States, the Skull Creek and Thermopolis shales.

2.1.2 The Viking Formation

The Viking is an eastward thinning wedge of coarse clastics, composed mainly of marine sediment, although it grades into non-marine sediment to the southwest. Channelized sandstones and conglomerates are recognized in west central Alberta, and

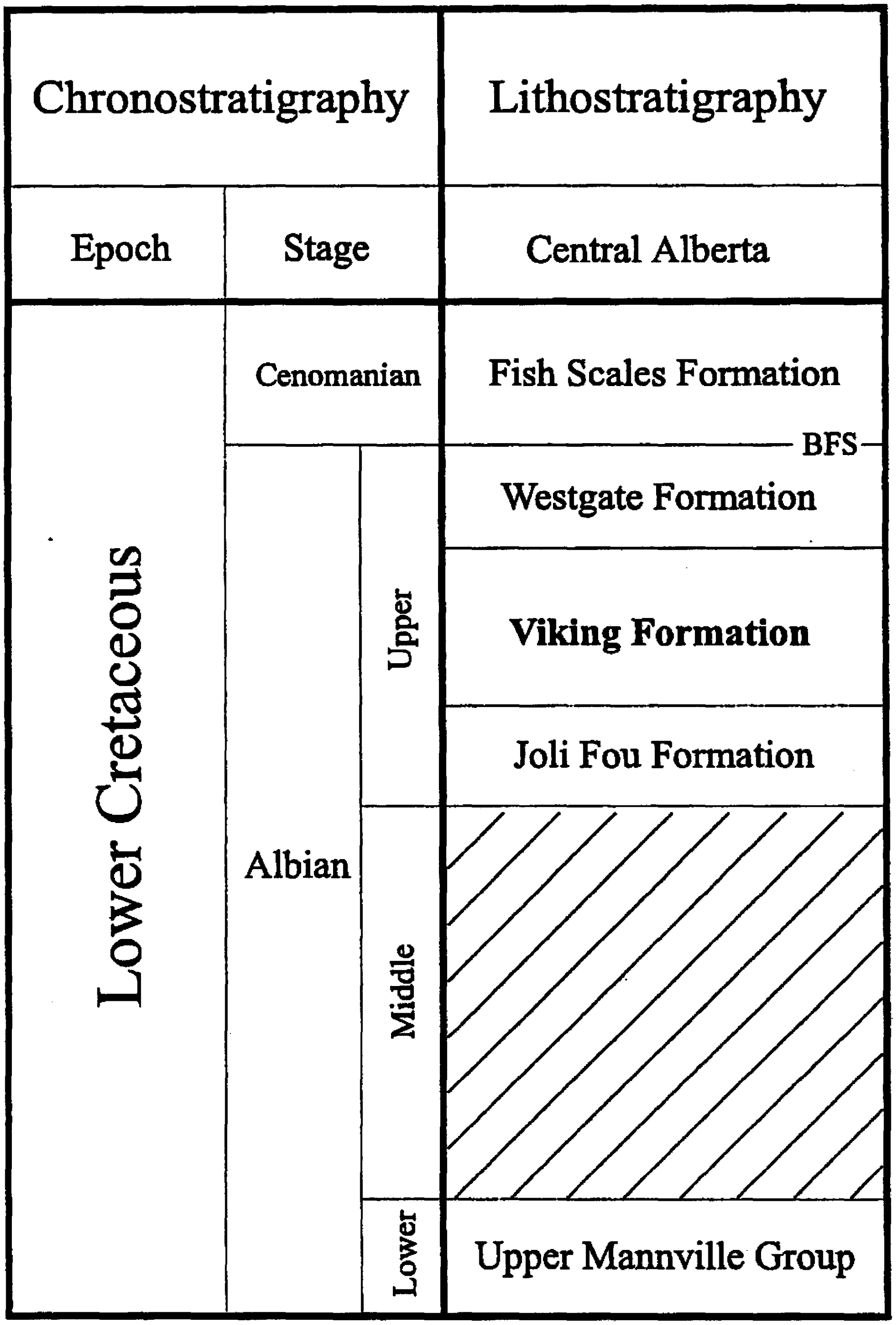


Figure 2.1 Chrono- and lithostratigraphic relationships of the Viking Formation in central Alberta.

conglomerates also occur as far east as Dodsland-Hoosier in southwest Saskatchewan. The Viking represents the regressive phase of the Kiowa-Skull Creek marine cycle (Caldwell, 1984). Viking equivalents (Fig. 2.2) include the following:

Bow Island Formation - SW Alberta
Newcastle Sandstone - Manitoba
Pelican Formation - NE Alberta
Paddy Member (Peace River Fm.) - NW Alberta/NE British Columbia
Walton Member (Boulder Creek Fm.) - NE British Columbia
Flotten Lake Sandstone - Saskatchewan
Vaughn-Bow Island Sandstone (Blackleaf Fm.) - Montana
Muddy Sandstone - Wyoming

There are no known locations of Viking outcrop, however equivalents such as the Pelican Formation and Bow Island Formation (known as Mill Creek Fm. in outcrop) are exposed at the surface in places.

2.1.3 The Westgate Formation

The Westgate Formation (Bloch et al., 1993) consists of marine shales deposited over the entire Western Canada Sedimentary Basin in response to a major relative sea level rise following Viking deposition. It formed during the initial stage of the Greenhorn transgression (Caldwell, 1984). This unit has also been referred to as the Lloydminster Shale, Colorado Formation or the Unnamed Shales. The Mowry Shale of Montana, Wyoming and the Dakotas is the U.S. equivalent.

The Westgate Formation ends at the Base of Fish Scales marker, which is a basin-wide condensed horizon. It contains abundant fish remains and represents deposition under poorly oxygenated bottom conditions (Leckie et al., 1994). This horizon marks the

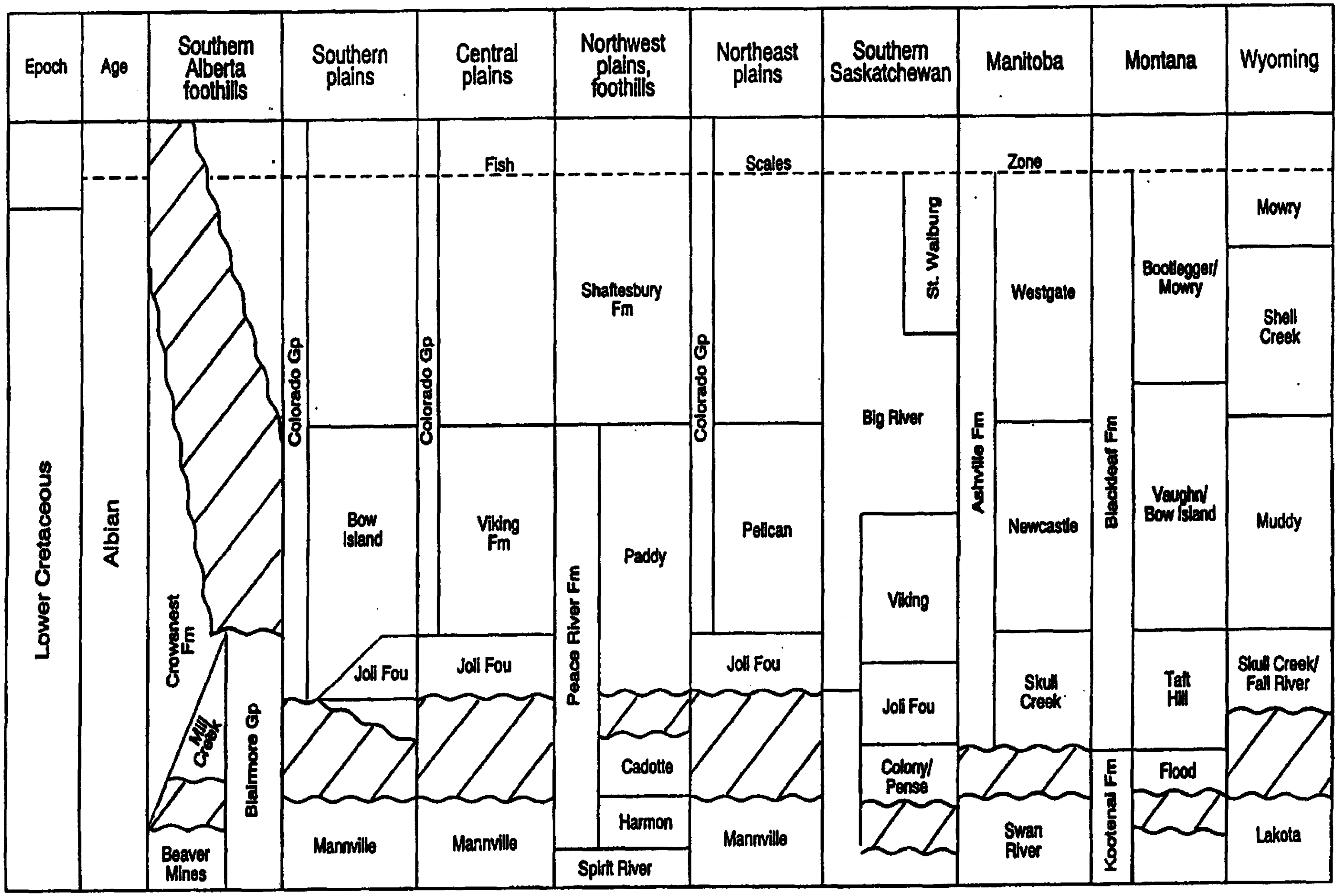


Figure 2.2 Viking Formation and stratigraphic equivalents. (after Reinson et al., 1994)

Albian-Cenomanian boundary.

2.2 Viking Biostratigraphy

Biostratigraphic analysis of the Viking in the past was hampered by a lack of preserved foraminifera. However, Viking equivalent sections in the upper Albian part of the Fort St. John group of northeastern B.C. have proven to contain a nearly continuous succession of silty shales, including a relatively well preserved arenaceous foraminiferal fauna (Stelck and Koke, 1987; Caldwell et al., 1993). Previously, the Joli Fou and Viking

<table>
<tr><th>Formation</th><th>Foraminiferal Zones</th><th>Foraminiferal Subzones</th><th>Substage</th></tr>
<tr><td></td><td></td><td>FISH SCALE MARKER</td><td>Cenomanian</td></tr>
<tr><td rowspan="3">Westgate</td><td rowspan="3">Miliammina manitobensis</td><td>Bulbophragmium swareni</td><td rowspan="10">Upper Albian</td></tr>
<tr><td>Haplophragmoides postis goodrichi</td></tr>
<tr><td>Verneuilina canadensis</td></tr>
<tr><td rowspan="4">Viking</td><td rowspan="7">Haplophragmoides gigas</td><td>Reophax troyeri</td></tr>
<tr><td>Trochammina umiatensis</td></tr>
<tr><td>Trochammina depressa</td></tr>
<tr><td>Reophax tundraensis</td></tr>
<tr><td rowspan="3">Joli Fou</td><td>Haplophragmoides gigas phaseolus</td></tr>
<tr><td>Haplophragmoides gigas gigas</td></tr>
<tr><td>Haplophragmoides uniorbis</td></tr>
</table>

Table 2. Foraminiferal zones and subzones identified in the Hasler Shale, northeastern B.C., related to their equivalent formations in central Alberta (modified after Caldwell et al., 1993).

Formations were simply assigned to the *Haplophragmoides gigas* zone, and the Westgate Formation was included in the *Miliammina manitobensis* zone (Caldwell et al., 1978). Stelck and Koke (1987) were able to subdivide the *H. gigas* zone into seven subzones (Table 2), the lowest three corresponding approximately to the Joli Fou interval, and the upper four corresponding to the Viking interval (Caldwell et al., 1993).

2.3 Absolute Age and Duration

The Viking Formation of southern Alberta was dated by Tizzard and Lerbekmo (1975) using a K-Ar technique on several bentonites within the formation. They obtained absolute ages between 94 - 105 M.a., but decided upon a single age of 100 ± 2 M.a. as the best date. Stelck and Koke (1987) obtained absolute dates above and below the *H. gigas* zone and combined this data with gross section thicknesses to obtain a duration of 1.5 M.a. for deposition of the upper four *H. gigas* subzones (equivalent to the Viking Fm.). They placed this interval roughly between 99 and 100.5 M.a. Caldwell (1984) provided an estimate of the duration of the entire Kiowa-Skull Creek cycle (i.e. Joli Fou and Viking Formations) of less than 4 M.a., but this was simply based upon time scales generated by other workers.

Recent estimates of entire late Albian time (Joli Fou, Viking and Westgate) have been published by Gradstein et al. (1995), who give a duration of approximately 3.3 M.a. (102.2 - 98.9 M.a.). Brolower et al. (1995) give a duration of about 7.1 M.a. (104.1 - 97 M.a.). If one assumes that the entire late Albian is divided evenly between the ten foraminiferal subzones of Stelck and Koke (1987) then each subzone represents between

330,000 and 710,000 years duration. Deposition of the Viking occurred during four subzones (Caldwell et al., 1993) and therefore a rough estimate of the duration of the Viking would be between 1.32 M.a. and 2.84 M.a. This agrees with the estimate by Stelck and Koke (1987) of 1.5 M.a. and by Power (1988) of 1-2 M.a.

2.4 Regional Structural Setting

The Viking Formation of central Alberta lies within the tectonically undeformed portion of the Western Canada Sedimentary Basin. The strata now dip at about 0.3° to the southwest and the Viking interval lies approximately 850 to 1450 m below the surface. No evidence of structural disturbance was found except for rare and highly localized micro-faulting (cm scale).

Major structural elements of the Alberta foreland basin include the Peace River Arch, the Sweetgrass (Bow Island) Arch and the edge of the deformed belt to the west (Fig. 2.3). The Peace River Arch began subsiding in the Mississippian and was probably still a basin during the upper Albian (Cant, 1988) and is therefore not likely to have been influential on sedimentation within this study area. The Sweetgrass arch was probably a positive feature during Viking deposition (Reinson et al., 1994) and may have greatly affected sedimentation in southeastern Alberta, possibly including eastern portions of this study area. The Sweetgrass Arch remained a positive feature unit at least Santonian time (Schröder-Adams, 1996).

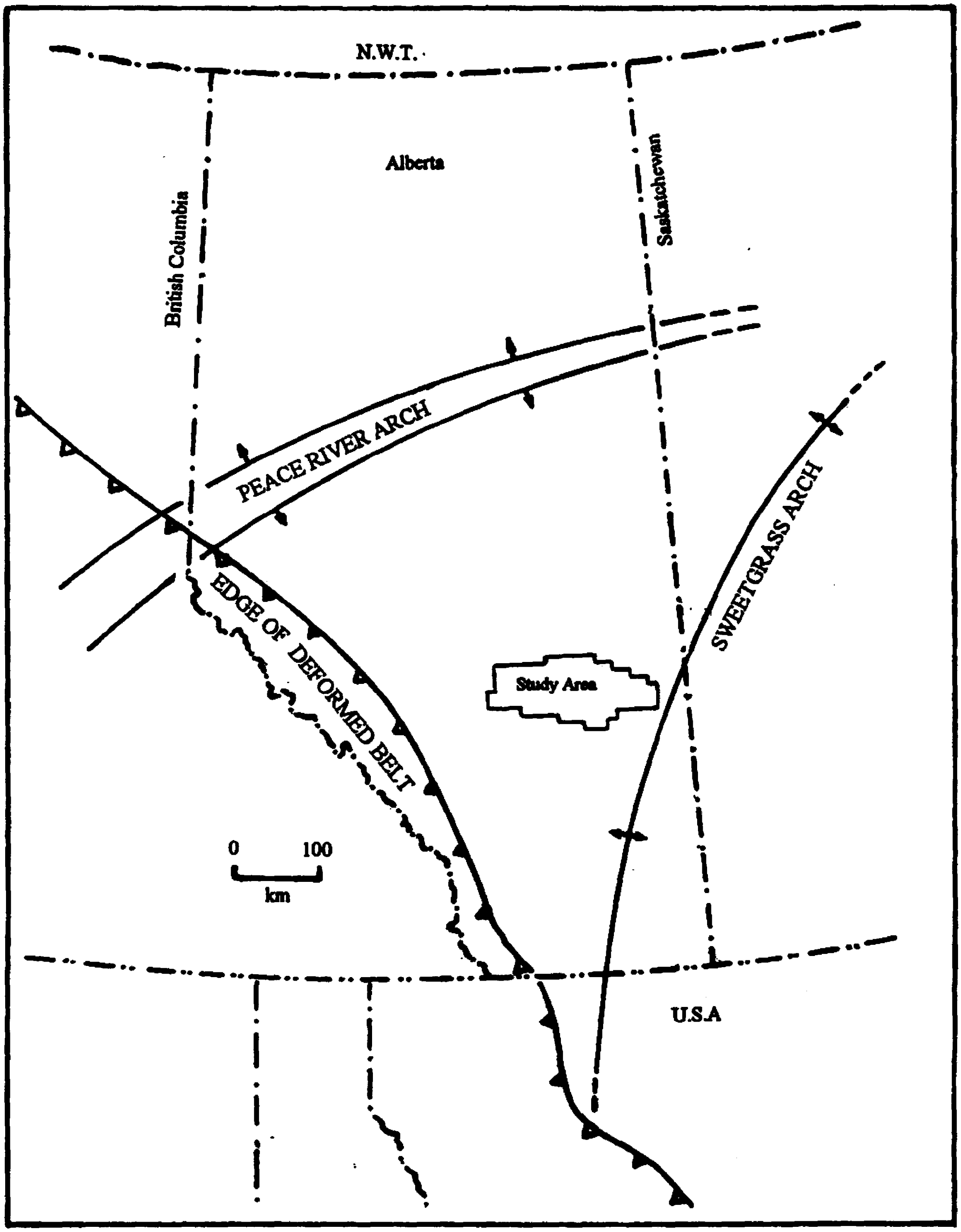


Figure 2.3 Major structural elements of the Western Canada Sedimentary Basin in comparison with study area location. (Modified from Wiseman, 1994)

CHAPTER 3: WELL LOG AND CORE CROSS-SECTIONS

3.1 Introduction

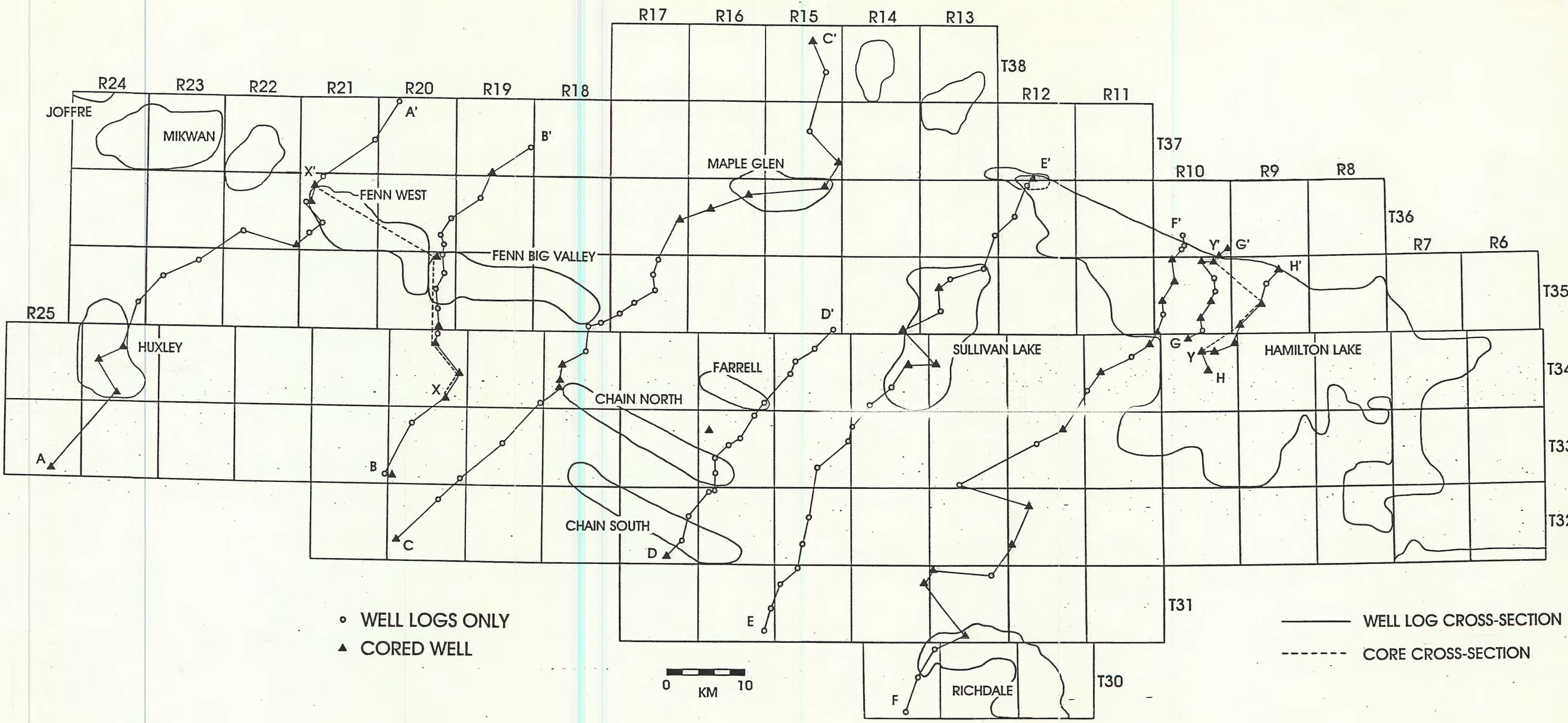
This chapter contains both well log and core cross-sections which were constructed in order to understand the subsurface geology of the Viking Formation within the study area. Correlations were made based upon well log signatures and comparison of sedimentary facies between cores. An organizational problem exists, because facies descriptions are needed to properly correlate the cross-sections, yet to place the facies in proper stratigraphic context, the cross-sections are needed. For the purpose of this thesis the cross-sections are presented first and sedimentological descriptions are presented in the following chapter, bearing in mind that both must be used concurrently to develop the regional stratigraphy.

Well log cross-sections consist of paired gamma ray (left) and resistivity (right) logs from each well (where available). Spontaneous Potential (SP) and sonic logs were occasionally substituted and have been marked accordingly. Logs from selected wells along a line of interest were first placed side by side in proper geographic order. Correlations were done by tracing and overlaying each adjacent well log so that individual log deflections and overall log shape could be matched, thus avoiding errors caused by 'eyeballing' the correlations. Core cross-sections were constructed utilizing information from the well log cross-sections and by matching distinct facies successions and contacts from the core itself.

Each cross-section must be hung on a stratigraphic datum, which should be easily recognizable, represent a nearly horizontal surface and be as close stratigraphically as possible to the Viking sandbodies. The flooding surface at the top of succession RV1 (Hamilton Lake Sandstone) has been chosen as a datum for all of the cross-sections presented in this thesis. This marker is easily picked over the entire study area, except where it has been locally eroded (and in this case an underlying log marker was used). Aside from the local erosion caused by subsequent events (BD1 or BD2), this flooding surface itself shows no marked erosion and is assumed to represent a relatively flat sea floor at the time of deposition. In reality there were probably gentle undulations and a shallow basinward dip on this surface.

Eight well log and two core cross-sections are presented (Fig. 3.1), which were reduced from a network of numerous working cross-sections (Fig. 1.2). These cross-sections were chosen because they best represent the vertical and lateral changes in geology within the study area. It should be noted that all presented cross-sections are oriented in a dip direction (SW-NE) because this is the direction with the greatest and most significant geological changes. The close spacing of adjacent working cross-sections in the strike direction (NW-SE) and numerous comparisons between them, permitted identification of key surfaces and facies successions from one cross-section to the next. Certain correlations are more apparent than others and therefore the following sections provide justification for the less obvious correlations. Figure 3.2 contains the legend of symbols used in construction of the core cross-sections.

Figure 3.1 Location map showing positions of well log and core cross-sections presented in this chapter with respect to Viking hydrocarbon fields.


R17
R16
R15
R14
R13
T38
R24
R23
R22
R21
R20
R19
R18
R12
R11
JOFFRE
MIKWAN
A'
B'
C'
T37
MAPLE GLEN
E'
R10
R9
R8
X'
FENN WEST
T36
F'
Y'
G'
H'
FENN BIG VALLEY
R7
R6
T35
R25
D'
HUXLEY
SULLIVAN LAKE
G
HAMILTON LAKE
FARRELL
Y
T34
H
X
CHAIN NORTH
T33
A
B
T32
CHAIN SOUTH
C
D
T31
E
WELL LOGS ONLY
CORED WELL
WELL LOG CROSS-SECTION
CORE CROSS-SECTION
0
KM
10
T30
F
RICHDALE

Legend

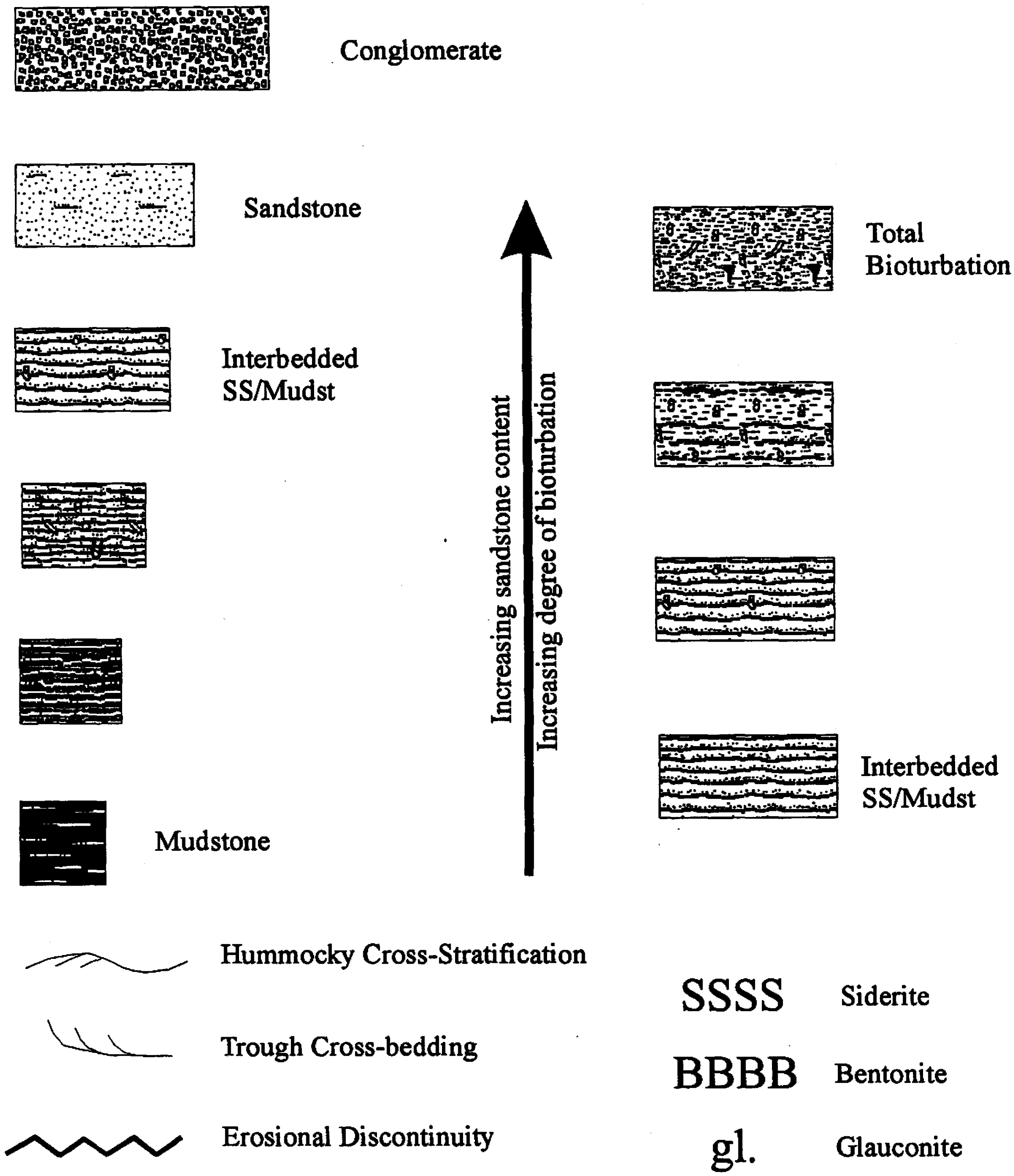


Figure 3.2 Legend used for core cross-sections X - X' and Y - Y'.

3.2 A - A'

Cross-section A - A' (Fig. 3.3) illustrates the subsurface geology between Huxley and Fenn West. The main sandstone at Huxley is contained within succession RV3 and is truncated vertically by BD3 and up-dip (NE) by the incision of BD1 in well 13-22-34-24. This incision is identified by the appearance of a 'shoulder' above the main sandstone. This 'shoulder' thins, and is completely removed by well 10-21-35-23. BD1 reappears in 4-35-35-23 and cuts downward stratigraphically towards the northeast, as evidenced by removal of regional log markers in 7-7-36-22 and 16-13-37-21. BD1 actually rises basinward (NE) between 16-13-37-21 and 15-32-37-20 at a gradient of about 8m/6km (0.08°). The main sandstone at Fenn West is prominent in the well logs, and lies above BD1. It is truncated vertically and up-dip (NE) by the incision of BD2 (IT), which first appears as a 'shoulder' above the main sandstone in well 1-17-36-21. BD2(RT) is first identified by the new 'shoulder' appearing below BD3 in 16-32-36-21. More of the succession above BD2(RT) is preserved in 16-13-37-21 and is characterized by two prominent log deflections (bentonites?). BD4 drops seaward (NE) along the entire section, culminating with the entire removal of the succession above BD3 and the uppermost of the two prominent log deflections above BD2(RT) between wells 16-13-37-21 and 15-32-37-20.

3.3 B - B'

Cross-section B - B' (Fig. 3.4) illustrates the subsurface geology from the

Figure 3.3 Cross-section A - A', composed of Gamma ray and Resistivity well logs. Oriented SW-NE from Huxley to Fenn West. Black bars indicate cored intervals.

A
A'
HUXLEY
FENN
10-3-33-25w4
10-4-34-24w4
6-20-34-24w4
13-22-34-24w4
14-12-35-24w4
10-21-35-23w4
4-35-35-23w4
7-8-36-22w4
8-1-36-22w4
7-7-36-21w4
1-17-36-21w4
14-19-36-21w4
16-19-36-21w4
4-32-36-21w4
16-32-36-21w4
16-13-37-21w4
15-32-37-20w4
VIKING ALLOFORMATION
WESTGATE FORMATION
BFS
BD4
BD3
BD1
BD2(IT)
BD2 (RT)
RV3
RV2
RV1
Datum
MxFS
JOLI FOU ALLOFM.
TOP MANNVILLE
0
m
25

southwestern margin of the study area to the sandbody at Fenn Big Valley. BD1 drops stratigraphically basinward, as evidenced by removal of regional log markers in 11-13-34-20, 2-23-35-20 and the datum in 10-13-36-20. BD1 rises basinward (NE) again between 2-4-27-19 and 1-13-37-19 at an average gradient of about 7m/6.5km (0.06°). The main sandstone at Fenn Big Valley lies above BD1 and is characterized by a gradual sandier upward log signature, with a bentonite at its base (prominent resistivity deflection, e.g. 16-35-35-20). The main Fenn sandstone is truncated vertically by BD2(RT) and up-dip (NE) by the incision of BD2(IT) between wells 16-35-35-20 and 12-1-36-20. Correlation of the BD2(IT) incision is based upon the loss of the gradual sandier upward log signature in 12-1-36-20. The BD2(RT) surface can be traced landward (SW) as far as 14-27-34-20 where it is truncated by BD3 as evidenced by the loss of the 'spike' above BD2(RT). Basinward (NE) the succession above BD2(RT) is again characterized by the two prominent log deflections (e.g. 1-29-36-19). All bounding discontinuities appear to rise stratigraphically basinward with respect to the datum northeast of 1-29-36-19. A prominent sandbody exists above BD4 between wells 11-13-34-20 and 8-2-35-20. This sandbody appears to 'shale out' seaward (NE) and is interpreted to onlap BD4 landward (SW) between 11-13-34-20 and 11-2-34-20. Erosion on BD4 is evidenced by removal of the prominent bentonite between 10-11-35-20 and 2-23-35-20.

3.4 C - C'

Cross-section C - C' (Fig. 3.5) illustrates the subsurface geology from the southwest, through Chain North and far to the northeast, beyond Maple Glen. BD1 cuts

Figure 3.4 Cross-section B - B', composed of Gamma ray and Resistivity well logs. Oriented SW-NE, from the southwestern study area to Fenn Big Valley. Black bars represent cored intervals.


B
B'
FENN
16-1-33-21w4
16-29-33-20w4
11-2-34-20w4
11-13-34-20w4
14-27-34-20w4
15-34-34-20w4
8-2-35-20w4
10-11-35-20w4
2-23-35-20w4
5-25-35-20w4
16-35-35-20w4
12-1-36-20w4
8-11-36-20w4
10-13-36-20w4
1-29-36-19w4
2-4-27-19w4
1-13-37-19w4
VIKING ALLOFORMATION
BEN
BD4
BD3
BD1
RSE
BD2
BD2 (RT)
BD2 (IT)
BFS
RV3
RV2
RV1
Datum
WESTGATE
FORMATION
CORE IN 10-35-35-20w4
JOLI FOU
ALLOFM.
MxFS
TOP MANNVILLE
0
m
25

downward stratigraphically to the northeast as evidenced by truncation of regional log markers at 8-21-33-19, 6-20-34-18 and local removal of the datum (6-22-35-17 to 10-34-35-17). The datum 'reappears' basinward (NE) as BD1 very gently rises stratigraphically (8m/30km or 0.015°). The asymmetrical incision of BD1(IT) between 6-20-34-18 and 5-27-34-18 is based upon the loss of characteristic regional log markers and replacement by a much sandier log response. The BD1(RT) surface is placed just below the prominent resistivity deflection (e.g. 6-2-35-18) which is interpreted to represent the characteristic bentonite at the base of the sandier upward main sandstone body at Fenn. A BD1(IT) incision is also speculated to exist northeast of 14-22-37-15, based upon other correlations in the Hamilton Lake (HMLK) area and a change in facies between the prominent sand 'spikes' of 7-12-37-15 and 10-27-38-15. As in section B - B', the incision of BD2(IT) in well 7-17-35-17 is based upon the loss of the underlying gradual sandier upward signature seen in well 8-7-35-17. Correlation of BD2(IT) between wells 6-22-35-17 and 6-27-35-17 was difficult because of subdued log profiles, but is based upon other sections which demonstrate that this surface commonly rises stratigraphically basinward (NE) after its inital incision. Tracing this surface basinward is difficult because its characteristic flooding surface is indistinguishable on the well logs and in core, suggesting that this surface has possibly become a correlative conformity (although one would still expect to see some representation of deepening). The prominent double log deflection does still exist above BD2 in places (e.g. 6-27-35-17, 14-22-37-15). Landward (SW) the BD2(RT) surface is truncated by BD3 as indicated by the loss of the 'shoulder' above BD2(RT) from 5-27-34-18 to 6-20-34-18. BD3 is truncated seaward (NE) between 10-34-35-17 and 11-13-36-17

Figure 3.5 Cross-section C - C', composed of Gamma ray and Resistivity well logs. Oriented SW-NE, from the southwestern study area, through Chain North, to beyond Maple Glen. Black bars represent cored intervals.

C
C'
14-7-32-20w4
6-27-32-20w4
6-1-33-20w4
8-21-33-19w4
8-1-34-19w4
CHAIN NORTH
12-8-34-18w4
3-17-34-18w4
6-20-34-18w4
5-27-34-18w4
6-2-35-18w4
14-1-35-18w4
8-7-35-17w4
7-17-35-17w4
6-22-35-17w4
6-27-35-17w4
10-34-35-17w4
11-13-36-17w4
10-20-36-16w4
10-26-36-16w4
7-35-36-15w4
7-12-37-15w4
14-22-37-15w4
7-14-38-15w4
10-27-38-15w4
VIKING ALLOFORMATION
BFS
WESTGATE FORMATION
BEN
BD4
RSE
BD1
BD3
RV3
RV2
RV1
DATUM
BD1(RT)
BD2
BD1(IT)
BD2(RT)
BD2(IT)
BD2(CC)
MxFS
TOP MANNVILLE
JOLI FOU ALLOFM.
0
m
25

as indicated by the loss of the sandier upward profile above BD3. The main sandstone of Chain North is found *above* BD4. The sharp based sandbody rests on mudstone and apparently 'shales out' basinward (6-20-34-18) and onlaps BD4 landward (SW) between 8-1-34-19 and 8-21-33-19. BD4 cuts downward stratigraphically in a basinward direction (NE) as evidenced by removal of the prominent bentonite in well 3-17-34-18.

3.5 D - D'

Cross-section D - D' (Fig. 3.6) illustrates the subsurface geology in a dip direction (SW-NE) across Chain South, Chain North and Farrell. As in previous sections, BD1 cuts downward stratigraphically to the northeast as evidenced by truncation of regional log markers in 8-31-32-16 and 14-32-32-16. The existence of the incision of BD1(IT) and overlying BD1(RT) in well 14-32-32-16 is based upon correlations from section C - C' and the more pronounced flooding surface of BD1(RT) further basinward (e.g. 11-35-33-16). The main sandstone at Farrell lies above BD1(IT) and cannot be traced between 12-1-34-16 and 14-17-34-15. It has either 'shaled out' up-dip (NE) or been truncated by BD1(RT). The succession above BD1(RT) is characteristically sandier upward. Northeast of Farrell this succession is truncated by BD2 as indicated by the presence of the double log deflection (e.g. 14-17-34-15) above BD2. Notice that an IT surface is not recognized for BD2 in this section. The double log deflection and BD2 are truncated landward (SW) by BD3 in 14-22-33-16, and basinward (NE) this interval is also thinned by erosion on BD3 (6-1-35-5). The reservoir sandstone at Chain North occurs above BD4. The sandbody rests sharply on mudstones and 'shales out' basinward (6-21-33-16).

Figure 3.6 Cross-section D - D', composed of Gamma ray and Resistivity well logs. Oriented SW-NE, from Chain South, through Chain North, to Farrell. Black bars represent cored intervals.

D
D'
CHAIN SOUTH
CHAIN NORTH
FARRELL
10-3-32-17w4
10-14-32-17w4
14-24-32-17w4
8-31-32-16w4
14-32-32-16w4
3-8-33-16w4
6-17-33-16w4
6-21-33-16w4
14-22-33-16w4
11-35-33-16w4
12-1-34-16w4
14-17-34-15w4
16-20-34-15w4
13-27-34-15w4
6-1-35-15w4
VIKING ALLOFORMATION
BFS
WESTGATE FORMATION
BD4
BEN
RSE
BD1
BD3
RV3
RV2
RV1
SP
DATUM
BD1(IT)
BD1(RT)
BD2
MxFS
TOP MANNVILLE
JOLI FOU ALLOFM.
0
m
25

It appears to onlap BD4 landward (SW) between 3-8-33-16 and 14-32-32-16. BD4 again shows downward stratigraphic cutting to the northeast as evidenced by the removal of the major bentonite in well 14-22-33-16.

3.6 E - E'

Cross-section E - E' (Fig. 3.7) illustrates the subsurface geology from the southwestern study area, through the middle of Sullivan Lake and into Hamilton Lake (HMLK). BD1 cuts stratigraphically downward to the northeast as shown by truncation of regional log markers in 16-32-31-15. The succession between BD1 and the immediately overlying horizontal correlation line, from 6-30-31-15 to 11-10-33-15, is equivalent to the BD1(IT) - BD1(RT) succession at Farrell, shown in section D - D'. The smooth horizontal correlation line is used because it is unclear whether or not there is erosion associated with this surface (which would be the correlative conformity of BD1(RT) at Farrell). The surface is picked just below the prominent deflection on the resistivity, possibly the characteristic bentonite which overlies BD1 (and BD1(RT)). Basinward BD1 is locally truncated by BD2 as evidenced by the loss of the sandier upward succession above BD1 and replacement with the double log deflection characterizing the post-BD2 succession (e.g. 10-19-34-13). The succession above BD1 is variably dissected by BD2 as can be seen between 14-8-35-13 and 6-28-35-13. The main sandstone at HMLK is found within the regional Viking at the top of RV1. There is a gradual increase in sandstone content within the HMLK sandstone from southwest to northeast. In well 2-4-37-12 BD1(IT) cuts into the HMLK sandstone. In the HMLK area, the top of the sandier up succession above BD1(IT) is clearly separated from a stratigraphically higher flooding surface correlated with BD2 and therefore the presence of a preserved BD1(RT) surface is suggested. It is also suggested that BD2 may become a correlative conformity this far northeastward, because of the greater preservation of underlying sediment and the lack of erosional evidence in core. The succession above BD2 is characterized by a sandier upward log shape. In places, however, this succession is dissected, and almost completely removed by BD3 (e.g. 7-2-35-14) or BD4 (e.g. 12-33-36-12). The uppermost sandier upward log shape in 7-2-35-14 and 14-8-35-13 is placed above BD3, as it compares most favourably with the upper of the two successions in adjacent wells 10-19-34-13 and 11-20-35-13. The incision of BD2(IT) in well 6-5-34-14 is based upon the abrupt incoming of a very large sandy 'spike' on the well log at this horizon. From this well to the next basinward well (13-10-34-14) the large log 'spike' has essentially disappeared, possibly due to 'shaling out' of the sandbody. The BD2(RT) surface continues landward (SW) and is truncated by BD3 (in 15-21-32-15) as evidenced by the loss of the sandier upward succession above BD2, which is replaced by the more subdued log signature from above BD3. The reason for truncating BD3 northeast of 11-10-33-15 by BD4 is based on similar and more obvious correlations from adjacent sections (D - D' and F - F') and the loss of the subdued, post-BD3 log profile. The reappearance of BD3 basinward (13-10-34-14) just below BD4 supports this correlation. BD4 once again shows significant downcutting to the northeast as evidenced by truncation of the major bentonite in 11-10-33-15 and truncation of BD3 in 10-12-36-13.

Figure 3.7 Cross-section E - E', composed of Gamma ray and Resistivity well logs. Oriented SW-NE, from the southwestern study area, through Sullivan Lake, to Hamilton Lake. Black bars represent cored intervals.

E
E'
13-1-31-16w4
10-13-31-16w4
6-30-31-15w4
16-32-31-15w4
11-9-32-15w4
15-21-32-15w4
11-10-33-15w4
10-24-33-15w4
16-25-33-15w4
6-5-34-14w4
13-10-34-14w4
11-23-34-14w4
10-19-34-13w4
7-2-35-14w4
14-8-35-13w4
11-20-35-13w4
6-28-35-13w4
1-35-35-13w4
10-12-36-13w4
3-20-36-12w4
12-33-36-12w4
2-4-37-12w4
SULLIVAN LAKE
HAMILTON LAKE
VIKING ALLOFORMATION
BFS
WESTGATE FORMATION
BD4
BEN
BD3
BD2
BD1
RV3
RV2
RV1
(RT)
(IT)
BD2(CC) ?
BD1(RT) ?
BD1(IT)
MxFS
TOP MANNVILLE
JOLI FOU ALLOFM.
0
m
25

3.7 F - F'

Cross-section F - F' (Fig. 3.8) illustrates the subsurface geology from Richdale to Hamilton Lake (HMLK). As in section A - A', the incision of BD1 in the southwest is identified by the appearance of a 'shoulder' below BD3 (6-23-30-14). BD1 then cuts stratigraphically downward to the northeast as evidenced by truncation of regional log markers in 2-35-31-13 and 11-7-32-12. BD1 is locally truncated by BD2, but a basinward incision of BD1 with a well developed overlying sandbody, 're-establishes' this surface in well 4-36-34-11 and subsequently in wells 10-7-35-10 through 11-9-36-10. Further incision on BD1 truncates the HMLK sandstone by 11-9-36-10. The BD2 surface has a small asymmetric incision, shown in well 11-26-33-12, which is based upon a similar relationship in section E - E' and the prominent well log 'spike' which corresponds to a thin conglomerate in core. The succession above BD2 is sandier upward and contains a prominent bentonite in wells between 6-4-33-13 and 11-7-34-11. This bentonite is not correlated with the bentonite in 10-29-32-12 (large log deflection) because there are clearly two bentonites, one above and one below BD2, as seen in well 6-4-33-13. The existence of two erosion surfaces above BD2 in well 10-29-32-12 is based upon recognition in core, and similar relationships observed in previous correlations. The truncation of BD2 landward (SW) of this well is suggested by the presence of only one erosion surface which is overlain by the characteristic log pattern and core facies of post-BD3 deposition (Allomember IV). Basinward (NE) BD3 shows erosion by gradually downcutting and completely removing the sandier portion above BD2, and then rising again to preserve the underlying sandy succession. BD3 is eventually truncated by BD4

Figure 3.8 Cross-section F - F', composed of Gamma ray and Resistivity well logs.

Oriented SW-NE, from Richdale to Hamilton Lake. Black bars represent cored intervals.

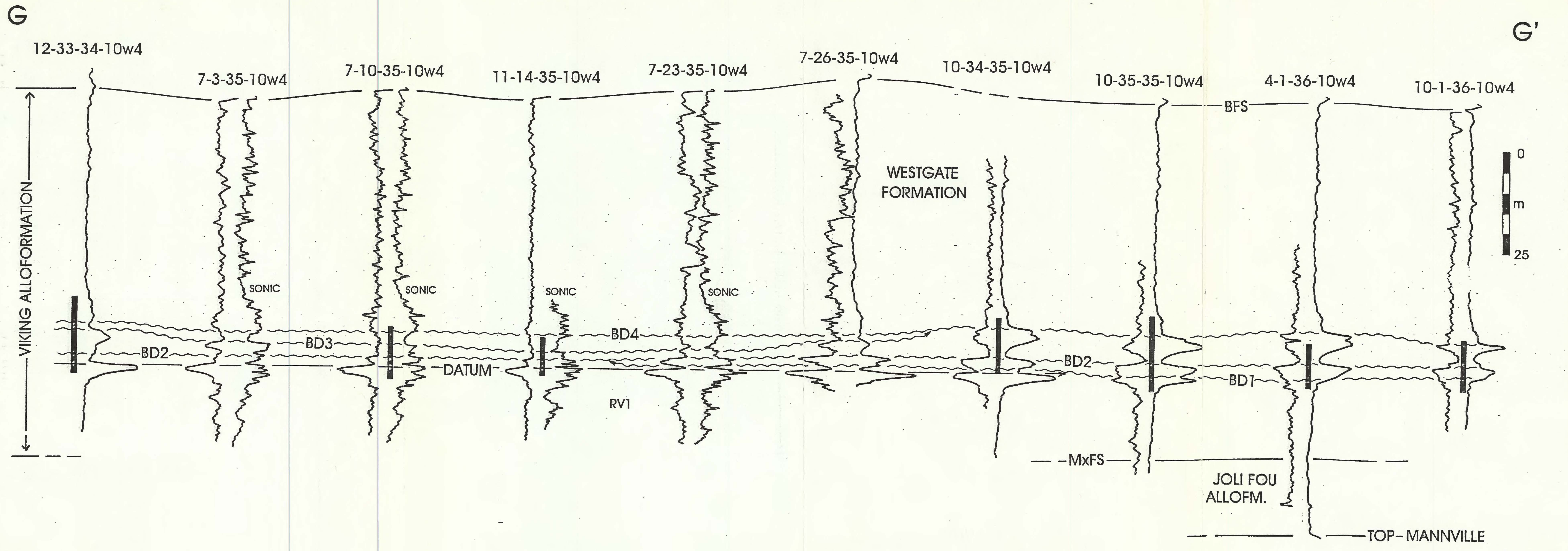
F
F'
RICHDALE
HAMILTON LAKE
11-3-30-14w4
6-23-30-14w4
10-36-30-14w4
10-4-31-13w4
10-25-31-14w4
11-31-31-13w4
2-35-31-13w4
11-7-32-12w4
10-29-32-12w4
6-4-33-13w4
6-21-33-12w4
11-26-33-12w4
11-7-34-11w4
3-20-34-11w4
7-27-34-11w4
4-36-34-11w4
4-6-35-10w4
10-7-35-10w4
10-18-35-10w4
2-29-35-10w4
14-32-35-10w4
12-4-36-10w4
14-4-36-10w4
11-9-36-10w4
VIKING ALLOFORMATION
BFS
WESTGATE FORMATION
BD4
BEN
BD3
BD1
RV3
RV2
RV1
DATUM
BD2
ONLAP
MxFS
JOLI FOU ALLOFM.
TOP MANNVILLE
0
m
25

between 2-29-35-10 and 14-32-35-10 as evidenced by removal of the muddy log response which overlies BD3 in the HMLK region. In the Sullivan Lake and HMLK area, there is some accumulation of sand above BD4 which appears to onlap BD4 in a landward direction (SW) between 6-21-33-12 and 6-4-33-12.

3.8 G - G'

Cross-section G - G' (Fig. 3.9) illustrates the subsurface geology in the Hamilton Lake (HMLK) area. The HMLK sandstone is the major sand 'spike' immediately below the datum. It is truncated to the northeast by incision of BD1. This incision is first seen in 7-23-35-10 as evidenced by the sudden appearance of the second sandstone 'spike'. The base of this second 'spike' is BD1, which cuts downward stratigraphically to the northeast. In well 7-26-35-10 there is mudstone preserved below BD1, but by 10-35-35-20 BD1 rests directly on the HMLK sandstone and by 4-1-36-10 the entire HMLK sandstone has been removed. BD2 is essentially flat lying along the length of the cross-section and is generally overlain by a muddy based, sandier upward succession which is the main sandstone interval of the Provost reservoir. In places, this succession is dissected by BD3 as shown by the gradual removal of the sandier upward succession from 12-33-34-10 to 11-14-35-10 and then its reappearance by 10-34-35-10. The very muddy log signal above BD3 is also gradually removed to the northeast, indicating truncation of BD3 by BD4 between wells 7-26-35-10 and 10-34-35-10. The 'ratty' fining upward log signal above BD4 represents a distal expression of the onlapping marker identified in section F - F'.

Figure 3.9 Cross-section G - G', composed of Gamma ray and Resistivity well logs. Oriented SW-NE, across the Hamilton Lake field. Black bars represent cored intervals.



G
G'
12-33-34-10w4
7-3-35-10w4
7-10-35-10w4
11-14-35-10w4
7-23-35-10w4
7-26-35-10w4
10-34-35-10w4
10-35-35-10w4
4-1-36-10w4
10-1-36-10w4
BFS
WESTGATE FORMATION
VIKING ALLOFORMATION
SONIC
SONIC
SONIC
SONIC
BD4
BD3
BD2
BD2
BD1
DATUM
RV1
MxFS
JOLI FOU ALLOFM.
TOP- MANNVILLE
0
m
25

3.9 H - H'

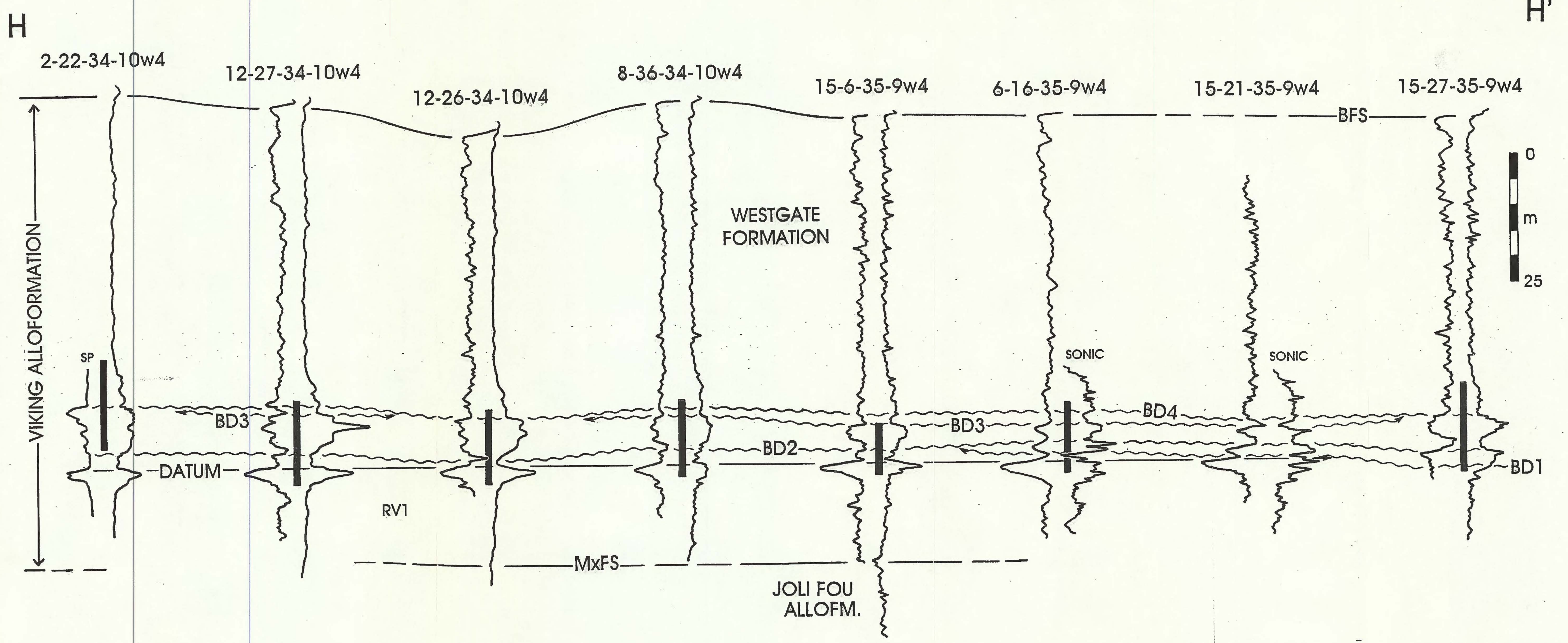
Cross-section H - H' (Fig. 3.10) also illustrates the subsurface geology in the Hamilton Lake area. The relationships in this section are nearly identical to those in G - G', the greatest difference being that BD3 shows less downcutting and therefore less of the muddy facies overlying BD3 is preserved.

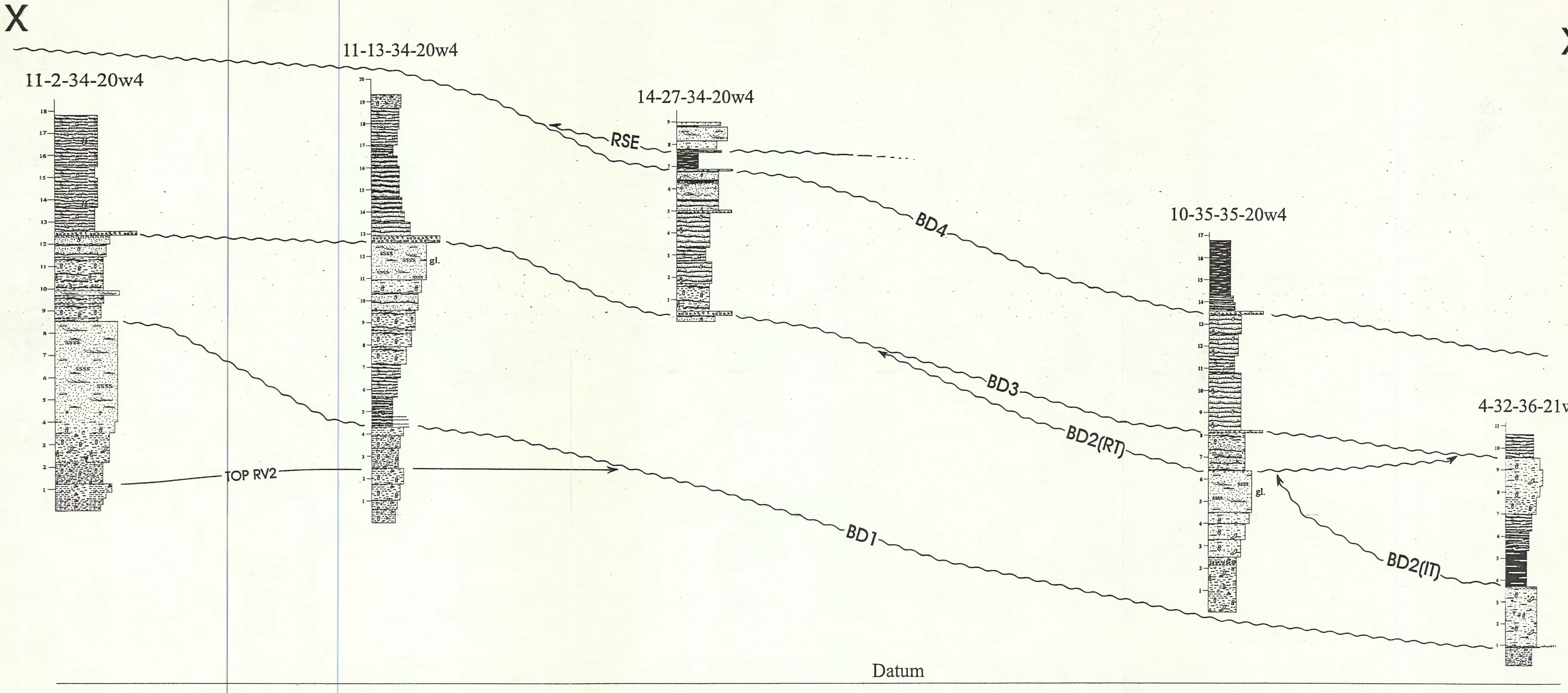
3.10 X - X'

Core cross-section X - X' (Fig. 3.11) illustrates the typical facies and bounding discontinuities in a dip direction across the linear sandbodies. Some of the measured sections illustrated in the cross-section are supported by the addition of colour photos from the boxed core.

BD1 cuts stratigraphically downward to the northeast, which can be seen by the loss of the well-developed cross-bedded sandstone from 11-2-34-20 to 11-13-34-20, and truncation of RV2 northeastward. The cross-bedded sandstone in 11-2-34-20 is typical of the reservoir facies at Chain South. BD1 is mantled by pebbles in 4-32-36-21 (Fig. 3.13) and scattered granules above the contact in 11-13-34-20. The sandier upward glauconitic, cross-bedded succession above BD1 (11-13-34-20 and 10-35-35-20) is characteristic of the reservoir sandstone at Fenn (Fig. 3.12). This succession is truncated up-dip (NE) by the incision of BD2(IT) in 4-32-36-21 (Fig. 3.13). The succession above BD2(IT) is characterized by a very muddy base which becomes sandier upward. Along strike at

Figure 3.10 Cross-section H - H', composed of Gamma ray and Resistivity well logs. Oriented SW-NE, across the Hamilton Lake field. Black bars represent cored intervals.


H
H'
2-22-34-10w4
12-27-34-10w4
12-26-34-10w4
8-36-34-10w4
15-6-35-9w4
6-16-35-9w4
15-21-35-9w4
15-27-35-9w4
BFS
0
m
25
WESTGATE FORMATION
VIKING ALLOFORMATION
SP
SONIC
SONIC
BD4
BD3
BD3
BD2
BD1
DATUM
RV1
MxFS
JOLI FOU ALLOFM.


X
X'
11-2-34-20w4
11-13-34-20w4
14-27-34-20w4
10-35-35-20w4
4-32-36-21w4
RSE
BD4
BD3
BD2(RT)
BD2(IT)
BD1
TOP RV2
gl.
Datum

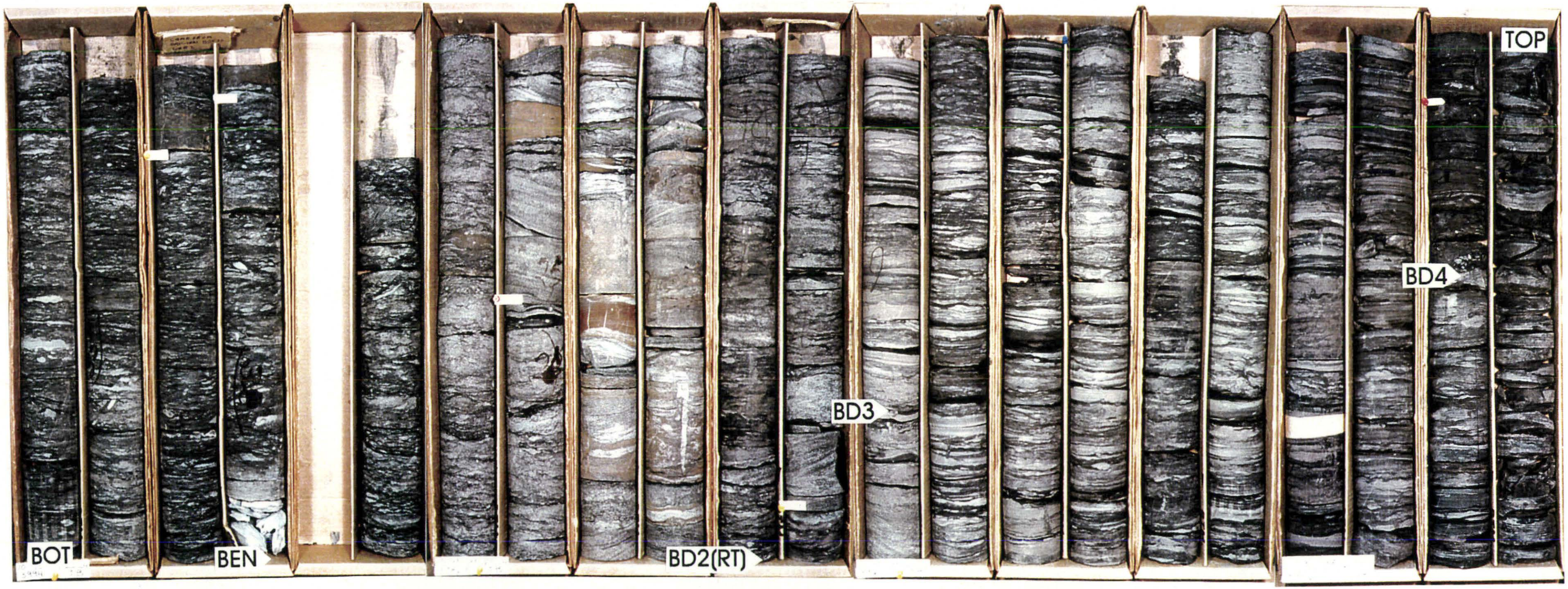


Figure 3.12 Core 10-35-35-20w4 (3994' - 3942'). Core is from onfield Fenn Big Valley. The main cross-bedded, glauconitic sandstone is part of the prograding shoreface succession above BD1 (BD1 below cored interval). This well is landward of the BD2(IT) incision. Note the presence of chert pebbles at BD3 and BD4. The contact of BD2(RT) has been cut. (3" core, 75 cm sleeves)

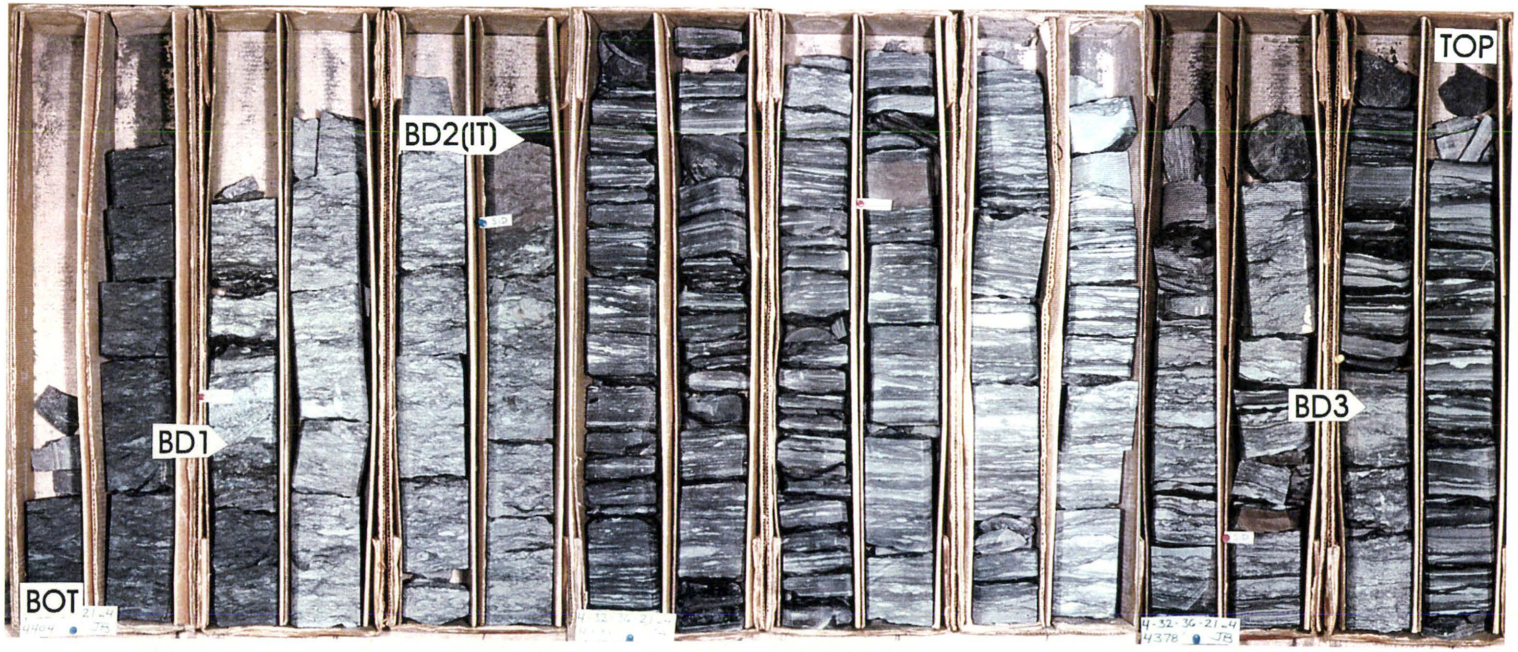


Figure 3.13 Core 4-32-36-21w4 (4404' - 4370'). Core is just northeast of Fenn West. The main sandstone of Fenn has been erosionally removed by incision of BD2(IT). Note the change from thoroughly bioturbated, fully marine sandstone to 'stressed' mudstone across BD2(IT). (3" core)

Figure 3.11 Core cross-section X - X'. Oriented SW-NE, illustrating facies relationships across the linear trend of fields (Joffre-Mikwan-Fenn-Chain N. & S.). Legend for measured sections from Figure 3.2.

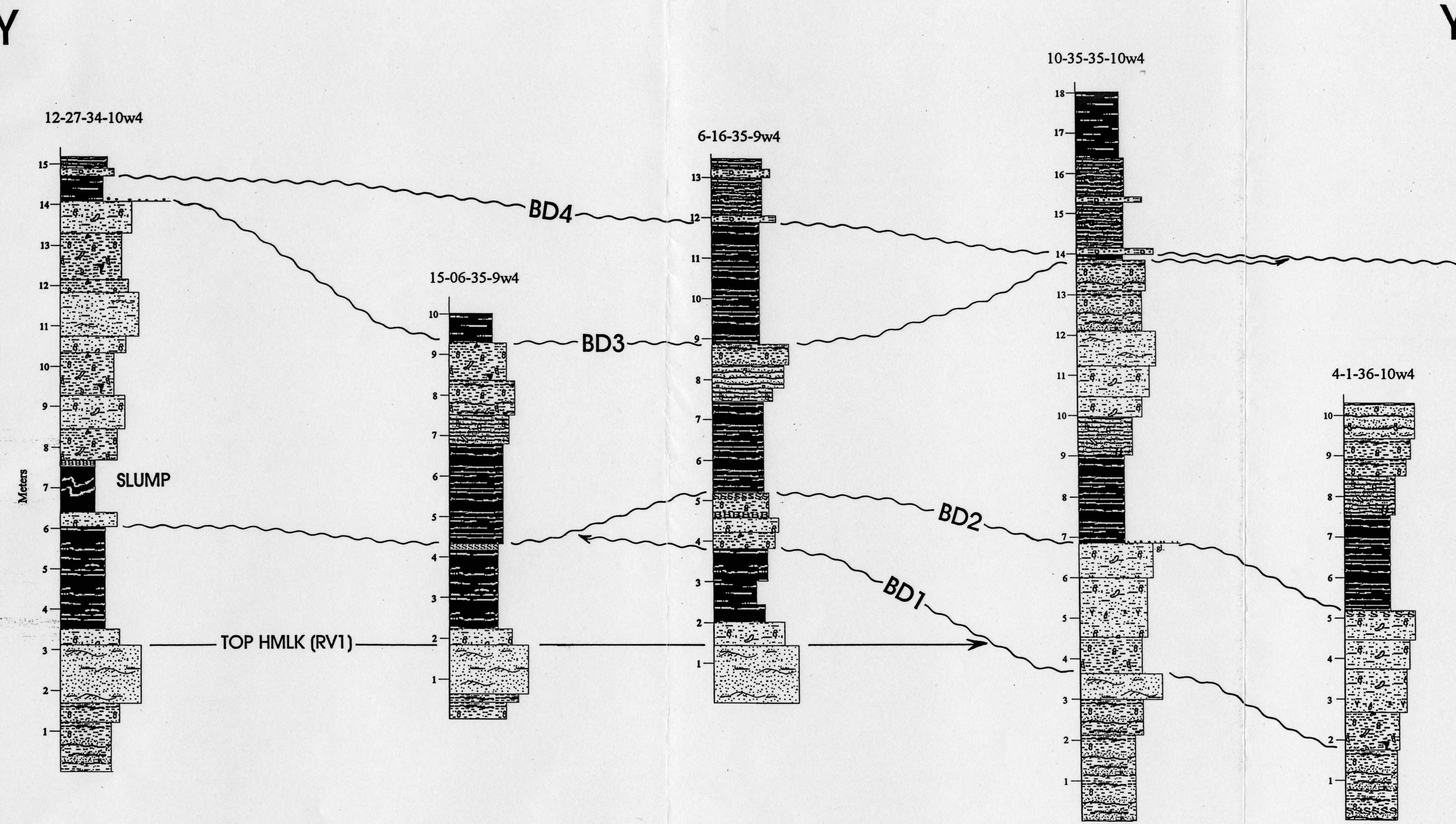
Figure 3.14 Core 14-27-34-20w4 (1194.5 - 1185.8m). Core is alongstrike (northwest) of Chain North. BD3 and BD4 are both mantled by chert pebble lags. The main sandbody consists of a sharp-based, cross-bedded sandstone resting on black mudstone above BD4. (4" core; 60 cm sleeves)

Joffre, this succession becomes conglomeratic and makes exceptional reservoir rock (Downing and Walker, 1988). This succession is truncated by BD2(RT), but in well 4-32-36-21, BD2(RT) has been truncated by BD3 as indicated by the interbedded facies characteristic of the succession above BD3 (Figs. 3.12, 3.13). The succession above BD2(RT) is only thinly preserved in the linear sandbody trend as seen in 10-35-35-20 (Fig. 3.12). BD3 is recognized by a well developed conglomeratic lag in all cores except 4-32-36-21, and is overlain by an interbedded facies. BD4 is also recognized by a sharp contact, with a pebbly lag overlain by black mudstones of the Westgate Formation (10-35-35-20; Fig. 3.12). However in well 14-27-34-20 (Fig. 3.14) a coarse cross-bedded, sharp-based sandstone unit overlies about 1 m of these black mudstones. The coarse layer appears to onlap BD4 to the southwest, but 'shales out' basinward (e.g cross-section C - C', between 8-21-33-19 and 6-20-34-18). This unit is characteristic of the sandbody at Chain North.

3.11 Y - Y'

Core cross-section Y - Y' (Fig. 3.15) illustrates the facies relationships and bounding discontinuities of the Hamilton Lake (HMLK) region. The HMLK sandstone is a relatively clean sandstone with well developed HCS, which is the producing interval of the HMLK field. This sandstone is truncated up-dip (NE) by the incision of BD1, which is first identified by the sudden appearance of a sharp-based, bioturbated muddy sandstone in well 6-16-35-9 (Fig. 3.16). The base of this sandstone (BD1) rests on mudstones above HMLK in well 6-16-35-9, but cuts stratigraphically downward to the northeast, resting directly on the HMLK sandstone in 10-35-35-10 and completely removing the HMLK sandstone by 4-1-36-10. BD2 is commonly very sharp, but there is little evidence of a lag, except the rare presence of coarse 'grit' or granules (10-35-35-10). The succession above BD2 is initially very muddy, but becomes sandier upward, in places displaying well developed HCS. This is the main sandstone of the Provost reservoir. The slumped section in 12-27-34-10 is likely a slumped equivalent of the thinly bedded mudstone in other cores. BD3 dissects this succession (6-16-35-9; Fig. 3.16) but rarely displays evidence of a coarse lag (e.g. 12-27-34-10). The mudstones above BD3 are quite distinct from those above BD4 and therefore it is easy to identify the truncation of BD3 by BD4 to the northeast. The lag above BD4 is characteristically bioturbated, 'gritty' and contains abundant scattered granules.

Figure 3.15 Core cross-section Y - Y'. Oriented SW-NE, illustrating the facies relationships across Hamilton Lake. Legend for measured sections from Figure 3.2.


Y
Y
12-27-34-10w4
15-06-35-9w4
6-16-35-9w4
10-35-35-10w4
4-1-36-10w4
Meters
SLUMP
BD4
BD3
BD2
BD1
TOP HMLK (RV1)

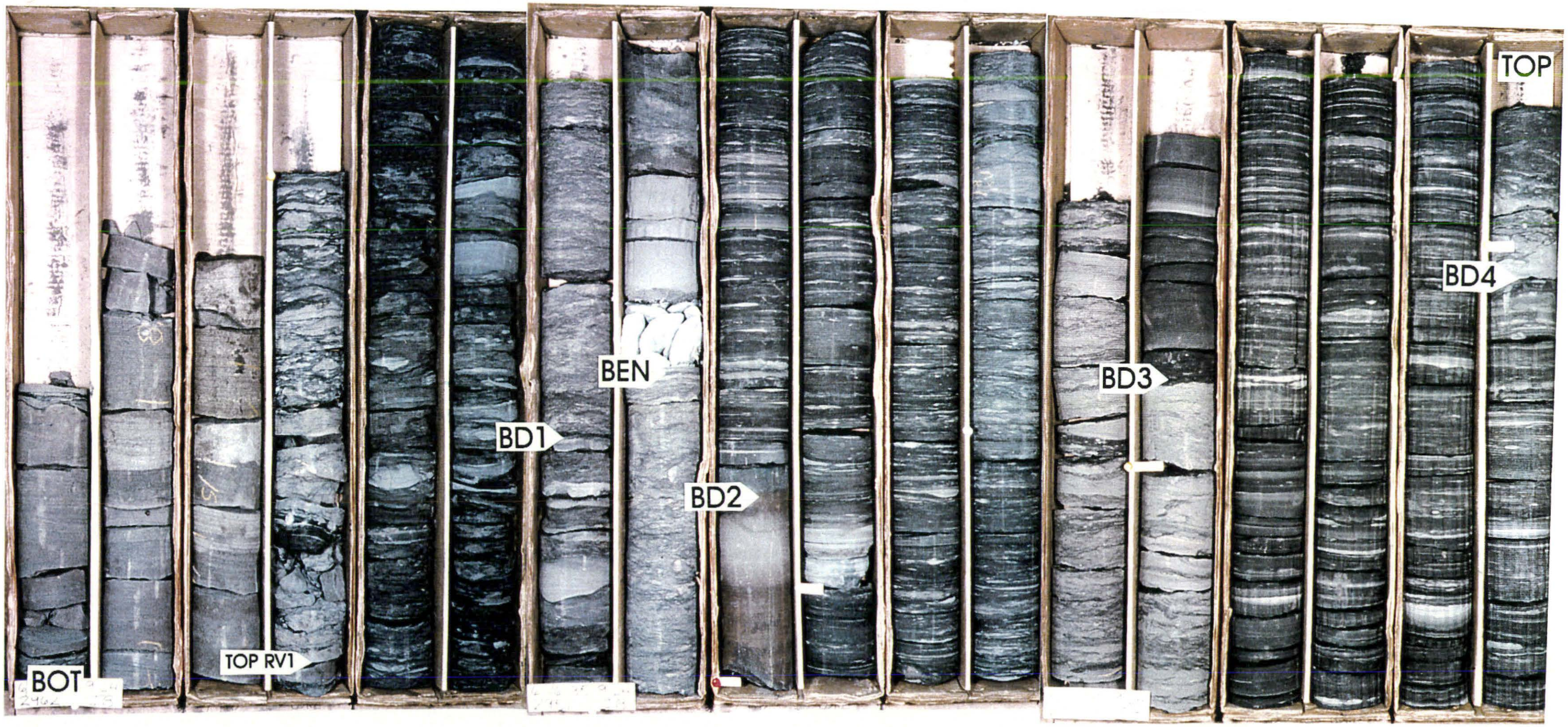


Figure 3.16 Core 6-16-35-9w4 (2962' - 2922'). Core is onfield Hamilton Lake. The main sandbody is the HCS sandstone at the bottom of the core. The BD1 incision is overlain by a thoroughly bioturbated, muddy marine sandstone. Note the knife sharp contact of BD3 with no coarse lag, and the equally sharp BD4 contact with a bioturbated 'gritty' lag. (3" core; 75 cm sleeves)

CHAPTER 4: SEDIMENTOLOGICAL DESCRIPTIONS AND INTERPRETATIONS OF ALLOMEMBERS

4.1 Introduction

In this chapter, the sedimentological characteristics of each allomember will be described, and a brief interpretation of the depositional environment suggested. Descriptions will comprise the physical and biogenic (trace fossils) sedimentary structures, grain size and sand content, and any trends observed within these variables. Bounding discontinuities will be described in detail, including development of firmground assemblages, coarse lags and possible siderite cementation below the contact. Each allomember will be described separately, and commonly will be divided into separate descriptions based on spatial criteria. The study area is about 100 km across in an approximate dip direction (SW-NE), resulting in considerable facies changes within individual allomembers.

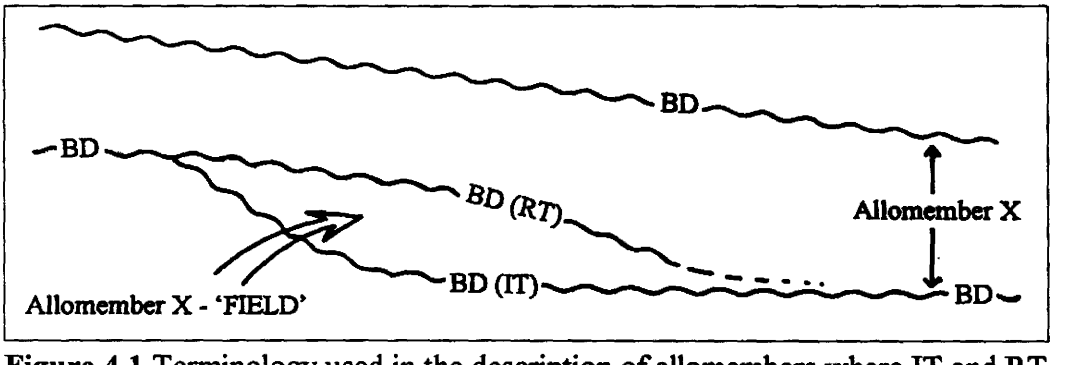


Figure 4.1 Terminology used in the description of allomembers where IT and RT surfaces are involved.

Description of allomembers is further complicated by the presence of Initial Transgressive (IT) and Resumed Transgressive (RT) surfaces (Fig 4.1). During a pause in an overall transgression, sediments are commonly deposited in the shoreface, above the IT surface. When trangression resumes, some of these sediments are preserved and some are 'planed off' by the RT surface. Following the resumed transgression more sediment may be deposited above the RT surface. Both 'packages' of sediment above and below the RT surface are considered part of the same allomember (Fig. 4.1) but may be quite different in their sedimentological characteristics and will be described separately in the following chapter. The succession between the IT and RT surfaces will be referred to as "Allomember # - Field name" (eg. Allomember II - Farrell; Fig. 4.1). The succession above the RT surface is related to the rest of the allomember in that area (i.e where there are no IT/RT surfaces) and is therefore described with the rest of that allomember.

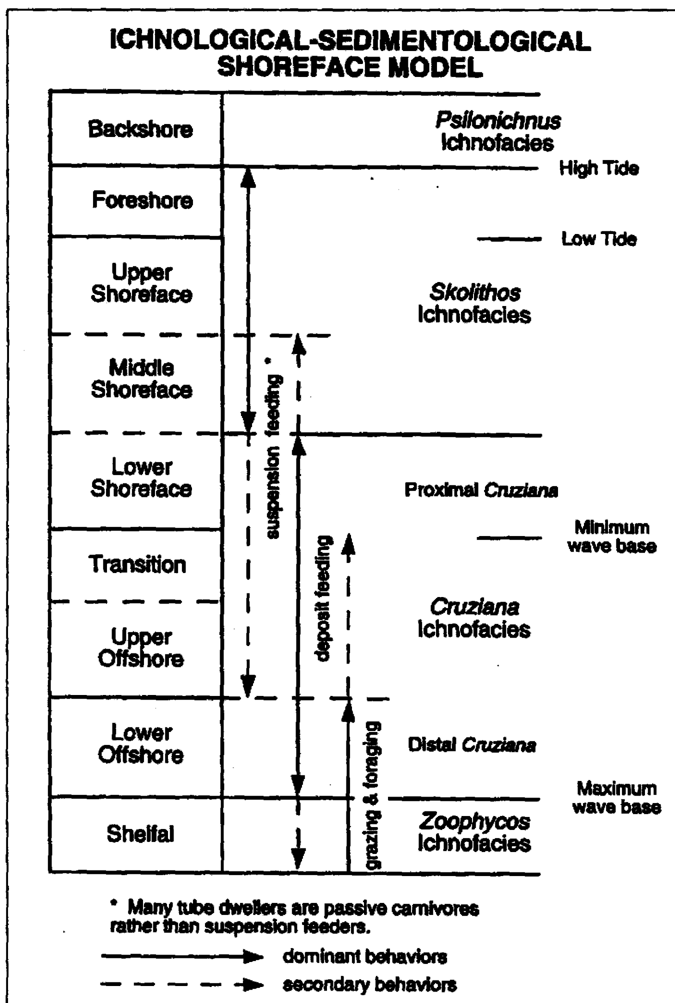


Figure 4.2 Idealized model of shallow marine ichnofacies successions (Pemberton and MacEachern, 1995).

Interpretations of

allomembers in this chapter will be restricted to a brief identification of the most likely depositional environment from the description provided. Full interpretations must be based on a more complete set of data including sedimentology, facies relationships and geometry of bounding discontinuities. The interpretations put forward in this chapter will be based upon ichnological and sedimentological characteristics, following the idealized shallow marine model of ichnofacies successions (Fig. 4.2) of Pemberton and MacEachern (1995). Deciding which category within Figure 4.2 to place a certain facies is never 'black and white', as there are very few trace fossils or sedimentary structures which alone suggest an exact position in the shallow marine environment. The term 'shelfal' in this scheme also needs some explanation, as the Western Canada Sedimentary Basin is considered to be a ramp type setting, with no shelf per se. Shelfal in this scheme refers to a distal offshore setting, well below fair weather wave base and probably approaching storm wave base.

4.2 Sedimentological Descriptions and Interpretations

4.2.1 Joli Fou Formation

The Joli Fou is bounded at its base by the major flooding surface overlying the Mannville Group. Conventionally the top of the Joli Fou Formation is picked at the first prominent rightward deflection of the resistivity log above the subdued log profile typical of the Joli Fou Formation (Boreen and Walker, 1991). Because the Viking Alloformation, with several allomembers, is defined in this thesis, it is also necessary to define the Joli Fou

Alloformation. Its top in this study is picked from well log signatures at the point of lowest resistivity or highest conductivity (Fig. 4.3). This is interpreted to represent the shaliest part of the Joli Fou - a candidate for the maximum flooding surface. With this definition the thickness of the Joli Fou Alloformation ranges from about 13 to 21 m, in general becoming thicker to the east.

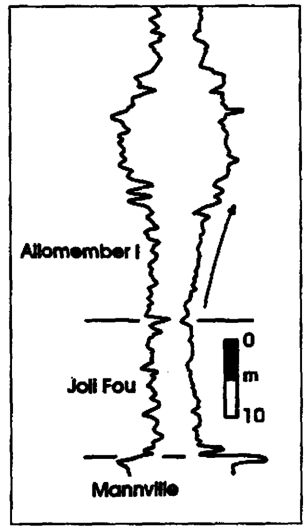


Figure 4.3 Typical well log signature of the Joli Fou Alloformation

Interpretation:

The Joli Fou is not cored in the study area but is interpreted as a marine shale based on its well log signature, stratigraphic position (below the marine regional Viking), regional extent and other authors' interpretations (Leckie et al., 1994).

4.2.2 Allomember I - Regional Viking

The Regional Viking (RV) sediment consists of stacked, coarsening upward successions capped by flooding surfaces. At any one place, a stack can contain 3 to 6 successions depending on the scale of subdivision. For simplicity, the regional Viking will be divided into 3 successions RV1, RV2 and RV3 (Fig. 4.4). The overall thickness of the regional Viking varies from 12 to 43 m, but this is dominantly influenced by erosion into the regional

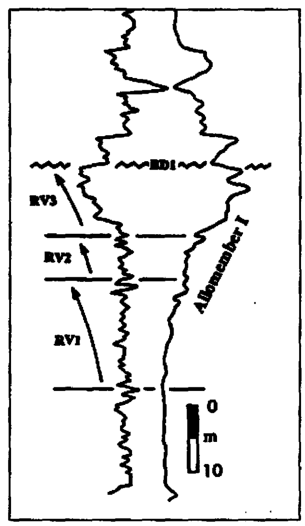


Figure 4.4 Typical well log signature of Allomember I.

Viking on surfaces BD1 and BD2.

Succession RV1

Where the entire thickness of RV1 is preserved it ranges from 13 to 21 m, generally increasing towards the southeast. RV1 is characterized by a sandier and coarsening upward succession, and contains the producing sandstone of the Hamilton Lake field, which is described separately. The succession is described in three parts including a lower, middle and upper portion.

The lower portion of RV1 would be considered part of the Joli Fou Formation in previous definitions. It becomes very slightly sandier upward and consists of black to grey mudstone with very rare silty laminations which are commonly very glauconitic. Scarce pyritized laminations may also be present and fish scales are present in places. Bentonites up to 30 cm thick may occur throughout. Bioturbation is very rare, but the traces *Helminthopsis* and *Planolites* were noted. The lower portion of RV1 grades into the middle portion of RV1 at the first prominent deflection to the right on the resistivity log. The succession grades upward from dominantly mudstone to sandy mudstone. The sand in the succession is typically vfU, but coarser individual grains up to mL occur towards the top. The unit is almost totally bioturbated by a marine assemblage of trace fossils including *Terebellina, Planolites, Teichichnus, Arenicolites, Zoophycos, Paleophycus* and small *Skolithos*. In places undulatory parallel laminations are preserved. Glauconite is present but not abundant throughout the succession. The upper portion of RV1 is similar to the middle portion, but is much sandier. One major bentonite (10-25 cm) is present in the upper portion of succession RV1. The upper contact is a gradational flooding surface into the overlying succession, RV2.

Interpretation:

The presence of glauconite and fish scales within the mudstone of the lower portion of RV1 suggests a shelfal marine environment. Upwards the succession gets sandier and coarser indicating progradation of offshore facies. The dominance of horizontal burrows of grazing and deposit feeding organisms indicates a *Cruziana* or distal *Cruziana* ichnofacies, corresponding to lower-upper offshore conditions (Fig. 4.2). Sandstone was likely deposited by storm generated currents, as indicated by rarely preserved wave formed sedimentary structures in sharp-based sandstone beds.

Hamilton Lake Sandstone (within RV1)

In the area of Hamilton Lake field the top of RV1 is much sandier than elsewhere in the study area. The succession is characterized by alternating sandstones and mudstones, both bedded and biogenically homogenized, with a gradational passage upward into well developed hummocky cross-stratified (HCS) sandstones (Fig. 4.5).

The lower portion of this succession, corresponding to the lower portion of RV1, was not observed in core within the study area. The middle portion of this succession (equivalent to the middle portion of RV1) becomes sandier upward, and consists alternately of preserved sandstone and mudstone beds, and totally bioturbated sections. Sandstone beds average 1-2 cm (max. 5 cm) in thickness and are typically sharp based with flat to undulating, parallel laminations. The sandstone is typically vfU, but varies between vfL and fL. Mudstone beds up to 10 cm are preserved. Bioturbated sections commonly contain traces of *Planolites, Terebellina, Skolithos, Zoophycos, Diplocraterion* and *Schaubcylindrichnus*, with rarer traces including *Chondrites, Paleophycus, Arenicolites, Siphonichnus* and *Helminthopsis*. This middle portion contains moderate to abundant glauconite and common sideritized zones up to 25 cm thick. A bentonite layer up to 6 cm thick is sometimes present.

The middle part of this succession grades upward (over about 50 cm) into the much sandier upper portion which is 0.45 - 2.48 m in thickness (avg. 1.3 m). The upper portion contains approximately 80 - 90 % sandstone with low angle, flat to gently undulating laminations (Fig. 4.5). Numerous low angle intersections and truncations of these laminations occur within the sandstone beds and are interpreted to represent HCS. Ripped up mud clasts are found at the base of some HCS beds. These beds or amalgamated bed sets reach 30 cm in thickness and are separated by mudstone beds up to 6 cm thick (average 1-2 cm). Sand is typically vfU to fL and contains small amounts of glauconite toward the base of this section. Most of the HCS beds are devoid of bioturbation but *Schaubcylindrichnus* and *Paleophycus* occur rarely, and *Rhizocorallium, Terebellina, Zoophycos* and *Diplocraterion* occur very rarely. *Planolites* is commonly found in the mudstone partings. A bentonite or very bentonitic sandy interval, up to 15 cm thick, is preserved in some locations within the sandstone. Away from the Hamilton Lake area, this succession becomes increasingly muddy laterally. HCS beds become thinner and more bioturbated with additional traces such as *Helminthopsis, Chondrites* and *Cylindrichnus* appearing. Eventually the unit grades laterally out into RV1 as

Figure 4.5 A) Well developed HCS of the Hamilton Lake sandstone (RV1) overlain conformably by RV2. 3" core from 12-33-34-10w4 (2940'-2927'). B) Detail of HCS, showing internal truncations of laminae (12-33-34-10w4; 2937').

described above.

The upper contact of the Hamilton Lake Sandstone is characterized by a bioturbated mixture (50/50) of sandstone and mudstone, 15-40 cm thick (Fig. 4.5). In places sandstone beds may be preserved, but typically the sediment is thoroughly bioturbated with traces including *Planolites, Terebellina, Skolithos* and rarely *Zoophycos* and *Teichichnus*. Sandstone grain size is commonly vfU/fL, but in places becomes coarser, reaching fU sand with rare granules or pebbles up to 15 mm in diameter. Rare wood fragments may also be found at this contact, which is interpreted as a flooding surface.

Interpretation:

The sandier nature, and greater preservation of physical sedimentary structures of RV1 in the Hamilton Lake area suggests a more proximal environment than RV1 in the rest of the study area. The middle portion is interpreted as lower-upper offshore conditions (based on its similarity to middle RV1 elsewhere) and the gradational transition into the upper sandy portion also suggests gradual progradation of more proximal marine conditions. The dominance of HCS and ripped-up mudstone clasts implies that the upper sandy portion was emplaced by sporadic storm generated currents in a transition-lower shoreface setting (Fig. 4.2). This interpretation is supported by a *Cruziana* ichnofacies comprising traces from a mixture of deposit and suspension feeding organisms.

Succession RV2

RV2 lies directly above RV1 and represents an overall sandier upward succession.

Within this succession there can be multiple smaller successions, especially towards the top where two such small (but prominently sandier-up) successions form characteristic regional well log markers. The base of the unit is commonly cored in the Hamilton Lake region, but the top is only rarely observed in core elsewhere in the study area. RV2 is 5 to 9 m thick where entirely preserved, and also appears to increase in thickness toward the southeast.

RV2 begins with a distinctive and easily identifiable mudstone, which reaches its maximum muddiness approximately 60 cm from the base. The mudstone is typically bentonitic and commonly contains sharp based sandstone beds. These beds are composed of vfL sand with flat to undulating, parallel laminations. Sandstones are typically a few centimeters in thickness (max. 11 cm), but are quite irregular in shape, commonly appearing lenticular. Bioturbation within this portion of the unit is scarce but distinct. Some of the sandstones contain numerous robust *Helminthopsis,* and the entire bed thickness is sometimes penetrated by unidentified vertical mud filled shafts. The mudstones rarely contain traces of *Terebellina* and *Planolites*. A thick siderite (max. 26 cm) is sometimes found above the muddiest part of this section. The style of bioturbation, the bentonitic mudstone and the lenticular sandstone beds combine to produce the distinctive aspect of this unit, making a good horizon for correlation between cores.

The upper portion of the RV2 succession becomes gradationally sandier upward. It is characterized by two smaller sandier up successions, the upper one becoming the sandiest. Both successions are almost totally bioturbated with only rare sandstone beds preserved (max. 4.5 cm thick). These sandstone beds show flat to undulating parallel laminations and have sharp bases. The sand is commonly vfL/vfU. Trace fossils include *Planolites, Helminthopsis, Terebellina, Chondrites, Teichichnus, Zoophycos* and *Rosselia*. Towards the top of the upper succession *Skolithos* and *Diplocraterion* burrows up to 20 cm deep are common. Thin bentonites (max. 2 cm) can be found towards the base of either of the small successions. The upper contacts are gradational flooding surfaces (over about 5 cm).

In northeastern parts of the study area, towards Hamilton Lake, the upper portion of RV2 becomes even sandier, with greater preservation of physical sedimentary structures. Sandstone beds up to 10 cm are preserved with low angle, flat to undulating laminations showing prominent internal truncations (interpreted as small scale HCS). Thin (1 cm) mud partings may also be preserved and intervals of total bioturbation occur with the same assemblage of traces described in the previous paragraph.

Interpretation:

Succession RV2 is interpreted as representing similar conditions to those of RV1. In this case there are two small progradational marine successions within RV2. The only difference from RV1 is that the top of RV2 contains abundant traces of suspension feeders in addition to deposit feeders, possibly indicating upper offshore-transition conditions (Fig. 4.2).

Succession RV3

RV3 lies stratigraphically above RV2 and consists of an overall sandier upward and coarsening upward succession with minor muddier sections. This unit characteristically grades from thoroughly bioturbated mudstones, to dominantly sandstone containing abundant physical sedimentary structures (Fig. 4.6). A number of hydrocarbon bearing fields are productive from the sandier portions of this succession including Huxley, Chain South, and Richdale. Its thickness is controlled by erosion on BD1 and BD2 and is up to 25 m thick.

RV3 begins with dark, totally bioturbated, bentonitic mudstone with little sand (vfL). Traces in this lower portion are abundant and diverse, including *Terebellina, Planolites, Schaubcylindrichnus, Teichichnus, Chondrites, Helminthopsis, Anconichnus, Skolithos, Asterosoma, Zoophycos, Cylindrichnus, Siphonichnus* and *Rosselia*. The unit becomes sandier upward. At four to five meters above the base there is commonly a thin (1 cm) bentonite which is directly overlain by a thin (up to 2 cm) sideritized zone. The unit continues to become sandier upward and coarsens to vfU or fL sandstone. Physical sedimentary structures also begin to be preserved, with 2 - 3 cm thick, sharp based sandstone beds characterized by flat to undulating, parallel laminations. Upwards the unit becomes dominantly sandstone with beds up to 25 cm thick that contain either angle of repose trough cross-bedding or low angle HCS. There are also some ripped-up mudstone clasts. Rare beds of sandstone appear to be structureless or contain very faint internal laminations. Preserved mudstone beds may reach 4 cm, but typically mudstone occurs as thin wispy partings obliterated by bioturbation. The assemblage of trace fossils also changes upward, decreasing in abundance and diversity. Traces include *Ophiomorpha, Skolithos, Paleophycus, Asterosoma* and *Macaronichnus simplicatus* (Fig. 4.7), with *Conichnus* rarely observed. *Planolites* are found in the mudstone partings. The sand may

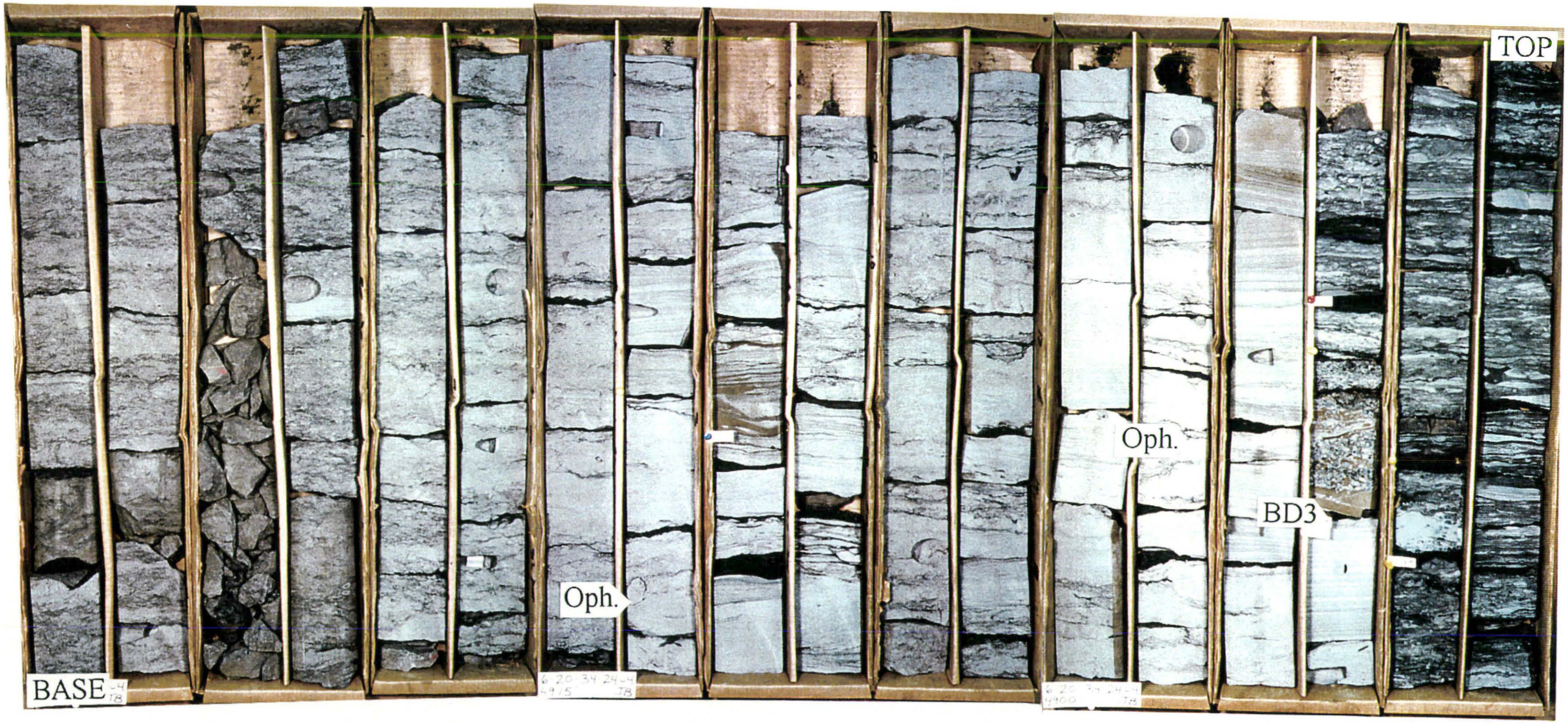


Figure 4.6 Example of succession RV3, onfield Huxley. BD3 separates RV3 (Allomember I) from Allomember IV. Core from well 6-20-34-24w4. Core is 3" in diameter and each sleeve is 75 cm in height. Oph. = *Ophiomorpha*.

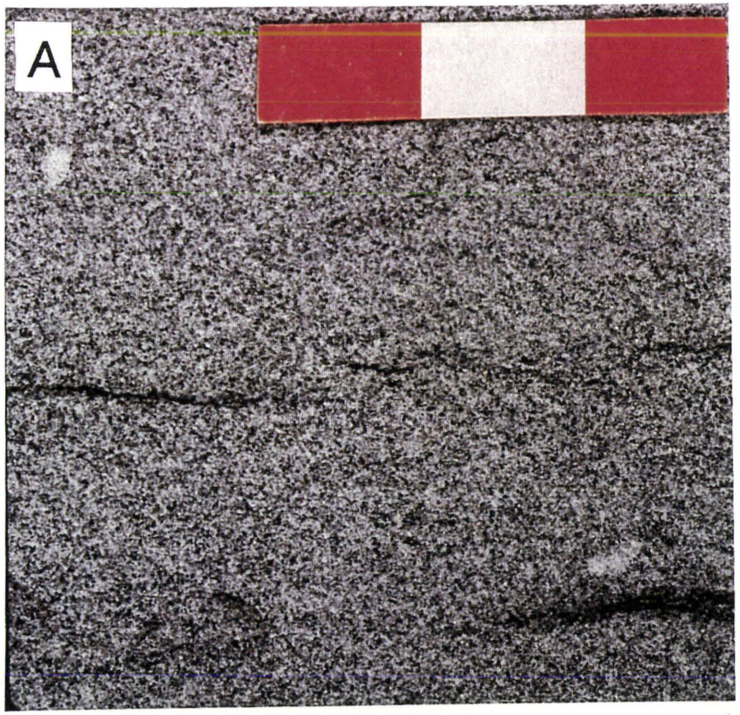


Figure 4.7 A) Example of *Macaronichnus simplicatus* within structureless sandstone of RV3 (6-36-34-25w4; 4970'). B) Structureless sandstone of RV3 showing mottled appearance (white patches) possibly caused by meiofaunal bioturbation (6-20-34-24w4; 4906'). Scale bar in cm.

contain little to abundant glauconite, and mud partings are commonly sideritized towards the top of this succession. Sand rarely reaches fU and very rare vcU grains were noted. The upper contact of RV3 is an erosional bounding discontinuity.

Interpretation:

The base of RV3 is thoroughly bioturbated by a diverse *Cruziana* ichnofacies, suggesting lower-upper offshore conditions. The succession gradually becomes sandier and coarser upwards, indicating progradation of a proximal marine environment. The upper portion of RV3 is dominated by vertical burrows of suspension feeders and rarely *Macaronichnus simplicatus*. This assemblage of trace fossils reflects the *Skolithos* ichnofacies and suggests a middle-upper shoreface environment (Fig. 4.2). The presence of HCS and trough cross-bedding supports a wave dominated shoreface environment.

4.2.3 Bounding Discontinuity One (BD1)

BD1 is an abrupt to sharp contact which truncates the underlying Regional Viking Successions (Allomember I). In places BD1 is a single continuous surface, whereas in other places it is divided into IT and RT surfaces, with a distinct facies succession between them. These surfaces are therefore described separately.

BD1 - Hamilton Lake

BD1 - HMLK is commonly very sharp, but in places is blurred by bioturbation. In a few places the sediment underneath is sideritized down to 15 cm below the contact. *Skolithos* burrows up to 25 cm deep, small unlined *Thalassinoides* and rare

Rhizocorallium penetrate below the contact, and are typically filled with fL to fU sandstone (Fig. 4.8). Immediately above the contact there is rarely a coarse lag composed of fU sand and very rare wood fragments.

BD1 (IT) - Farrell

The IT surface at Farrell is sharp and the underlying sediment is sideritized down to 13 cm below the contact. Unlined horizontal burrows (*Thalassinoides*?) containing fL sand occur a few cm under the BD1 (IT) surface. There is no coarse lag immediately above the contact.

BD1 (RT) - Farrell

The RT surface at Farrell is abrupt but there is no evidence of a coarse lag, or of burrows penetrating downward from the surface.

BD1 - Southwestern Study Area

The BD1 surface in the SW half of the study area is typically very sharp. *Thalassinoides* and *Skolithos* burrows (up to 50 cm deep) commonly penetrate downward from BD1. These are filled with coarse material (up to cL sandstone and rare granules, max. 3 mm) which in places is very glauconitic. Immediately above the contact there is very commonly a coarse lag which is extremely variable both in thickness and in content. In places it is merely a thin veneer of fU sandstone grains, but elsewhere it is almost 1 m thick and consists of glauconitic pebbly sandstone (up to mU sand; pebbles to 15 mm).

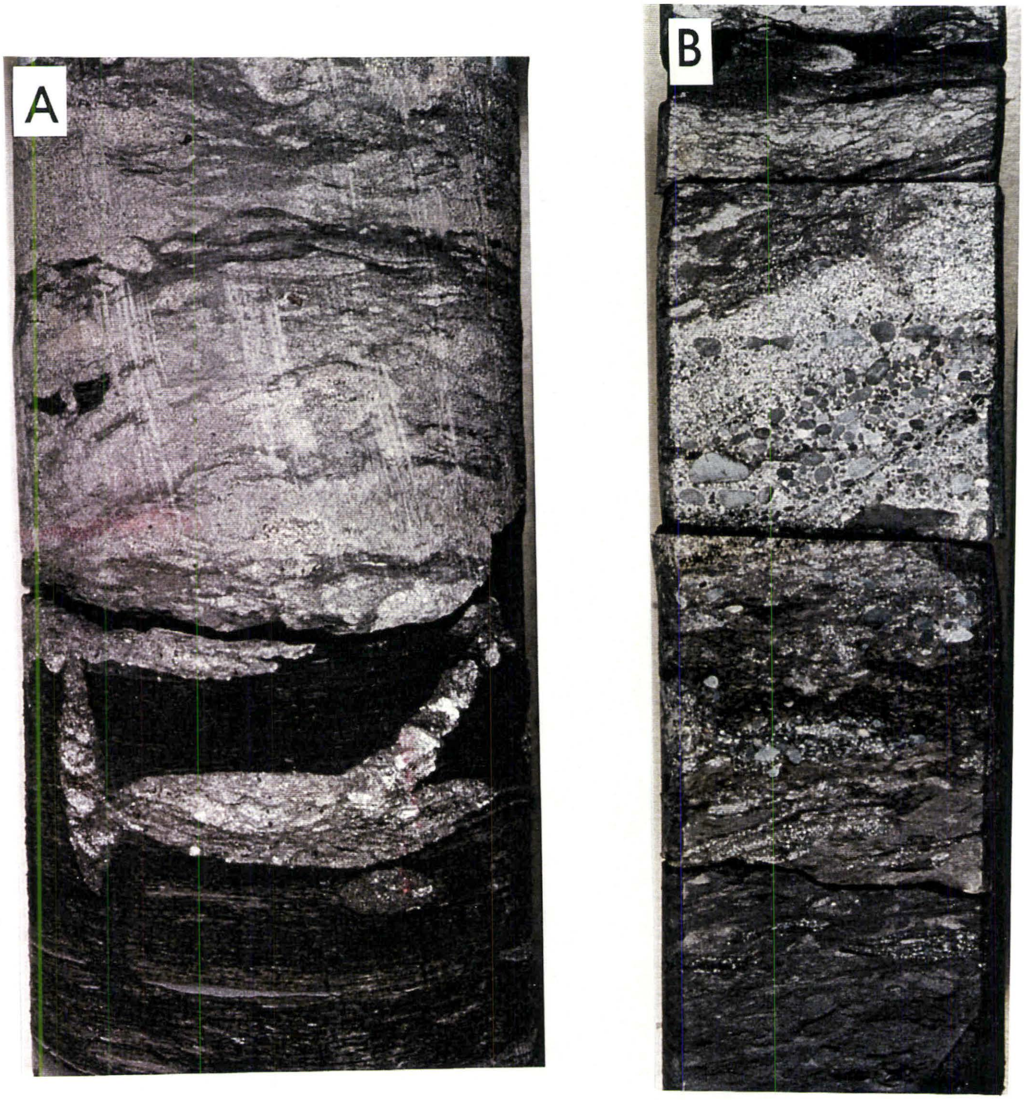


Figure 4.8 A) BD1 at Hamilton Lake. Note the sharp contact with underlying mudstones of RV2 and prominant *Glossifungites* burrow (*Thalassinoides*?) subtending this surface (3" core from 4-17-35-7w4; 865.5 m). B) BD1 at Fenn West. Note the conglomeratic transgressive lag resting on this surface and the granules and coarse sand which are burrowed into underlying 'regional Viking' mudstones (3" core from 4-32-36-21w4; 4401').

The pebbly sandstones rarely contain low angle to angle of repose cross-stratification, and in places are interbedded with thin mudstone beds. Well rounded siderite clasts (max. 6 cm) and zones of sideritization are common within the lag. Bioturbation of the lag occurs in places including the traces *Planolites, Helminthopsis, Terebellina, Zoophycos* and *Paleophycus*. One core appears to have dissected part of a gravel ripple resting on the discontinuity (Fig. 4.8).

Downing and Walker (1988) identified similar characteristics of BD1 (E1 in their terminology) at Joffre. A pebble or granule bed commonly mantled this surface, averaging 1 cm thick, with pebbles up to about 10 mm in diameter. Similar beds occurred up to 1 m above the basal contact and were commonly dispersed into the surrounding mudstones by bioturbation.

Interpretation:

The sharp contact of BD1 over most of the study area, with a coarse lag developed immediately above the contact, suggests a widespread erosion surface. This interpretation is supported by the presence of a *Glossifungites* ichnofacies developed below the contact, comprising dominantly *Thalassinoides* and *Skolithos*. The regional extent of this surface, development of a firmground trace fossil suite and overlying marine succession, suggests exhumation by transgressive erosion.

4.2.4 Allomember II

Allomember II occurs over much of the southwestern part of the study area but is only locally preserved northeast of the main Fenn trend. In places (Farrell and Hamilton

Lake) Allomember II is divided by a RT surface.

Allomember II - Southwestern study area

Allomember II is up to 11 m thick. In the main Fenn trend and southwestward, Allomember II has a characteristic sandier and commonly coarser upward trend. The base of the section is mostly bioturbated with the partitioning of sandstone and mudstone still evident but few distinct beds preserved. Those sandstone beds which are preserved average 2 - 4 cm (max. 8 cm) and show flat to undulating laminations or ripple cross-lamination. Mudstones reach 2 cm in thickness. At the base, sandstone is typically vfU and makes up 30 - 50 percent of the sediment. Except in the Huxley area, there are commonly scattered granules/pebbles (max. 10 mm) and coal clasts throughout the section, although they are more concentrated towards the base. Distinct granule beds are preserved in places, and less commonly thicker (max. 17 cm) cross-bedded sandstone beds are preserved. Traces include abundant *Helminthopsis*, *Planolites*, *Terebellina* and *Zoophycos*, in addition to *Siphonichnus, Teichichnus, Rosselia, Schaubcylindrichnus, Asterosoma, Paleophycus, Cylindrichnus*, small *Diplocraterion* and *Skolithos*, and rare *Chondrites*. Upwards, Allomember II gets sandier and coarser, typically fU, with increased preservation of bedding and increased bed thicknesses. The unit also becomes more glauconitic upwards. Where the uppermost part of this succession is preserved (typically onfield Fenn), it is dominantly cross-bedded, fU sandstone, with rare thin mudstone beds (max. 1 cm). Angle of repose cross-stratification is dominant with sets up to 20 cm thick, and minor amounts of low angle stratification. Bioturbation is scarce, but includes large *Skolithos* and *Diplocraterion* burrows (max. 13 cm deep) and rare *Planolites* in the mudstones. Bands of siderite are very common, up to 8 cm thick, and rounded siderite clasts are also prevalent.

Interpretation:

The base of Allomember II in the southwestern study area contains a fully marine suite of trace fossils, dominated by grazing and deposit feeding organisms. This suggests a distal *Cruziana* ichnofacies indicating lower offshore conditions (Fig. 4.2). Sharp based, thin, wave rippled sandstone beds and granule beds indicate deposition from storm generated currents. Upwards the succession becomes coarser and sandier suggesting progradation of more proximal sediments. The presence of more and thicker physical sedimentary structures, including trough cross-bedding and rare HCS suggests a transition-shoreface environment. The dominance of suspension feeding traces implies a *Skolithos* ichnofacies, supporting a middle shoreface interpretation (Fig. 4.2).

Allomember II - Farrell

Allomember II at Farrell is up to 5 m thick. It is a sandier upward succession dominated by a characteristic white sandstone and abundant glauconite. Sandstone content at the base is approximately 50%, increasing to approximately 80% towards the top. At the base, the succession is totally bioturbated by *Planolites*, *Chondrites*, and *Helminthopsis*. Sandstone is fL/fU and coarsens upward to a maximum of mU, with scattered granule/pebbles (max. 9 mm). Upwards the succession becomes more glauconitic and abundantly sideritized. Low angle, undulating stratification is developed in places near the top, but most of the sediment is still bioturbated.

Interpretation:

The succession of Allomember II at Farrell begins, at its base, with a *Cruziana* ichnofacies of the upper offshore (Fig. 4.2). Progradation of a more proximal environment is suggested by a gradual upward coarsening and sanding, until small scale HCS is developed, presumably representing transition-lower shoreface conditions.

Allomember II - Hamilton Lake

Allomember II at Hamilton Lake is up to 4 m thick. It is an almost totally bioturbated mixture of sandstone and mudstone. Sandstone content at the base of the succession is about 40 -50 % and increases upwards to 80 %, and the sandstone coarsens upward from vfU to fU. Rare preserved sandstone beds (max. 1 cm) contain flat to undulating, parallel laminations. Glauconite is prominent in this allomember and typically increases in abundance upward. Trace fossils increase in abundance and diversity upward. The succession is dominated at the base by *Helminthopsis, Terebellina, Planolites* and *Chondrites*, and upwards begins to include *Zoophycos, Siphonichnus, Rosselia, Skolithos, Asterosoma, Schaubcylindrichnus* and rarely *Paleophycus* and *Teichichnus*. Coal clasts are commonly scattered throughout the unit, and in places pyrite nodules exist in the lowest metre. Sideritized horizons are common, up to 66 cm thick. In places a bentonite up to 14 cm thick is preserved at approximately one metre from the base.

Interpretation:

The Allomember II succession at Hamilton Lake contains a very diverse marine assemblage of trace fossils, displaying *Cruziana* ichnofacies at the base and reaching a proximal *Cruziana* ichnofacies at the top (Fig. 4.2). This change in ichnofacies, in addition to the sandier and coarser upward succession, suggests a prograding environment from upper offshore to possibly lower shoreface conditions.

4.2.5 Bounding Discontinuity Two (BD2)

BD2 is commonly less pronounced than other discontinuities in the study area. The surface is generally sharp, but in places becomes less distinct and even gradational. BD2 has also been divided into IT and RT surfaces at Mikwan and Fenn, but can only be recognized as one surface elsewhere in the study area.

BD2 (IT) - Mikwan-Fenn

The initial transgressive surface of BD2 at Mikwan and Fenn fields is usually very sharp and is typically mantled by a lag no thicker than 2 cm. This lag ranges from a thin scattering of coarse sandstone grains above the contact (Fig. 4.9), to a lag of small pebbles (max. 6 mm). In places *Skolithos* and *Diplocraterion* burrows penetrate below the contact to depths greater than 20 cm, and are passively filled by mL-cL sandstone. The underlying sediment is sideritized, in a few places, to depths of 11 cm below BD2.

BD2 (RT) - Mikwan-Fenn

The resumed transgressive surface of BD2 at Mikwan is commonly sharp and covered by a coarse lag 1 - 16 cm thick composed of chert pebbles up to 10 mm in diameter. At Fenn the contact is indistinct in places and sharp in others. There is commonly no lag above the contact at Fenn.

BD2 - Elsewhere

The BD2 surface in the area northeast of Mikwan and Fenn fields (Maple Glen area) becomes indistinct, in places displaying a gradational contact and only a subtle flooding surface. In places there are a few scattered granules (max. 5 mm) found near the contact.

The BD2 surface in the Sullivan Lake/Hamilton Lake area is typically very sharp and in places is underlain by up to 22 cm of siderite. In approximately 50% of the cores there is no lag overlying this surface (Fig. 4.9) but the other half show a variable coarse lag. In a few places (particularly toward the southwest) there is a lag up to 9 cm thick of thoroughly bioturbated (*Helminthopsis* and *Planolites*) sandstone (up to cU). In other places the lag comprises a veneer of granules (2 - 5 mm) which fill *Thalassinoides* and *Skolithos* burrows penetrating below the contact (Fig. 4.9). To the extreme SE of the Hamilton Lake area, there is commonly a coarse veneer of pebbly sandstone (mL sand to 11 mm pebbles) which mantles BD2. In places *Skolithos* and *Diplocraterion* burrows (max. 20 cm deep) protrude downward from this surface and are filled with sandstone up to mL. Glauconite and pyrite are locally concentrated within the lag.

Interpretation:

The regional extent, sharpness and common occurrence of a coarse lag directly above the BD2 contact (both IT and RT surfaces) indicates a widespread erosion surface.

Figure 4.9 A) BD2 at Hamilton Lake. Note the knife sharp contact but lack of a coarse lag resting on this surface. A firmground *Skolithos* burrow penetrates below the contact, filled with coarse sand (3" core from 12-24-35-9w4; 907 m). B) BD2 (IT) at Fenn West. Note the sideritized underlying muddy sandstones and the presence of coarse sand grains within beds above the contact (3" core from 4-32-36-21w4; 4392').

A TSE is suggested based upon the above mentioned characteristics and the presence of firmground *Skolithos* and *Diplocraterion* burrows of the *Glossifungites* ichnofacies, which extend below the contact, and the presence of marine conditions above the contact.

4.2.6 Allomember III

Allomember III is also divided by a RT surface similar to Allomember II, and shows significant facies changes laterally. This succession is not preserved much further southwest than the main linear sandbody trend (i.e Mikwan, Fenn, Chain). The following description is divided into four parts: 1) Allomember III - FENN, BD2 (IT) -BD2 (RT), equivalent to the producing succession at Joffre, 2) Allomember III - FENN, BD2 (RT) - BD3, 3) Allomember III - Maple Glen, where the base of the succession is often difficult to pick, possibly because BD2 has become a correlative conformity, and 4) the Hamilton Lake/Sullivan Lake area.

Allomember III - FENN, BD2 (IT) - BD2 (RT)

Allomember III in the main Mikwan-Fenn trend is up to 6.5 m thick. The succession is typically sandier upward and in places coarsens upward. The lowest 50 - 100 cm is generally composed of a black mudstone that contains thin (avg. 3-4 mm) vfL to vfU sandstone beds. The only trace fossils found in this basal section are small *Planolites*. Upwards the sandstone beds gradually become thicker and bioturbation more prevalent in places. Sandstone beds may reach thicknesses of 15 cm, displaying angle of repose cross-bedding, but more commonly are 1-3 cm thick with gently undulating parallel laminations.

Grain size is commonly fU to mU and granules (max. 8 mm) are dispersed throughout the upper section, in places as discrete beds. Trace fossils are slightly more diverse upward, commonly including *Teichichnus, Planolites, Zoophycos*, and small *Skolithos*, and more rarely *Terebellina*, *Schaubcylindrichnus* and small *Diplocraterion*. Glauconite is abundant in places and sideritized zones rarely occur, up to 6 cm thick. Multiple thin bentonitic horizons were also noted.

Also to the southwest of Hamilton Lake field, one core within the BD2(IT) - (RT) interval displayed a 30 cm unit which consisted of granules (max. 4 mm), mL sandstone, and mudstone bioturbated by *Helminthopsis, Planolites* and *Skolithos*, and all capped by a clean 10 cm granule sandstone bed (max. 7 mm granules).

Interpretation:

The base of this succession contains a stressed trace fauna within dominantly black mudstone. The reason for the this stress is unclear, but it is suggested that these conditions may reflect poorly oxygenated shelfal conditions. Davis and Byers (1993) also suggested that decreased diversity, size and amount of bioturbation within the Mowry Shale of Wyoming (late Albian) was due to deposition within oxygen-depleted waters. The succession gradually becomes sandier and coarser upward, indicating progradation of proximal facies. Storm emplaced wave rippled sandstone beds are common and the assemblage of trace fossils reflects a restricted *Cruziana* ichnofacies (low abundance and diversity), suggesting upper offshore-transition conditions for the top of the succession (Fig. 4.2).

How JOFFRE Fits In

The main sandbody at Joffre lies between surfaces E2 and CM4 in Downing and Walker's (1988) terminology (association 3). This succession is equivalent to Allomember III - FENN, BD2(IT)-BD2(RT) but the facies change significantly alongstrike (Fig. 4.10). At Joffre, much of the sandbody consists of cross-bedded sandstones, glauconitic sandstones, granule sandstones and pebbly sandstones, which shale out abruptly to the northwest, where the coarse facies are delicately interstratified with black, stressed mudstones. There is a well developed fining of grain size toward the southeast along the length of Joffre field (Downing and Walker, 1988), and by Mikwan and Fenn the reservoir quality sandstones are replaced by the muddy coarsening upward

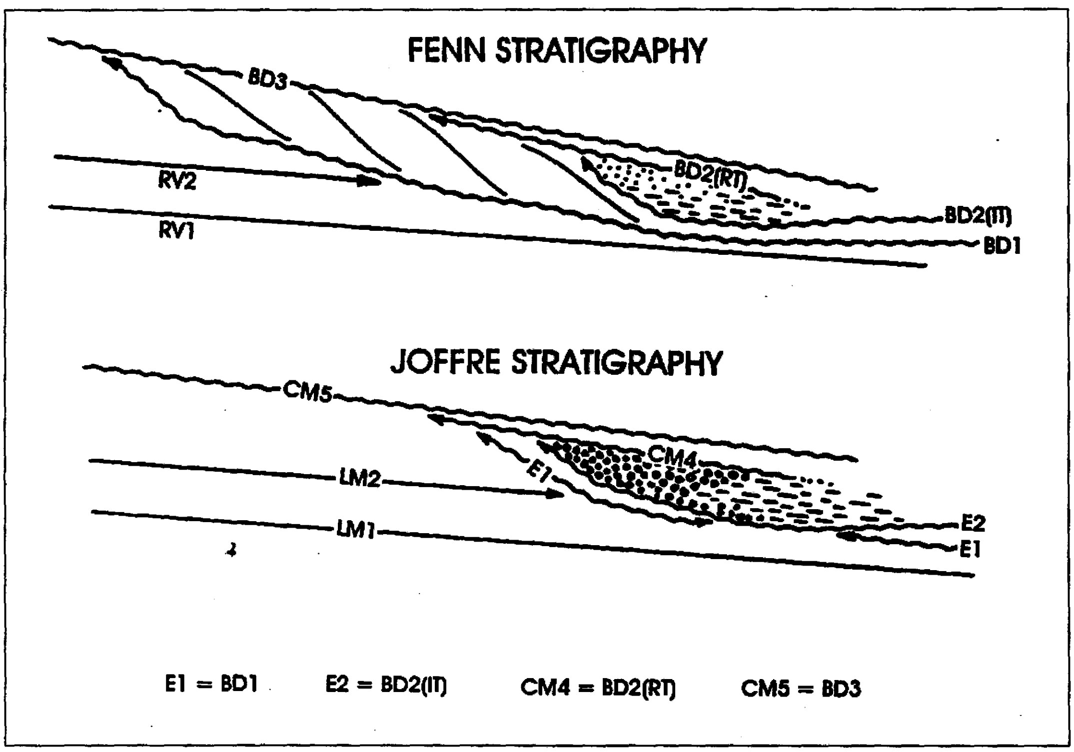


Figure 4.10 Comparison of stratigraphy and terminology between Fenn (current study) and Joffre (Downing and Walker, 1988).

succession described in Allomember III - FENN, BD2(IT) - BD2(RT).

The other major difference between the stratigraphy at Joffre vs Fenn, is the extent of BD1 (E1 at Joffre) and the increased preservation of Allomember II (association 2 at Joffre). At Joffre, BD1 (E1) forms an asymmetrical incision just southwest of the BD2 (E2) incision, whereas at Fenn, BD1 can be traced for 20-30 km to the southwest (Fig. 4.10). The succession above BD1 at Joffre (association 2; Downing and Walker, 1988) is a thoroughly bioturbated muddy sandstone, which coarsens upward slightly, but is only preserved to a maximum of 4.5 m. At Fenn, this succession (Allomember II) is also well bioturbated at its base, but can be up to 11 m thick, becomes coarser and sandier upward, with well developed, glauconitic cross-bedded sandstone, and forms the reservoir rock at Fenn.

Allomember III - FENN, BD2 (RT) - BD3

Above BD2 (RT) along the main sandbody trend Allomember III is up to 5 m thick. The succession becomes slightly sandier upward in places and typically alternates between interbedded sandstone and mudstone beds, and dominantly bioturbated zones. The sandstone beds average 1 - 2 cm in thickness (max 7 cm) and contain a variety of grain sizes ranging from vfU to mL. Stratification is typically low angle gently undulating parallel laminations, but in places displays angle of repose cross-bedding. Mudstone beds average 5 mm (max. 3 cm). In highly bioturbated intervals, the traces *Teichichnus, Terebellina, Cylindrichnus, Schaubcylindrichnus, Zoophycos, Chondrites* and small *Skolithos* were noted. Glauconite is mostly scarce, but is found to be locally abundant, and up to two bentonites were identified.

Interpretation:

The alternation of mudstone and sharp based wave rippled sandstone beds indicates a storm dominated offshore environment. The assemblage of trace fossils consists of a variety of grazing, deposit feeding and suspension feeding organisms, reflecting a *Cruziana* ichnofacies and corresponding to upper offshore conditions (Fig. 4.2).

Allomember III - Maple Glen

The base of Allomember III - Maple Glen is difficult to identify in the Maple Glen area, but the succession commonly becomes sandier upward and coarsens upward. Overall, sandstone content increases upward from about 40% to a maximum of 90 %, , and grain size ranges from vfL to fU. Interbedded sandstone and mudstone beds alternate with more bioturbated intervals. The sandstone beds increase in thickness upwards, averaging 2-3 cm near the bottom and 4-5 toward the top (max 18 cm). Low angle gently undulating parallel laminations change upward into well developed small scale HCS beds, and sets of climbing ripples up to 6 cm thick occur in a few places. Trace fossils are diverse but not overly abundant in any one place and include *Planolites, Zoophycos, Teichichnus, Skolithos, Arenicolites, Terebellina, Helminthopsis, Paleophycus, Chondrites, Schaubcylindrichnus* and rarely *Diplocraterion, Rosselia* and *Siphonichnus*. Up to three thin bentonites occur throughout the section, but one 14 cm thick bentonite was noted near the base of the allomember in one core.

In places, the top of the succession becomes gradationally muddier again, with fL sandstone, and scattered pebbles bioturbated throughout. The diversity of traces is reduced to include only *Terebellina, Helminthopsis, Teichichnus* and small *Skolithos*.

Interpretation:

Allomember III - Maple Glen becomes coarser and sandier upward, indicating progradation of the marginal marine environment. The base of the succession contains thin wave rippled sandstone beds which become thicker upward, eventually developing into small scale HCS. Trace fossils are dominated by grazers and deposit feeders, reflecting distal *Cruziana* to *Cruziana* ichnofacies. The combination of physical and biogenic sedimentary structures indicates conditions changing from lower offshore to transition (Fig. 4.2).

Allomember III - Northeast (Sullivan Lake/Hamilton Lake)

Allomember III reaches a maximum preserved thickness of 11 m in the northeastern study area. It consists of an overall sandier upward succession that contains up to three stacked, smaller sandier upward successions within it. The first succession characteristically begins with a "pinstriped" black mudstone. The vfL sandstone "pinstripes" average only a few mm and bioturbation of this interval is restricted to small *Planolites*. Commonly there is a thick (2 - 17 cm) white bentonite which occurs near (< 2 m) or directly upon the lower contact. A slumped bentonitic siltstone is commonly associated with this bentonite. Upwards, this first succession becomes sandier and beds become thicker (avg. 1-2 cm), but more bioturbated and in places totally homogenized.

Traces include *Teichichnus, Terebellina, Helminthopsis, Planolites*, and small *Skolithos*, and less commonly *Schaubcylindrichnus, Zoophycos, Chondrites, Arenicolites, Rosselia, Diplocraterion* and *Siphonichnus*. In places the succession continues to become sandier and slightly coarser (vfU) upward, and thick beds (max. 35 cm) displaying HCS become prevalent. Mudstone beds occur up to 2 cm thick and mudstone rip-up clasts are locally found at the bases of sandstone beds. Scattered chert granules (max. 3 mm) and coal clasts occur in a few places. Trace fossils in this sandy facies commonly destroy stratification and include *Helminthopsis, Planolites, Asterosoma*, small *Skolithos* and in places *Rosselia, Paleophycus, Zoophycos* and *Chondrites*. The second and third successions within this allomember are similar to the first except that they begin directly with the interbedded and bioturbated section, without the basal "pinstriped" section. Contacts between the three successions are invariably gradational. In the southwestern Hamilton Lake area, a thick bentonite (10 -18 cm) is commonly observed close to the gradational contact between the second and third sandier up succession.

Interpretation:

The 'pinstriped' mudstone is similar to that described for Allomember III in the main trend (BD2(RT)-BD2(IT)) and is similarly interpreted as reflecting stressed shelfal conditions (Fig. 4.2). This stress is represented by a very low abundance and diversity of trace fossils, possibly indicating poorly oxygenated conditions. Upwards the succession becomes sandier and begins to include a diverse marine assemblage of trace fossils reflecting distal *Cruziana* to *Cruziana* ichnofacies. In places well developed HCS is prevalent indicating wave dominated conditions with trace fossils again reflecting the

Cruziana ichnofacies. This combination of physical and biogenic sedimentary structures suggests progradation of marine environments from shelfal, through lower offshore, to transition conditions (Fig. 4.2). The occurrence of three of these stacked successions implies three separate progradational events followed by deepening.

4.2.7 Bounding Discontinuity Three (BD3)

BD3 is a very sharp surface that can be traced over much of the study area and has a coarse lag which typically decreases in grain size from southwest to northeast.

In the southwest, BD3 is a sharp surface which typically has a relatively thick (up to 19 cm) lag covering it (Fig. 4.11). The lag varies from clast supported chert pebble conglomerate to a pebbly sandstone with a mL/mU matrix. Pebbles are commonly around 10 mm in diameter, reaching a maximum of 21 mm. Sideritized mudstone clasts up to 7 cm are also incorporated into the lag. The sediment below the contact is in places sideritized down to a maximum of 30 cm. Unlined *Skolithos* burrows were observed in places penetrating up to 30 cm below the contact, filled with fU/mL sandstone.

Along the main sandbody trend (Mikwan, Fenn, Chain North) this contact is still knife sharp and is typically covered by a coarse lag, 2.5 - 24 cm thick. The lag is commonly clast supported, especially near the base, and poorly sorted. Chert pebbles reach 27 mm in diameter and where matrix supported, the sandstone is fL/fU. A laminated but deformed rip-up clast was preserved in one lag, and rounded sideritized mudstone clasts are common. The underlying sediment is sideritized in places down to 30 cm below the contact. *Diplocraterion, Skolithos* and *Thalassinoides* burrows were all

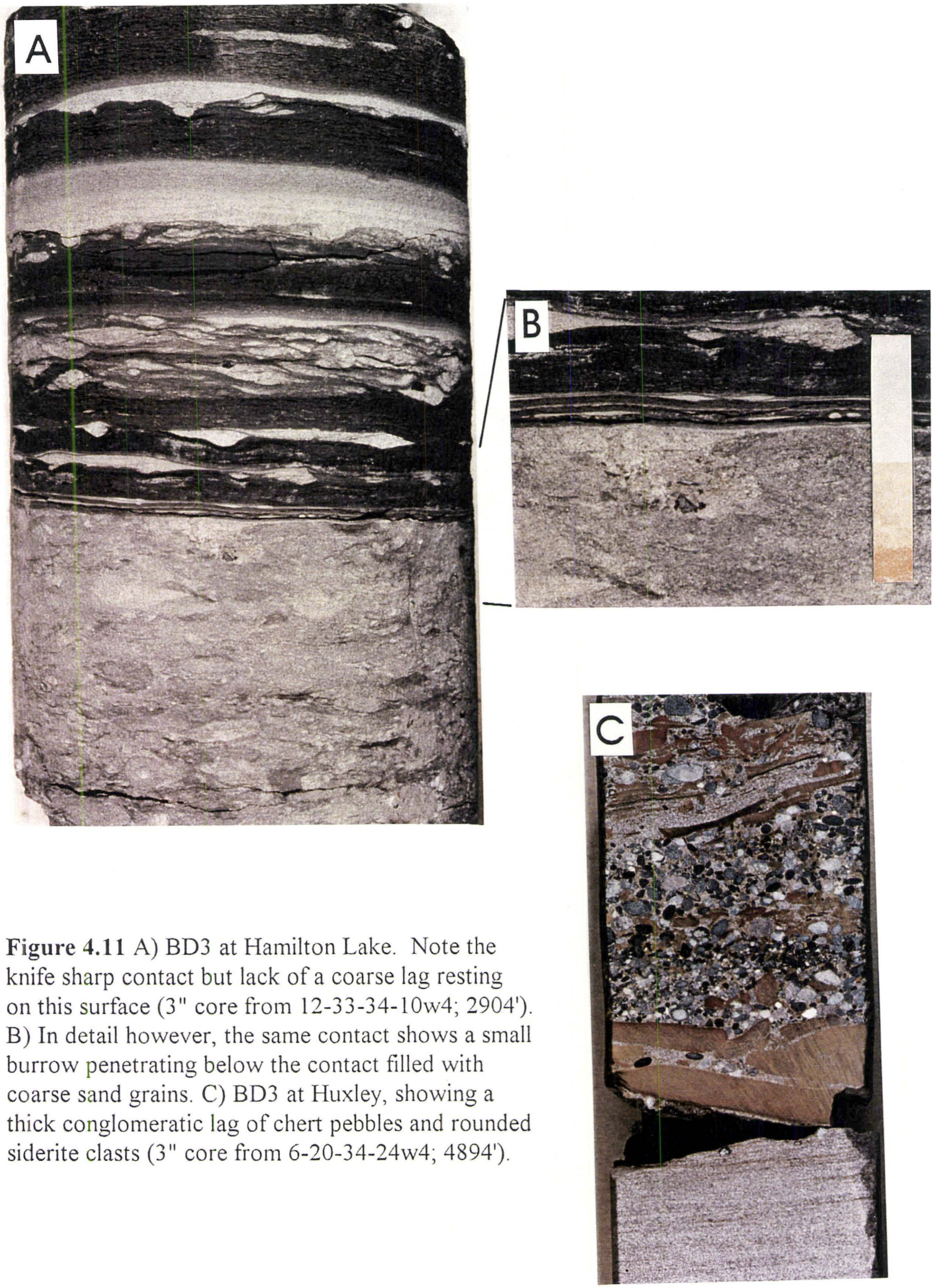


Figure 4.11 A) BD3 at Hamilton Lake. Note the knife sharp contact but lack of a coarse lag resting on this surface (3" core from 12-33-34-10w4; 2904'). B) In detail however, the same contact shows a small burrow penetrating below the contact filled with coarse sand grains. C) BD3 at Huxley, showing a thick conglomeratic lag of chert pebbles and rounded siderite clasts (3" core from 6-20-34-24w4; 4894').

locally observed to penetrate below the BD3 contact (max. 8 cm) and were typically filled with fL to mU sandstone. Rarely this contact was knife sharp but contained no lag upon its surface.

In the northeastern study area BD3 remained a very sharp contact, but the overlying lag was greatly reduced in grain size and commonly was not present at all. At Sullivan Lake field the lag is 15 - 20 cm thick and consists of fL/fU, muddier-up, pebbly sandstone (max. 9 mm pebbles). Bioturbation of the lag by *Helminthopsis* and *Planolites* was observed. *Skolithos, Diplocraterion* and *Thalassinoides* burrows extended a maximum of 7 cm below the contact, filled with fL/fU sandstone. At Hamilton Lake field, BD3 is characteristically sharp with no lag mantling the surface (Fig. 4.11). In places, granules (max. 6 mm) could be found at the contact and scarce burrows such as *Skolithos* and *Diplocraterion* were observed penetrating below the contact. The underlying sediment is sideritized to a depth no greater than 10 cm.

Interpretation:

BD3 is a regionally extensive sharp surface which typically has a coarse lag mantling it. The presence of unlined, passively filled *Skolithos*, *Diplocraterion* and *Thalassinoides* burrows subtending from this contact suggests colonization of an exhumed firmground by a *Glossifungites* suite of trace fossils. These characteristics plus the overlying marine succession suggest that BD3 is a regionally extensive TSE.

4.2.8 Allomember IV

Allomember IV contains a characteristically sandier upward succession which displays significant lateral facies changes from the southwestern to the northeastern parts of the study area. Due to the lateral variations of facies, the following description of allomember IV will be divided into three parts: 1) Southwest of a line parallel to Chain South field, 2) within the main Mikwan-Fenn-Chain North trend, 3) Northeast section, i.e. Sullivan Lake and Hamilton Lake fields.

Allomember IV - Southwest (Huxley, Chain South, Richdale)

In the southwestern study area Allomember IV is preserved to its greatest thickness (22 m) and displays a very characteristic sandier upward succession, although the lowest five meters becomes slightly muddier upward in places. The lower portion of this succession is commonly very bioturbated but also contains intervals of relatively well preserved alternating sandstone and mudstone beds averaging 1 cm in thickness. Preserved sandstone beds are sharp based with gently undulating parallel laminations. Sandstone is typically vfL/vfU, but this lower portion is characterized by numerous scattered chert granules and pebbles (max. 27 mm). These pebbles are bioturbated into the surrounding sediment or are found in discrete sharp based beds. Traces in this lower part of the succession include *Planolites, Terebellina, Helminthopsis, Teichichnus, Zoophycos, Cylindrichnus*, small *Skolithos, Rosselia* and rare *Chondrites*. Pyrite nodules and coal clasts are abundant in places.

The succession gradationally increases preservation of physical sedimentary structures, bed thicknesses and sandstone content upwards. In the upper portion of this succession sandstone beds average 10 cm thick (up to 45 cm) and contain low angle flat to gently undulating laminations. Low angle truncations of laminations are common, interpreted as HCS, and mudstone rip-up clasts are locally found at the bases of these sandstone beds. Preserved mudstones average 1-2 cm thick (up to 12 cm). Traces in this upper portion are dominated by *Zoophycos, Chondrites* and *Planolites*, but other traces include robust *Rosselia* (up to 9 cm high, 6 cm diam.), *Helminthopsis, Terebellina, Skolithos, Conichnus, Asterosoma, Paleophycus, Schaubcylindrichnus* and *Siphonichnus*. Sandstone is commonly vfU, buff in colour and contains rare granule beds. Siderite bands become relatively common (max. 9 cm thick) and a distinct thick white bentonite (~ 20 cm) is characteristic of this succession.

Interpretation:

The gradual increase in preservation of physical sedimentary structures, sandstone bed thicknesses and sandstone content upward, indicates the progradation of higher energy environments. At the base, storm emplaced wave rippled sandstone beds and granule beds are commonly bioturbated by grazing and deposit feeding organisms, reflecting a distal *Cruziana* ichnofacies of lower offshore origin. Upwards, the presence of well developed HCS and a relatively diverse assemblage of trace fossils (*Cruziana* ichnofacies) indicate upper offshore to transition conditions in a wave dominated environment (Fig. 4.2).

Allomember IV - Main trend (Mikwan, Fenn, Chain North)

Allomember IV within the main trend of linear reservoirs is typically 4-6 m thick. It displays an extremely characteristic succession which variably alternates from intervals of well preserved interbedded sandstones and mudstones, to intervals dominated by bioturbation. The sandstone is typically vfL/vfU but the lowest meter commonly contains coarser beds of fU sandstone or granules/pebbles (max. 13 mm) which decrease in abundance upward.

In intervals of well preserved bedding, sandstone beds average about 1 cm (max. 5 cm) and mudstones average 1-2 cm thick (max. 7 cm). Sandstone beds are sharp based, commonly lenticular and often show upward fining (colour grading). Internal laminations are flat to gently undulating and in places display unidirectional ripple cross-lamination. Sandstone beds show soft sediment deformation and display loading of underlying mudstones in places. Bioturbation is scarce but *Planolites* and *Cylindrichnus* are not uncommon.

In intervals dominated by bioturbation, bedding is distorted or non-existent. Traces include *Terebellina, Planolites, Cylindrichnus, Teichichnus, Helminthopsis, Schaubcylindrichnus, Siphonichnus, Zoophycos*, and small mud-lined *Skolithos*. Rarely *Chondrites, Paleophycus, Asterosoma* and small *Rosselia* are present.

Numerous thin bentonitic horizons occur throughout the section but one prominent bentonite, up to 35 cm thick, is common near the top of the succession.

Locally, in three cores (8-2-35-20w4, 14-27-24-20w4, 2-33-34-20w4), a sharp based sandstone occurs at the top of the succession. The preserved thickness of this sandstone unit ranges between 0.95 and 1.82 m. The base of this unit is very sharp and is mantled by lag of clast supported conglomerate ranging from a thin veneer to 10 cm thick. Chert pebbles in the lag are up to 24 mm in diameter and one small *Skolithos* was noted penetrating downward 2.5 cm from the lag. The sandstone itself has a distinct buff colour and is typically vfU, with interbedded mudstones. Sandstone beds are sharp based, 2-40 cm thick and commonly grade upward into mudstones (up to 6 cm thick). Internal laminations in the sandstone beds show well developed HCS. The trace fossils within this unit are very characteristic. Sandstones are dominated by *Helminthopsis, Zoophycos* and *Terebellina*, and mudstones are full of *Chondrites*. *Asterosoma* and *Planolites* are also present.

Interpretation:

This succession is dominated by interbedded sandstone and mudstone, which are commonly bioturbated by grazing and deposit feeding organisms. These trace fossils reflect the distal *Cruziana* ichnofacies and are indicative of a lower offshore environment (Fig. 4.2). The sharp based wave rippled sandstone beds support a storm dominated offshore interpretation.

The locally preserved sharp based sandstone unit at the top of the succession contains well developed HCS and is lightly bioturbated by grazing and deposit feeding traces. This combination of structures suggests a transition-lower shoreface environment (Fig. 4.2), and the sharp base of the sandstone unit on underlying mudstones may reflect a forced regression (Plint, 1991).

Allomember IV - Northeast Section

Allomember IV is locally preserved in places overlying Sullivan Lake and Hamilton Lake fields up to a maximum 5 m thick. At Sullivan Lake the base of the succession is dominantly mudstone, with thin vfL sandstone beds (avg. 3-5 mm), producing a 'pinstriped' appearance. Only rare, small *Planolites* occur in this lower portion. Upwards the succession very gradually becomes sandier and slightly coarser (vfU). Sandstone beds get thicker upwards (max. 3 cm) showing flat to undulating laminations. Bioturbation also increases upwards with traces including *Helminthopsis, Terebellina, Teichichnus, Planolites* and small mud-lined *Skolithos*. Sandstone may reach 80-90 % near the top of the succession. A 1 cm bentonite occurs at the base in places.

Where preserved, allomember IV at Hamilton Lake is typically like the 'pinstriped' mudstone described in the preceding paragraph. There is a very slight increase in sandstone beds upward, some of which display good colour grading. Bioturbation is scarce with only small *Planolites* and rare *Terebellina* and *Helminthopsis*. Typically this succession remains dominantly mudstone, but in very few places it develops a very sandy upper portion, similar to that described for Sullivan Lake.

Interpretation:

The stressed 'pinstriped' mudstones at the base of this succession are again interpreted as being deposited in an oxygen depleted shelfal environment. The gradational sandier upward nature of the succession reflects progradation of a distant shoreface. The sandier upper portion contains traces of dominantly deposit feeding organisms, reflecting a *Cruziana* ichnofacies, corresponding to upper offshore-transition conditions (Fig. 4.2).

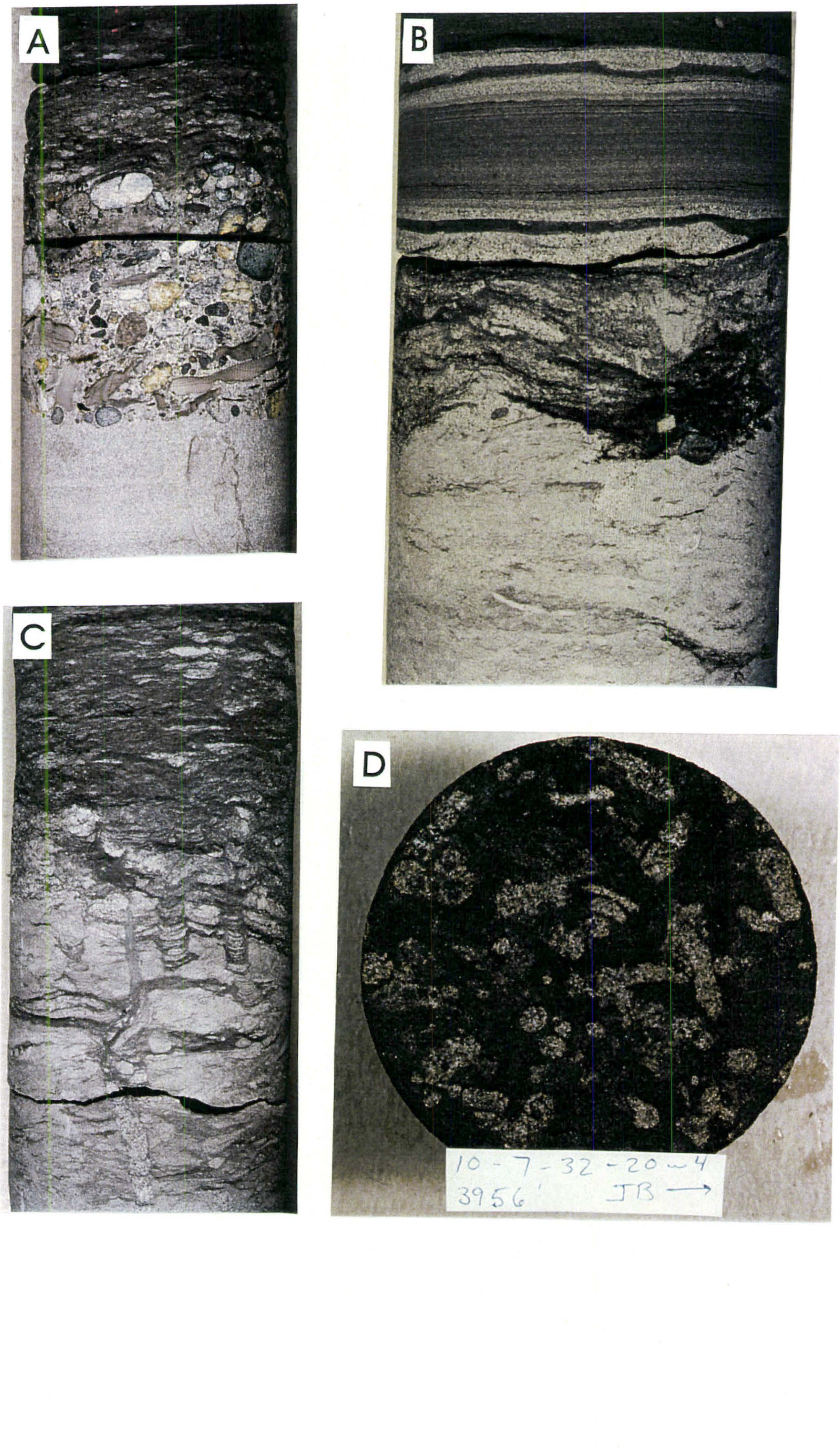
4.2.9 Bounding Discontinuity Four (BD4)

BD4 is a sharp, scoured surface which is traceable across the entire study area. It has a continuous coarse lag developed directly above it which typically decreases in grain size from the southwest to the northeast of the study area.

In the southeastern half of the study area, BD4 is a sharp surface, mantled by a very coarse lag (Fig. 4.12A). The lag is commonly composed of a clast supported, chert pebble conglomerate, with pebbles commonly reaching 20 mm (max. 31 mm). This conglomerate ranges in thickness between a thin veneer of pebbles to 26 cm thick, and is poorly sorted. The lower portion of the lag is typically clast supported, but upwards becomes matrix supported with the matrix ranging from mudstone to fU/mL sandstone. Well rounded siderite clasts up to 2.7 cm are also present. In places the sediment immediately below the contact is sideritized down to a maximum of 23 cm. Scarce burrows are found protruding downward from this contact, including small *Skolithos*, and *Thalassinoides*, which are filled with fL to mL sandstone.

In the northeastern half of the study area, BD4 is still very sharp, but the lag is significantly different. The lag consists of a totally bioturbated mixture of pebbly sandstone and mudstone which gets muddier upward (Fig. 4.12B, C). The average thickness is approximately 10 cm (max. 25 cm) and the sandstone is typically fL to mL with scattered granules and pebbles (max. 10 mm). The sediment is thoroughly homogenized by abundant *Teichichnus, Helminthopsis, Terebellina* and *Planolites*, and rarely by *Skolithos, Diplocraterion, Thalasinoides, Zoophycos, Asterosoma* and *Schaubcylindrichnus*. Commonly there are burrows penetrating downward from the BD4 surface to a maximum 11 cm, including *Skolithos, Diplocraterion*, and *Thalassinoides* (Fig. 4.12D). They are filled with fU sandstone.

Figure 4.12 A) BD4 from the southwestern study area (11-7-30-12w4; 3048'). Note the sharp based, chert pebble lag. B) BD4 from northeastern study area (11-13-36-17w4; 3400'). C) BD4 from the northeastern study area (11-33-33-13w4; 3234.5'). Note the *Skolithos* burrow subtending this surface, filled with the coarser sandstone from above, representing the *Glossifungites* ichnofacies. D) Bedding plane view of numerous *Diplocraterion, Skolithos and Arenicolites* burrows filled with medium sandstone, associated with the BD4 surface, representing the *Glossifungites* ichnofacies (10-7-32-20w4; 3956). There are more than twenty individual burrows visible, indicating a very dense population.


A
B
C
D
10-7-32-20w4
3956' JB →

In the Hamilton Lake area (T34-T35, R9-R10) there is a peculiar association of trace fossils preserved below the BD4 contact. In cores where the BD4 surface directly overlies a dark mudstone facies of Allomember IV, there is commonly a *Zoophycos* and *Chondrites* assemblage, which penetrate below the contact and contain the coarser material (fU sandstone) of the above mentioned lag. The peculiarity of finding these specific traces below an erosional contact (presumably in a firmground) is discussed later (see Chapter 5).

Interpretation:

The sharp and often scoured nature of BD4, coupled with the coarse lag which rests directly above it, suggests that BD4 is an erosion surface. The regional extent of BD4 (Walker, 1995), the presence of a *Glossifungites* assemblage of trace fossils (*Skolithos*, *Diplocraterion* and *Thalassinoides*) subtending from this surface, and the overlying marine succession all support formation by transgressive erosion. The decreasing grain size of the overlying lag from southwest to northeast suggests that the probable source area of the lag was to the southwest. The occurrence of *Zoophycos* and *Chondrites* burrows subtending the BD4 surface may represent a distal expression of the *Glossifungites* ichnofacies (see Chapter 5).

4.2.10 Allomember V

Allomember V comprises the sediment between BD4 and the Base of Fish Scales marker, and is between 28 m and 60 m thick. Stratigraphically, Allomember V of the Viking Alloformation is equivalent to the lithostratigraphic Westgate Formation.

Allomember V is dominantly composed of black mudstones, but also contains coarse tongues of sandstone.

The dominant facies of allomember V is a very black mudstone, commonly with thin (avg. 2-3 cm) vfL sandstone beds. These beds are typically sharp based, with gently undulating laminations and ripple cross-lamination. Rare slumping of beds was noted. Bioturbation is very scarce, with rare *Planolites* and *Helminthopsis*, but fish scales are commonly encountered on bedding planes. Two white bentonites occur in places, approximately 10-15 cm thick. A common characteristic of this allomember is the occurrence of numerous siderite horizons, which range in thickness from 2 cm to 30 cm. In places, directly above some of these siderites, there is a thin unit (1-19 cm) of fL - mL sandstone, and scattered chert granules and pebbles (max. 20 mm). These sandstones are sharp based and totally bioturbated by *Teichichnus, Planolites, Diplocraterion, Skolithos, Terebellina* and *Helminthopsis*. In the Hamilton Lake region, there is a prominent and relatively thick (avg. 80 cm) "tongue" of this sediment, which is thickest and sandiest in the southwest and becomes thinner and muddier to the northeast. This tongue of sediment "shales out" to the northeast into a series of interstratified, thin fU sandstones and the mudstones which are typical of the Westgate Fm.

Interpretation:

The black mudstones of Allomember V contain abundant fish scales and locally traces of grazing organisms (*Helminthopsis*) suggesting deposition in a marine shelfal environment (Fig. 4.2). Coarse pebble stringers and thin sandstone beds represent storm emplaced deposits form a distant shoreface. Where a significant accumulation of coarse sediment occurs, this may represent the offshore equivalent of a distant shoreface regression.

Allomember V - Chain North

Allomember V is described separately in the locality of the Chain North field, because it is the producing stratigraphic horizon. The lowest 1 to 2 m of sediment above BD4 is the black mudstone described in the previous section. Resting sharply on this mudstone is 50 to 150 cm of sandstone, commonly coarsening upward from fU to mU sand with scattered granules and pebbles (max. 18 mm). At Chain North, the sandstone is relatively clean, and displays well developed, angle of repose cross-stratification, with sets up to 7 cm thick. In places, thin (2-4 cm) mudstone beds are preserved and mudstone rip-up clasts are found in some sandstone beds. Alongstrike from Chain North (northwestward) the unit becomes muddier and moderately bioturbated by *Teichichnus, Planolites, Terebellina* and *Skolithos* burrows. Above this sandy section, Allomember V grades back to the typical mudstones of the Westgate Fm. described in the previous section, over approximately one meter.

Interpretation:

The coarse 'tongue' of cross-bedded sandstone contains trace fossils dominated by deposit and suspension feeding organisms. This combination of structures reflects a proximal *Cruziana* ichnofacies, indicating lower shoreface conditions. The sharp base of the sandstone, directly on top of shelfal mudstones, may represent a regressive surface of erosion formed by a 'forced regression' (Plint, 1991).

CHAPTER 5: DISTAL *GLOSSIFUNGITES* SUITE

5.1 The *Glossifungites* Ichnofacies

The *Glossifungites* ichnofacies corresponds to a suite of trace fossils which develop in firm unlithified substrates. The development of a firmground is commonly attributed to subaerial exposure or to burial and dewatering (MacEachern et al., 1992). In clastic settings, such as the Viking, the *Glossifungites* assemblage is typically associated with erosionally exhumed substrates which commonly occurs in shallow water settings as a result of erosional shoreface retreat (Pemberton et al., 1992). Thus *Glossifungites*

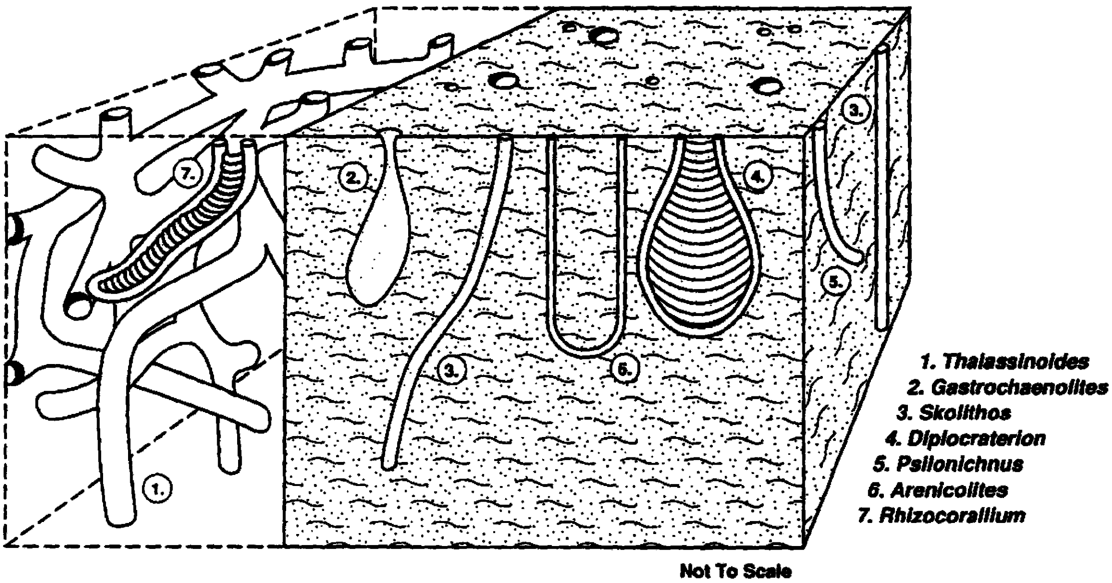


Figure 5.1 Trace fossil association characteristic of the *Glossifungites* ichnofacies (Modified from Frey and Pemberton, 1984, *in* MacEachern et al., 1992).

assemblages commonly mark erosional discontinuities; a trend observed with the transgressive surfaces of erosion of this study (BD1- 4).

Firmground traces are dominated by vertical to sub-vertical dwelling structures of suspension feeders such as *Skolithos, Diplocraterion* and *Arenicolites* (Fig. 5.1). However dwelling structures of deposit feeding organisms such as *Thalassinoides* and *Rhizocorallium* are also members of the *Glossifungites* suite (MacEachern et al., 1992). The firm walls of these structures allow the burrows to remain open after the organism vacates the burrow and subsequent depositional events led to passive infilling of the open structure. The development of the *Glossifungites* ichnofacies is as follows:

1) Exhumation of the substrate down to a firmground.

2) Colonization of the exposed firmground surface.

3) Passive infilling of burrows during subsequent depositional events.

5.2 Possible Firmground *Zoophycos - Chondrites* Assemblage

In the Hamilton Lake field of the current study area (T34-35, R9-10), an unexpected assemblage of traces was discovered penetrating below an erosional discontinuity. The assemblage consisted of *Zoophycos* and *Chondrites* burrows, which were found excavated 3 - 4 cm below the sharp BD4 surface (Fig. 5.2). The *Zoophycos* burrows are actively filled with fU sandstone and granules within the spreiten.

The substrate below the discontinuity is composed entirely of black mudstone with very thin (max. 3 cm) vfL sandstone beds. Bioturbation is limited to abundant *Helminthopsis* in places, rare *Planolites* and very rare *Terebellina*. *Zoophycos* and

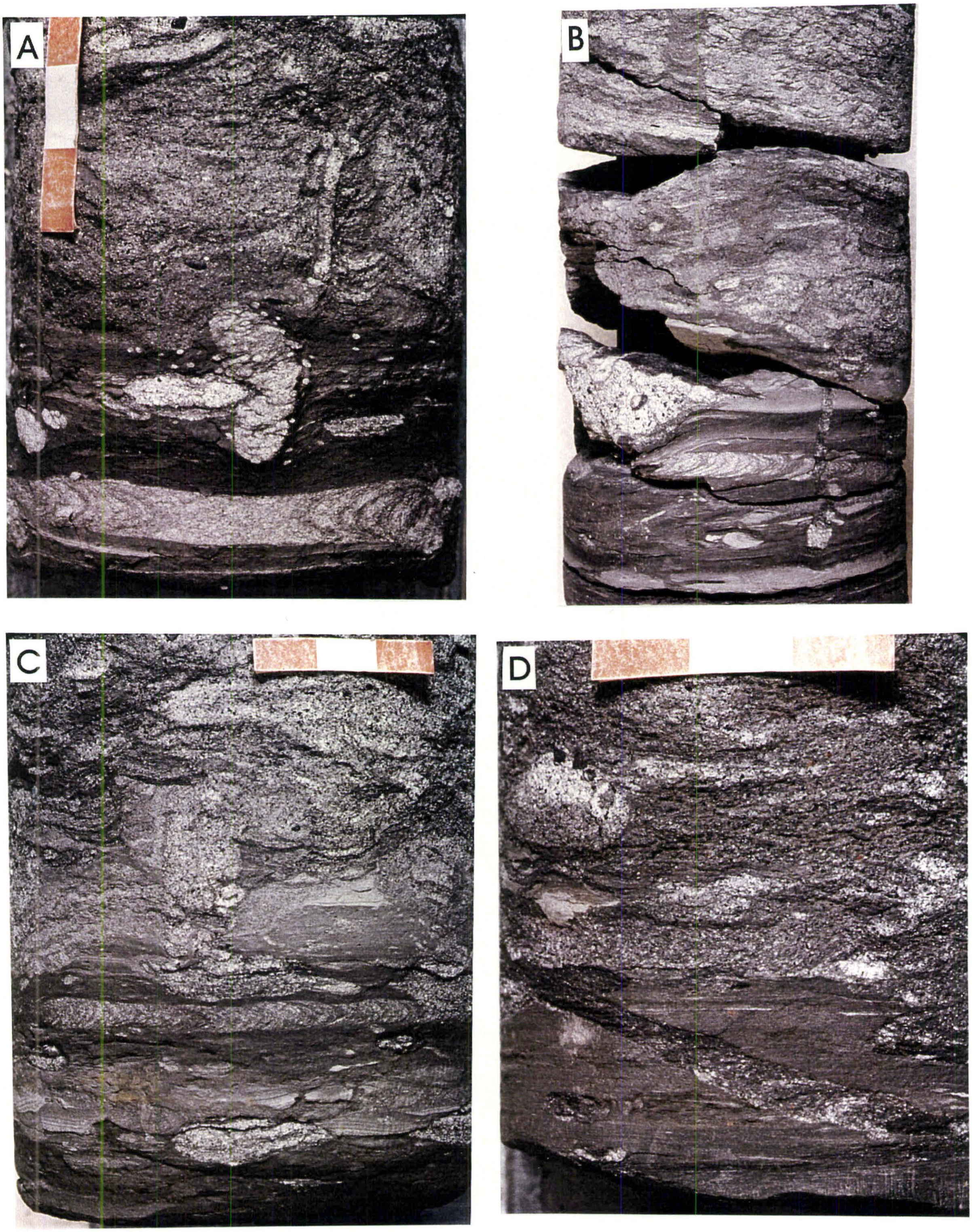
Figure 5.2 Examples of the *Zoophycos* - *Chondrites Glossifungites* assemblage subtending BD4. Note the fill of the *Zoophycos* burrows (side packed structures) is of similar grain size to the material from the overlying lag deposit, but much coarser than it surrounding material. Other prominent burrows include *Skolithos, Thalassinoides, Teichichnus* and *Helminthopsis* (*Anconichnus*). Scale is in cm.

A) 2-36-34-10w4; 2923'

B) 12-27-34-10w4; 2881'

C) 12-32-34-9w4; 2906'

D) 6-13-35-9w4; 2968.5'


A
B
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Chondrites burrows are not found as part of the pre-erosion trace fossil suite.

The facies overlying the discontinuity consists of a thoroughly bioturbated mixture of fU/mL sandstone and mudstone. Granules and pebbles (max. 9 mm.) are commonly scattered throughout. The sediment is gradationally muddier upward but is 5 - 25 cm thick before grading back to mudstone. Trace fossils within this coarser material include abundant *Teichichnus* and *Helminthopsis*, and sparse *Planolites, Thalassinoides, Terebellina* and small *Skolithos*.

The *Zoophycos* and *Chondrites* burrows clearly post-date the erosion surface and the *Zoophycos* are clearly filled with the coarser material which lies above the discontinuity. This relationship suggests that the *Zoophycos* and *Chondrites* burrows in question should be considered viable constituents of the *Glossifungites* ichnofacies.

The *Zoophycos - Chondrites* assemblage only exists when the discontinuity (BD4) overlies the muddy substrate of Allomember IV. Cross section Y -Y' (Chapter 3) shows the limited preservation of this allomember in the Hamilton Lake area. In places where BD4 directly overlies the sandier and coarser facies of Allomember III, the *Zoophycos - Chondrites* assemblage is not found associated with the discontinuity.

5.3 Significance and Implications of the *Zoophycos - Chondrites Glossifungites* Suite

The existence of *Zoophycos* and *Chondrites* burrows in a firmground environment has not been previously described. Most authors accept that the *Zoophycos* trace is produced by infaunal sediment feeders, forming spreiten by excretion of ingested sediment from beneath the sediment-water interface (Kotake, 1989). Could such a grazing organism sculpt its way through a firm substrate? The fact that organisms of dwelling structures such as *Diplocraterion* and *Rhizocorallium* are known to produce spreiten in firmground environments supports the possibility (J. MacEachern, pers. com., 1996). Several authors (Ekdale and Lewis, 1991; Olivero and Gaillard, 1996) have observed that *Zoophycos* crosscuts most previous bioturbation structures and are very rarely compacted, suggesting that burrowing must have occurred late in a firm substrate. These conditions are also needed in order that the *Zoophycos* organism can keep a long open tube connected to the surface without fear of substrate collapse. In fact, Ekdale and Lewis (1991) went as far as to suggest that the *Zoophycos* intervals of the Amuri Limestone Group (Upper Cretaceous-lower Oligocene) of New Zealand may reflect obscure omission surfaces.

The assemblage of *Zoophycos* and *Chondrites* in Mesozoic strata are typically associated with the lower offshore to shelf settings (Pemberton et al., 1992) where restricted oxygen levels produce stressful conditions. This would imply, in the case of the Viking occurance, that following the BD4 transgression, conditions quickly returned to lower energy before colonization of the surface. The lack of well developed "nearshore" facies above the BD4 contact supports this statement. These characteristics may warrant classification of this assemblage as a distal expression of the *Glossifungites* ichnofacies (Burton and MacEachern, 1997).

A second implication of the firmground *Zoophycos* burrows concerns their ethology. The material within the burrows is typically fU sandstone, which is clearly not reworked from the surrounding material (max. vfL), but comes from the lag above BD4. Kotake (1989) also noted this relationship in *Zoophycos* burrows of the Shiramuza Formation, Boso Peninsula, central Japan. Fecal pellets within the burrows were composed of tuffaceous material which could only have come from a tuff layer situated above the *Zoophycos* trace. Kotake (1989) felt this indicated that the burrow producer did not feed on organic matter within the host sediment but rather foraged on detritus on the sea floor. The organism clearly segregated its feeding place from its excretory place (Fig. 5.3). Kotake (1989) developed a model for the successive production of the *Zoophycos* helical spreiten (Fig. 5.4). The *Zoophycos* associated with BD4 of the current study supports the behavioural characteristics proposed by Kotake (1989), in that the component material of the spreiten and burrow fill is intimately related to the type of sediment on the paleo-sea floor.

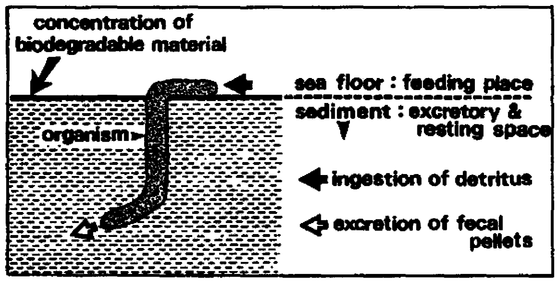


Figure 5.3 Spatial utilization of the *Zoophycos* tracemaker (Kotake, 1989).

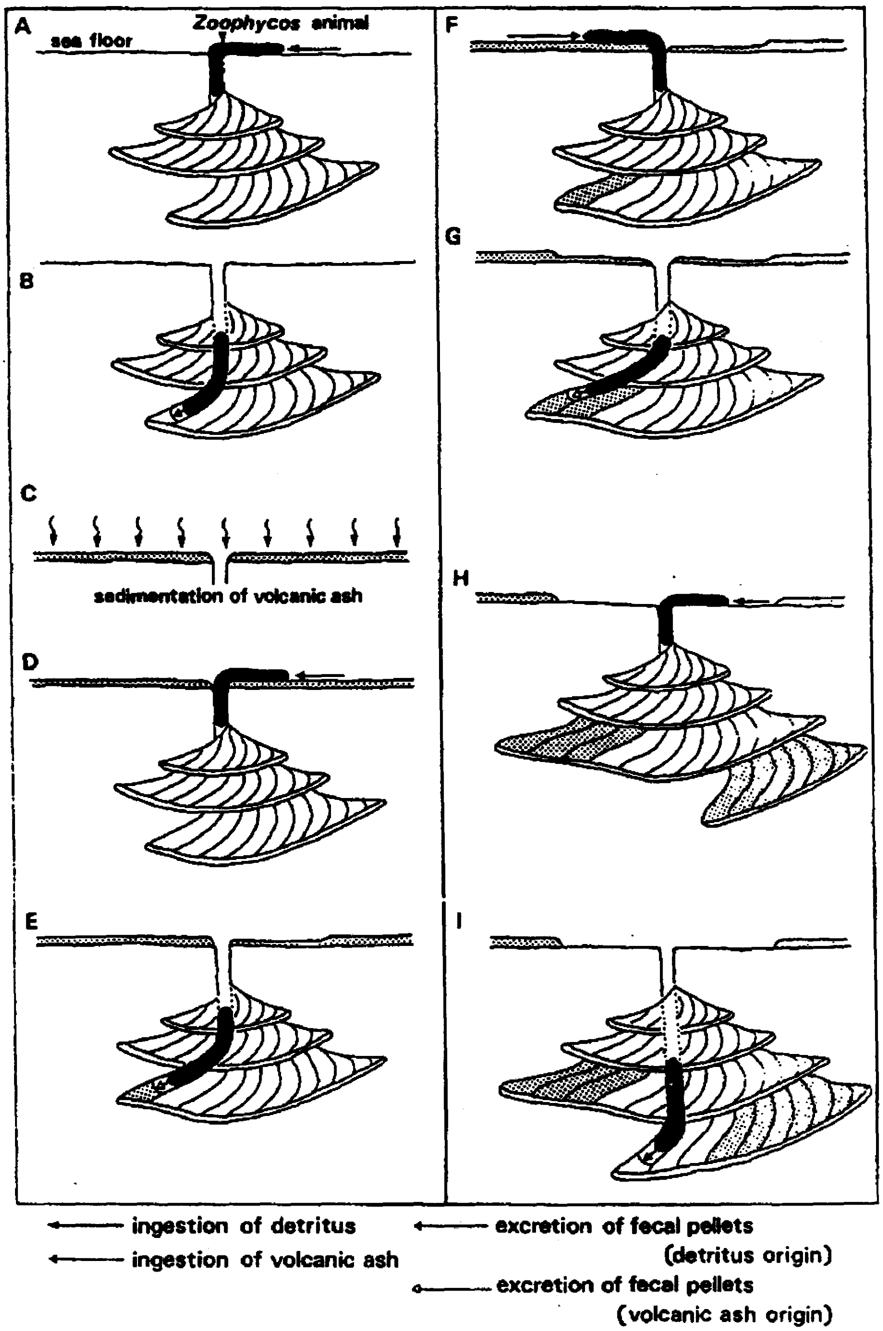


Figure 5.4 Model for the successive production of helical spreite in a *Zoophycos* burrow, incorporating detritus from the sea floor (Kotake, 1989).

CHAPTER 6: DETAILED INTERPRETATION AND DEPOSITIONAL HISTORY

6.1 Introduction

This chapter summarizes the depositional history of the Viking Formation within the study area, based upon the synthesis of data presented in earlier chapters. The combination of facies descriptions with well log and core cross-sections allows for the construction of a high resolution stratigraphy related to fluctuations of relative sea level (RSL).

Four regionally extensive bounding discontinuities are recognized within the study area (BD1-4), which separate the five documented allomembers (I-V). Formation of these discontinuities and deposition of the various allomembers is complex and therefore will be discussed in detail, beginning with the oldest Viking sediments.

6.2 Deposition of Regional Viking Successions (Allomember I)

6.2.1 Deposition of RV1

Before deposition of the 'regional Viking' successions, the Joli Fou sea was at its greatest extent. During this time a maximum flooding surface formed and it is taken here as the base of the Viking Alloformation. Gradually RSL began to drop, bringing the source of coarse clastics closer to the study area and producing the sandier upward succession of RV1 (Fig. 6.1 A). The widespread nature of RV1, its largely offshore character, and the presence of a nearly continuous bentonite in the upper sandier portion, suggest deposition occurred aggradationally over most of the study area, below fair weather wave base. However, in the southeast of the study area RV1 becomes sandier and thicker, with close to 90% HCS sandstone at the top, possibly suggesting a near shoreface depositional environment.

The fact that RV1 is thicker and sandier in the southeast suggests that the source area may lie a little farther to the southeast. This may be a local sediment source because Boreen and Walker (1991) found that regional successions become thicker and sandier northwestward in the Willesden Green area, and Pattison (1991) showed they become thicker and sandier to the west or northwest in the Crystal area, implying a source area to the west or northwest. Isopaching the thickness of RV1 within the current study area would help to gain a better understanding of thickness changes and possible source directions.

Previous studies of the Viking in central Alberta have shown that shorelines in general are oriented NW-SE (Downing and Walker, 1988; Boreen and Walker, 1991) with the source area somewhere to the southwest. The trend of shorelines for regional Viking successions is not known. The possibility of a source area in the southeast for the Hamilton Lake sandstone (RV1) implies major changes in paleogeography for the southeastern Alberta Viking basin. Nevertheless, there is other evidence which may support a southeastern source area.

Firstly, the Viking Formation at Sedalia, a large hydrocarbon field just southeast of

HMLK, appears to be producing from the same interval as the Hamilton Lake Sandstone (as suggested by the examination of one Sedalia core). This suggests that the top of RV1 remains sandy over the HMLK - Sedalia area to the southeast.

Secondly, the Sweetgrass (Bow Island) Arch skirts the edge of the current study area and may have influenced sedimentation by producing a paleotopographic high in southeastern Alberta and west-central Saskatchewan. Arnott et al. (1995) attributed the cyclic deposition of the upper Albian, Bootlegger Member of Montana to episodic reactivation of the ancestral Sweetgrass Arch. Schröder-Adams et al. (1996) also suggested that the Sweetgrass Arch in southern Alberta may have formed a positive bathymetric feature during the Santonian.

Finally, the existence of conglomeratic transgressive lags in the Viking at Hoosier-Dodsland fields of western Saskatchewan (Pozzobon and Walker, 1990) may indicate a greater proximity to a source area, since granules and pebbles are rare in the HMLK area. A similar trend of increasing grain size of transgressive lags is seen on most of the TSEs within this study from northeast to southwest (i.e. toward the source area).

Deposition of RV1 was terminated by a rise of RSL, producing the flooding surface at the top of this succession.

6.2.2 Deposition of RV2

Succession RV2 was deposited below fair weather wave base over the entire study area (Fig. 6.1 B), suggesting aggradation in an offshore environment, susceptible to intense bioturbation in places. The pair of sandier upward successions within RV2 suggest multiple progradation events of a distant shoreline, influenced by minor fluctuations of RSL. In general, RV2 thickens toward the southeast, similarly to RV1. This may indicate the source area for RV2 also lay to the southeast. Deposition of RV2 was terminated by a rise in RSL which produced the flooding surface at the top of this succession.

6.2.3 Deposition of RV3

Deposition of RV3 begins in an offshore environment but a drop of RSL is suggested by the sandier and coarsening upward nature of this succession. The shoreface prograded into the study area at least as far as Huxley (Fig. 6.1 B), as indicated by the presence of *Macaronichnus simplicatus* and supported by the presence of abundant *Ophiomorpha* within HCS and trough cross-bedded sandstones of middle to upper shoreface origin. The trend of this shoreline is difficult to determine because no incision is preserved and thickness changes are strictly controlled by erosion on BD1 or BD2.

6.3 Formation of BD1 and Deposition of Allomember II

6.3.1 Major Drop of RSL - Crystal 1 & Allomember II - HMLK

Following deposition of 'regional Viking' successions 1-3, a major drop of RSL moved the shoreline seaward of the Hamilton Lake area, subaerially exposing everywhere to the southwest (Fig. 6.1 C). In the Crystal area, this lowering of RSL resulted in the cutting of the first valley (CR1) identified by Pattison and Walker (1994), which incised into several regional Viking successions (Fig. 6.1 C). Northeast of HMLK the lowering of sea level caused fair weather wave scouring of previously deposited sediments of Allomember I (RV1-3). As RSL began to rise, southwestward transgression began causing wave scour and truncation of the top of RV1 (HMLK sandstone) along the sharp northeastern edge of HMLK field (Fig. 6.1 C). Continued transgression moved the shoreline landward, rising stratigraphically above the HMLK sandstone and then pausing 4-5 km southwest of the HMLK northeastern edge. This pause preserved the BD1(IT) - HMLK surface which forms an asymmetric incision open to the northeast (Fig. 6.1 C). Above this incision, the shoreface prograded to the northeast out of the study area, depositing the sandier upward, bioturbated, muddy sandstones of Allomember II - HMLK. It is possible that this lowstand or early transgressive shoreface deposit is correlative with either of the lowstand or early transgressive shoreface deposits identified at Lindbrook or Joarcam respectively (Walker and Wiseman, 1995). Attempts to correlate between Joarcam and Allomember II - HMLK show evidence that shoreface trends are somewhat continuous between these sandbodies (Pearson, 1997), but positive confirmation that these shorefaces are time equivalent is still lacking.

Transgression resumed again as RSL began to rise following deposition of Allomember II - HMLK, and the uppermost shoreface sediments were presumably 'planed off' by a BD1(RT) - HMLK surface (Fig. 6.1 D). This surface has subsequently been removed by erosion on BD2 except possibly at the northwestern tip of Hamilton Lake field.

6.3.2 BD1 Transgression - HMLK to Farrell

While the shoreline was at HMLK, the area southwest of HMLK was presumably subaerially exposed. After truncation of Allomember II - HMLK by BD1(RT) - HMLK, RSL continued to rise, moving the shoreline landward by erosive shoreface retreat, thereby removing all evidence of subaerial exposure. Possibly as much as 5 - 15 m (Walker and Plint, 1992) of previously deposited sediments (Allomember I) were removed. Thus the sharp TSE (BD1) was formed, mantled by a lag of the coarsest material winnowed out of the coastline (Fig. 6.1 D).

During this transgression, the incised valley at Crystal was slowly being flooded from the marine end. This produced estuarine conditions within the valley and caused deposition of a tripartite estuarine valley fill (Pattison and Walker, 1994). These deposits are considered as transgressive deposits of Allomember II - CRY (Fig. 6.1 D). Presumably as transgression continued southwestward the valley fill deposits were truncated by a ravinement surface BD1 - CRY (Fig. 6.1 D), but this surface has been removed by a later erosional event (BD3; TSE 3 in Pattison and Walker, 1994).

As the transgression continued landward, rising sea level caused the TSE to rise stratigraphically , which resulted in greater preservation of regional Viking successions southwestward. However, the BD1 surface in places cuts gently *downward* stratigraphically (0.015 - 0.08°) to the southwest. This scenario can be explained if the shoreface cut horizontally into gently seaward-dipping deposits of Allomember I during a stillstand of RSL. Examples of stratigraphic downcutting in a landward direction are common in the Cardium Formation of central Alberta and detailed descriptions of this process are well summarized by Walker and Eyles (1988).

Transgression continued as far as Farrell, where a pause in the overall transgression occurred. An asymmetrical shoreface incision was preserved (BD1(IT) - FAR; Fig. 6.1 D) which is most pronounced just southwest of Farrell. During this pause, sand was supplied to the shoreface causing local progradation, seen as the sandier upward succession at Farrell (Allomember II - Farrell; Fig. 6.1 D). The orientation of this shoreline was NNW - SSE as defined by tracing the line of incision alongstrike, until it gradually dies out to the northwest under Fenn West and to the southeast at the eastern end of Chain South. The main sandbody at Farrell is therefore interpreted as a transgressively incised shoreface deposit.

6.3.3 BD1 Transgression - Farrell to Huxley

Following deposition at Farrell, transgression resumed as RSL began to rise again. This resumed transgression planed off the uppermost shoreface sediments at Farrell, creating BD1(RT) - FAR (Fig. 6.1 E). Transgression continued southwestward, producing the sharp BD1 surface which rises stratigraphically landward (SW). Much of the underlying regional Viking (RV2, RV3) was eroded during this erosional shoreface retreat, but greater and greater thicknesses are preserved landward (SW). The transgression continued at least as far as Huxley (Fig. 6.1 E), where BD1 is truncated by a later erosional event (BD3).

6.3.4 Allomember II - Highstand Progradation

The BD1 transgression reached its maximum extent southwest of Huxley as RSL stabilized. During the ensuing highstand of sea level, continued supply of sand to the shoreface resulted in extensive progradation. This progradation continued for a distance of over 30 km to the northeast, at least to Fenn and over top of Allomember II - Farrell (Fig. 6.1 E). This produced the sandier upward, offshore to shoreface succession of Allomember II, found over much of the southwestern study area. Northeast of Fenn very little of the Allomember II highstand deposits is preserved.

6.4 Formation of BD2 and Deposition of Allomember III

6.4.1 Lowering of RSL

After deposition of Allomember II, a small drop of RSL occurred (Fig. 6.1 F). Just how far the shoreline regressed is difficult to determine, because no lowstand shoreline is recognized associated with BD2. Also, although there is erosion by BD2 at HMLK, as shown by dissection of Allomember II - HMLK (Fig. 6.1 F), alongstrike from HMLK at Maple Glen it is difficult to even recognize the BD2 surface let alone demonstrate erosion on it. It is suggested that this lowering of sea level was relatively small and short lived, such that no lowstand deposits were developed. Erosion by BD2 at HMLK may have occurred in a submarine environment as fair weather wave base was forced onto the deposits of Allomember II - HMLK. The same surface at Maple Glen may have received little or no erosion, and as such would be considered a correlative conformity.

6.4.2 BD2 Transgression - HMLK to Joffre

A rise in RSL initiated the landward formation of BD2. Shoreface retreat during transgression resulted in some erosion of the underlying Allomember II highstand deposits. This transgression continued landward to the northeastern edge of the Fenn fields, where a pause in the overall transgression preserved an asymmetric shoreface incision (BD2[IT] - JOF) open to the northeast (Fig. 6.1 G). This incision was also recognized at Joffre, where it was termed E2 by Downing and Walker (1988). During the initial stages of this pause of RSL, deposition in the distal reaches of the shoreface incision occurred in a quiet oxygen-depleted environment as indicated by the low abundance and diversity of trace fauna. As sand and coarse sediment continued to be supplied to the shoreface, eventually progradation occurred, slowly filling the incision (Fig. 6.1 G). This progradation brought about higher energy conditions and with it greater mixing of oxygenated waters, thereby increasing the abundance and diversity of trace fossils upwards. This incision and progradation is preserved as the mudstone-based, sandier upward, incised shoreface deposits (Allomember III - Main trend) which truncate Allomember II northeast of Fenn. Alongstrike at Joffre, considerably greater input of coarse sediment produced a much coarser and better developed shoreface succession (Downing and Walker, 1988).

The BD2(IT) incision at Joffre becomes less pronounced at Fenn and is difficult to recognize further to the southeast. Small incisions on BD2 were identified at the southern end of Sullivan Lake, but lack of core and well data make it difficult to confirm incised shoreface deposits. This shoreline is remarkably straight and trends in a NW-SE direction.

6.4.3 BD2 Transgression - Joffre and southwestward

Following deposition of the transgressive shoreface deposits at Joffre, RSL began to rise again. The resumed transgression 'planed off' the uppermost shoreface sediments, creating BD2(RT) above the main trend of linear sandbodies (Fig. 6.1 H), which was termed CM4 (Core Marker 4) by Downing and Walker (1988). Sea level rise continued, causing transgression of the sea (and formation of BD2) at least as far southwest as Chain North, beyond which BD2 has been truncated by a later erosional event (BD3).

6.4.4 Allomember III - Highstand Deposition

The position of the highstand shoreline is unknown for Allomember III because most of these deposits are erosionally removed toward the southwest. However, preservation of a sandier upward succession above BD2 (and BD2(RT)) northeast of Fenn and in the Sullivan Lake, Hamilton Lake/Provost area suggests that substantial progradation of the shoreline occurred. The preserved highstand deposits of Allomember III were deposited entirely below fair weather wave base. Deposition in the northeastern study area began in a shelfal environment, probably within oxygen depleted waters as suggested by the 'stressed' mudstones at the base of the succession. The shoreline prograded with at least two periods of intermittent deepening, probably caused by small rises of RSL. Increases in sandstone content, and abundance and diversity of trace fossils upwards in the succession indicates progradation of offshore sediments with correspondingly better oxygenated waters.

The preserved succession never reaches shoreface conditions within the study area but does display well developed HCS sandstones of a transitional association (Fig. 4.2; Pemberton and MacEachern, 1995). These sandstones form the producing interval at the southwestern edge of the large Provost reservoir (Fig. 6.1 H). Without further study to the northeast it remains unclear how deposition of reservoir quality sandstones of offshore-transition origin could persist another 50 km to the northwest, from only a southwestern shoreline.

6.5 Formation of BD3 and Deposition of Allomember IV

6.5.1 Major drop of RSL

After deposition of Allomember III a major drop of RSL occurred which moved the shoreline seaward, beyond the northeastern edge of the study area (Fig. 6.1 I). During this lowstand of sea level, the entire study area would have been subaerially exposed. It is assumed that at this time the second incision event at Crystal (CR2, Fig. 6.1 I ; SB2, Pattison and Walker, 1994) was cut to approximately the same depth as the first incision. This lowstand event may also correspond to lowstand shoreface deposits identified at Beaverhill Lake (Walker and Wiseman, 1995).

6.5.2 BD3 Transgression & Allomember IV - CRY

The shoreline began to move landward (SW) again as RSL started to rise. Erosional shoreface retreat may have removed all evidence of subaerial exposure and dissected the underlying deposits of Allomember III - PROV (Fig. 6.1 J). In places over HMLK, BD3 cuts stratigraphically downward in a landward direction (SW). This can again be explained by horizontal erosion of seaward dipping strata (Walker and Eyles, 1988). The sparse lag scattered above BD3 at HMLK can be attributed to a lack of coarse material in the 5-15 m of section being eroded during transgression.

Continued sea level rise caused flooding of the incised valley at Crystal, where the fill (Allomember IV - CRY; Fig. 6.1 J) is dominated by input from the fluvial end, expressed by the dominance of fluvial sandstones and conglomerates (Pattison and Walker, 1994). Transgression continued southwestward, with BD3 truncating the second valley fill of Crystal, as well as eroding the original ravinement surface of the first Crystal valley fill (Fig. 6.1 J).

Without pausing, the BD3 transgression continued southwestward to the Joffre-Fenn trend, where it truncates BD2(RT) - JOF. Farther southwest at Huxley, BD3 also truncates BD1. The TSE can be traced to the southwestern edge of the study area and probably continues considerably farther. The transgressive lag above BD3 becomes much coarser at, and southwest of, the Joffre-Fenn trend, probably due to the greater availability of pebble sized material.

The lowermost sediments of Allomember IV in the extreme southwest of the study area tend to consist of pebbly mudstone which fine upwards. These sediments were likely deposited during the BD3 transgression, as storm emplaced pebble stringers in transgressive mudstones, which have subsequently been mixed by bioturbation.

6.5.3 Allomember IV - Highstand to Early Falling Stage Deposition

After maximum transgression somewhere to the southwest of the study area, the ensuing highstand deposition began. The thick sandier upward succession (max. 22 m) preserved in the Huxley to Richdale area (Fig. 6.1 K) represents the progradation of offshore to transition facies (Fig. 4.2; Pemberton and MacEachern, 1995). A wave dominated environment is suggested by the abundance of well developed HCS towards the top of the succession. The same succession has been recognized between Caroline and Joffre by numerous other workers (Hein et al., 1986; Leckie, 1986; Boreen and Walker, 1991; Leckie and Reinson, 1993). At Caroline the succession displays swaley cross-stratified (SCS) sandstones and is in places capped by non-marine facies (Davies and Walker, 1993).

The gradational sandier upward deposits of Allomember IV can be traced northeastward to about the area of Chain North, where the succession begins gradationally but is capped by a thin (1-2 m) sharp-based sandstone unit displaying characteristics of transition-lower shoreface environments. This upper sandstone unit is interpreted as a deposit formed at the 'toe' of a forced regressive shoreface (Plint, 1991), marking the late stages of highstand or early falling stage of RSL.

The Allomember IV deposits to the northeast (Sullivan Lake-HMLK) show very thin sandstone beds in stressed mudstone, which probably reflect the distal, oxygen-depleted deposits of the thicker-bedded highstand deposits to the southwest. In places at Sullivan Lake and HMLK, Allomember IV becomes much sandier upward (to nearly 90% sandstone) in less than 5 m (Fig. 6.1 L), which supports the suggested forced regression in the southwest.

6.6 Formation of BD4 and Deposition of Allomember V

6.6.1 Major Drop of RSL

During the later stages of deposition of Allomember IV, a small drop of RSL occurred (Sect. 6.5.3). This may have been heralding (or been part of) the major drop of RSL which is interpreted to have occurred after deposition of Allomember IV. The shoreline was moved a great distance seaward (NE) out of the study area (Fig. 6.1 L). Presumably the entire study area was subaerially exposed at this time. No known incised valleys are associated with this fall of RSL.

6.6.2 BD4 Transgression - Allomember V

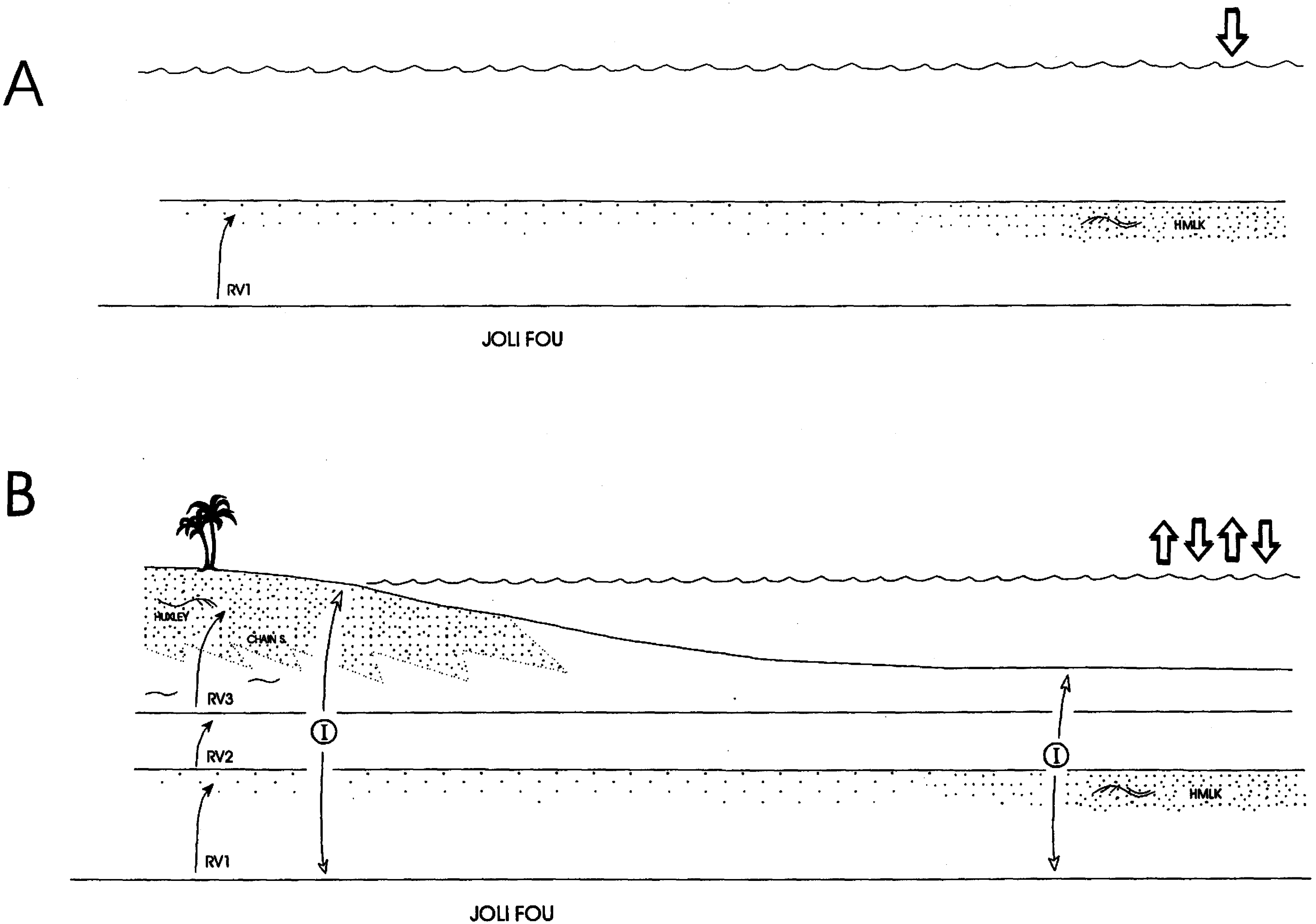
The final position of the shoreline northeast of the study area is unknown. However, RSL began to rise again, possibly removing 5-15 m of section as the shoreface retreated southwestward, eroding any evidence of subaerial exposure. This transgression began rapidly and was continuous, leaving very little development of nearshore facies and only a thin lag of coarse material. The erosional nature and speed of the transgression at HMLK may be indicated by the development of a distal *Glossifungites* ichnofacies comprising *Zoophycos* and *Chondrites* (Burton and MacEachern, 1997).

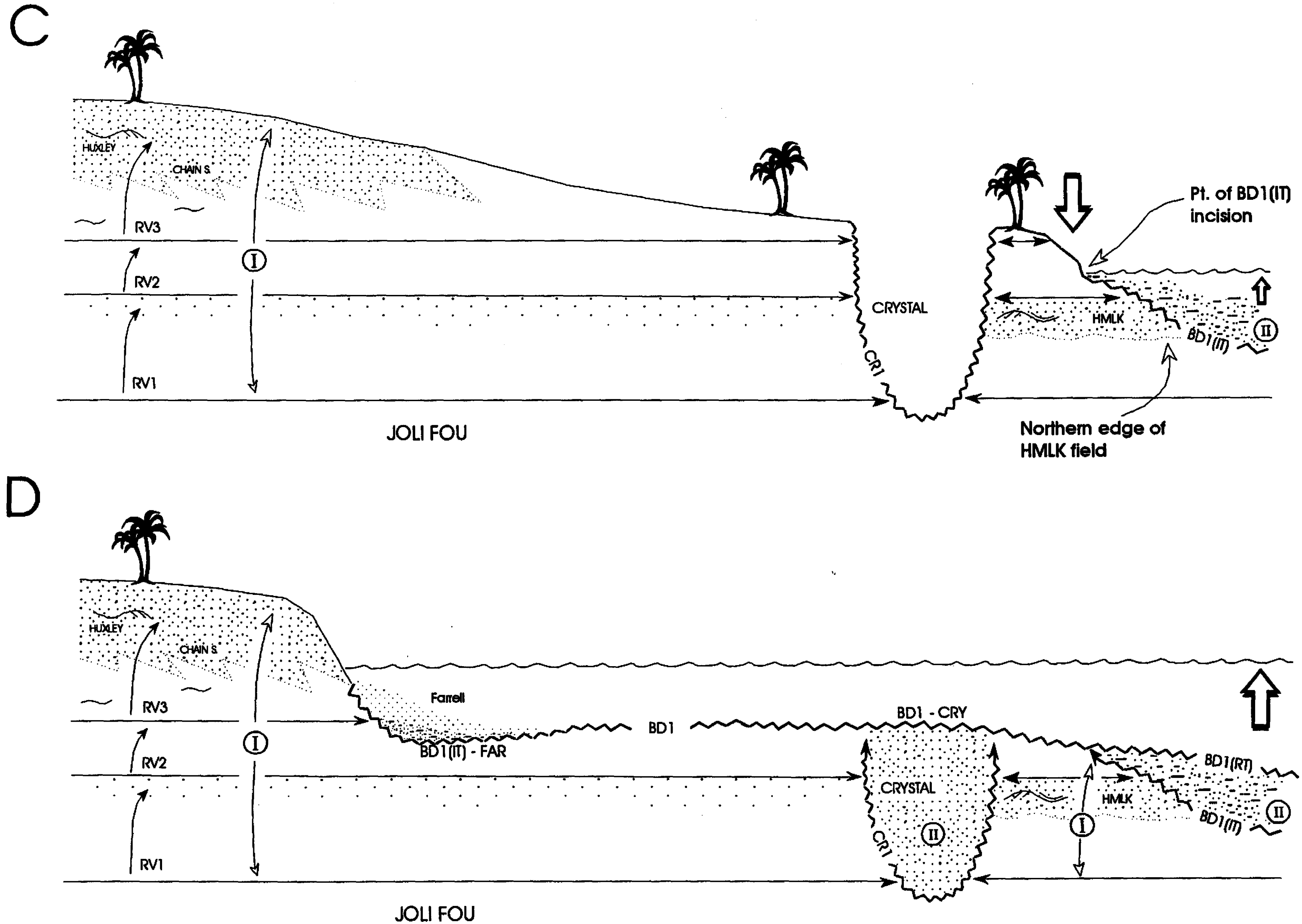
As transgression continued in the HMLK-Sullivan Lake area, transgressive mudstones were being deposited above the TSE in a shelfal setting (Fig. 6.1 M). Periodically, short lived, minor drops of RSL forced thin, sharp-based accumulations of coarse sediment onto previously deposited transgressive mudstones. This 'gritty' sand was commonly bioturbated into the surrounding mudstone, and then blanketed by more mudstone as transgression resumed. This process produced the sharp based 'gritty' mudstone units which occur above, and onlap onto BD4 in the HMLK-Sullivan Lake area.

Transgression continued southwestward to just south of Chain North. Here again a small drop of RSL brought fair weather wave scour onto previously deposited transgressive mudstone. During this regression, as much as 50-150 cm of lower shoreface sandstone prograded 7-8 km directly on top of the underlying mudstone (Fig. 6.1 M). This 'tongue' of coarse sediment onlaps BD4 landward, and 'shales out' seaward. As RSL began to rise again, resumed transgression stranded this sandbody and blanketed it in transgressive mudstone (Fig. 6.1 N). The sandbody at Chain North is therefore interpreted as a forced regressive lower shoreface sandbody, formed within an overall transgression. Davies and Walker (1993) first described and interpreted sandbodies of this type within the Viking, onlapping BD4 (VE4 in their terminology) in the Caroline-Garrington area.

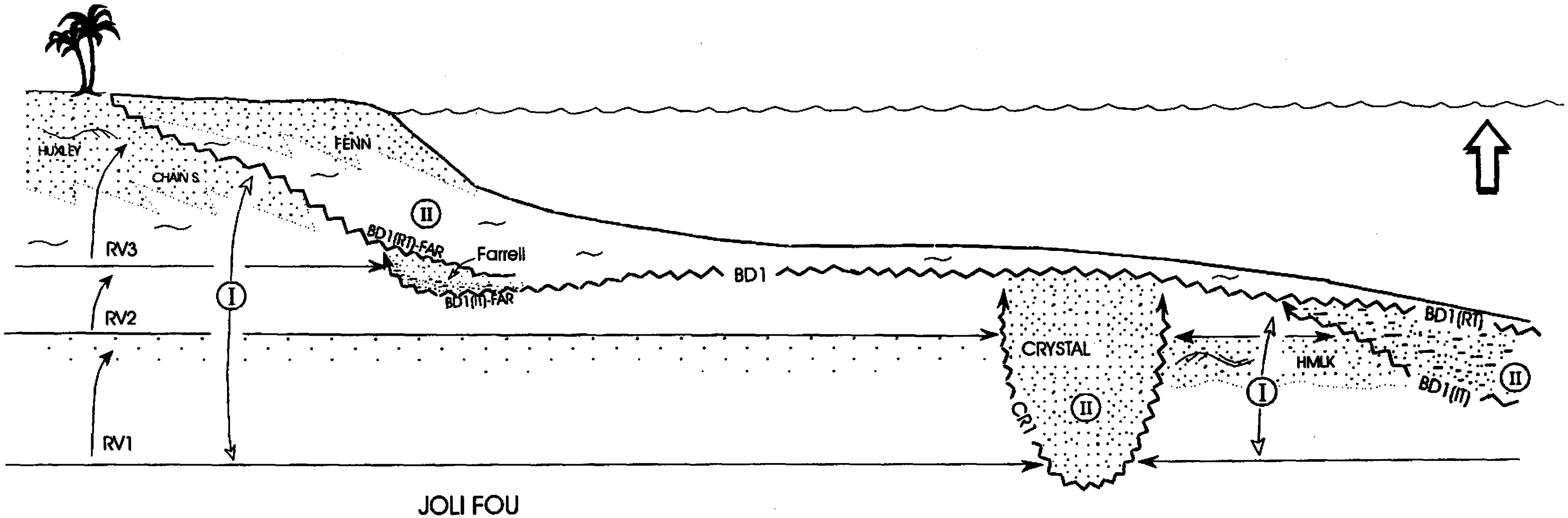
Following deposition of the sandbody at Chain North, transgression continued to the southwest out of the study area (Fig. 6.1 N). The remaining deposits of Allomember V are black mudstones indicating that RSL continued to rise and the study area remained in deep marine conditions for the remainder of deposition of the Viking Alloformation. The maximum extent of this deepening is probably recorded by the Base of Fish Scales Marker, a condensed horizon capping the Viking Alloformation (Fig. 6.1 N).

Figure 6.1 (A-N) The following nine pages illustrate the step by step depositional history of the Viking Alloformation in central Alberta. Major bounding discontinuities are labelled BD1 - 4 and allomembers are circled Roman Numerals I - V. Arrows indicate a rise or fall of relative sea level. The illustrations are oriented roughly SW-NE but do not follow a straight line of section, but rather are composite sections showing stratigraphic relationships of various Viking fields. The two incisions at Crystal (CR1 and CR2) are superimposed between Joffre and Hamilton Lake by projecting their positions alongstrike. See text for details. No scale is implied.

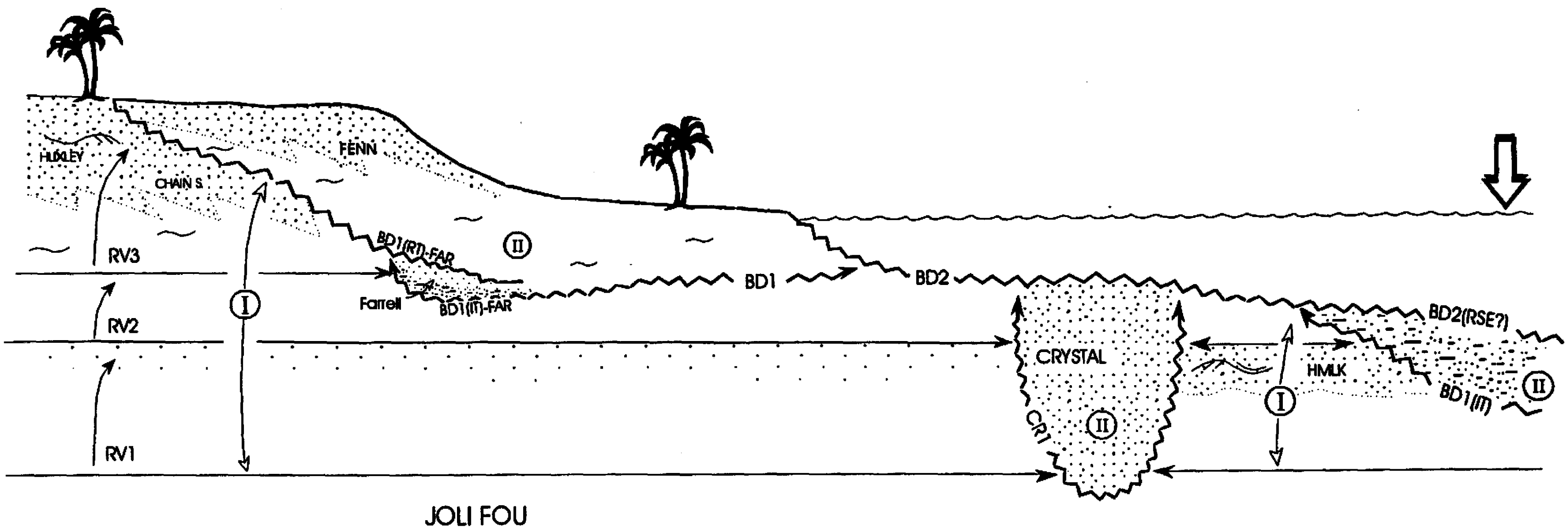

A
HMLK
RV1
JOLI FOU
B
HUXLEY
CHAIN S.
RV3
RV2
RV1
I
I
HMLK
JOLI FOU


C
HUXLEY
CHAIN S.
RV3
RV2
RV1
I
CRYSTAL
CRI
JOLI FOU
Pt. of BD1(IT) incision
HMLK
BD1(IT)
II
Northern edge of HMLK field
D
HUXLEY
CHAIN S.
RV3
RV2
RV1
I
Farrell
BD1(IT) - FAR
BD1
BD1 - CRY
CRYSTAL
CRI
II
HMLK
BD1(RT)
BD1(IT)
JOLI FOU

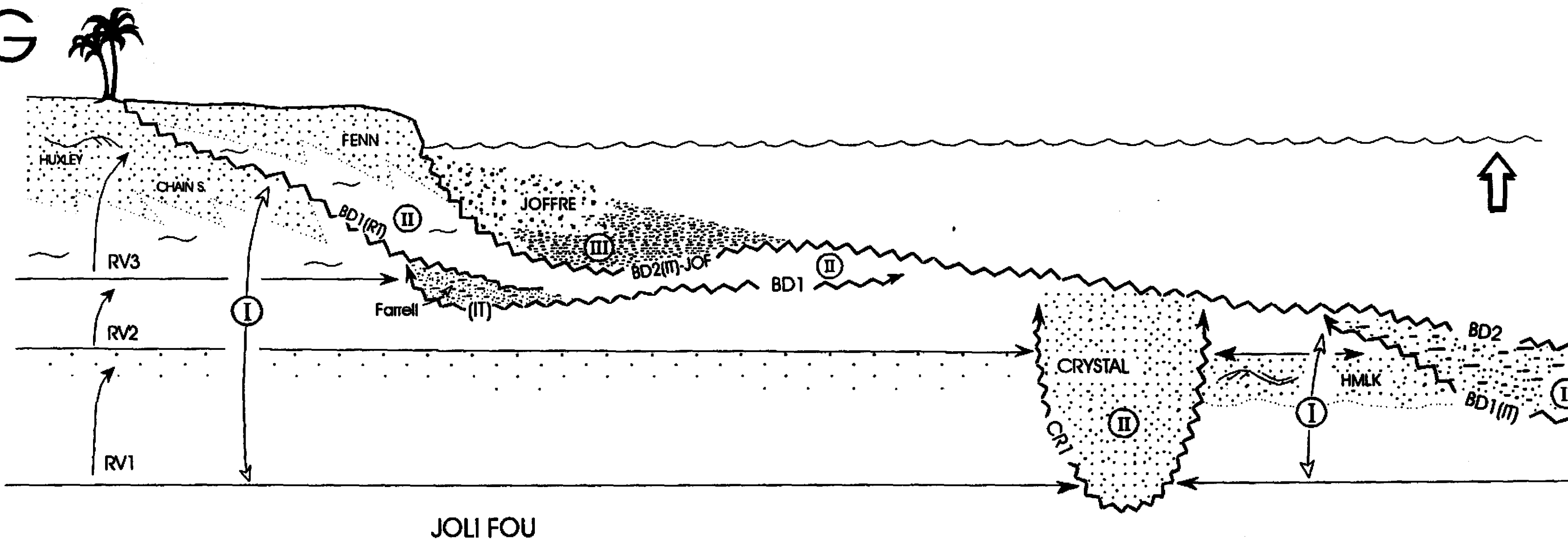
E


HUXLEY
CHAIN S.
FENN
II
BD1(RT)-FAR
Farrell
BD1(IT)-FAR
RV3
RV2
RV1
I
BD1
CRYSTAL
CR1
II
HMLK
I
BD1(RT)
BD1(IT)
II
JOLI FOU

F

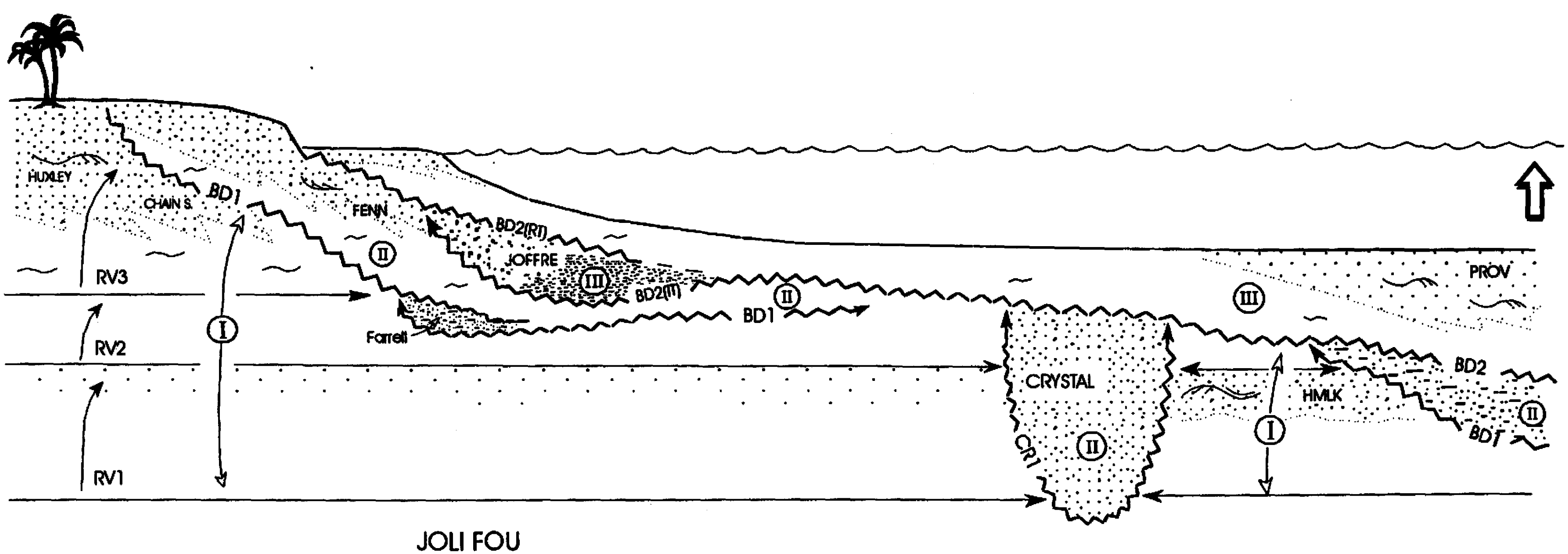

HUXLEY
CHAIN S.
FENN
II
BD1(RT)-FAR
Farrell
BD1(IT)-FAR
RV3
RV2
RV1
I
BD1
BD2
CRYSTAL
CR1
II
HMLK
I
BD2(RSE?)
BD1(IT)
II
JOLI FOU

G



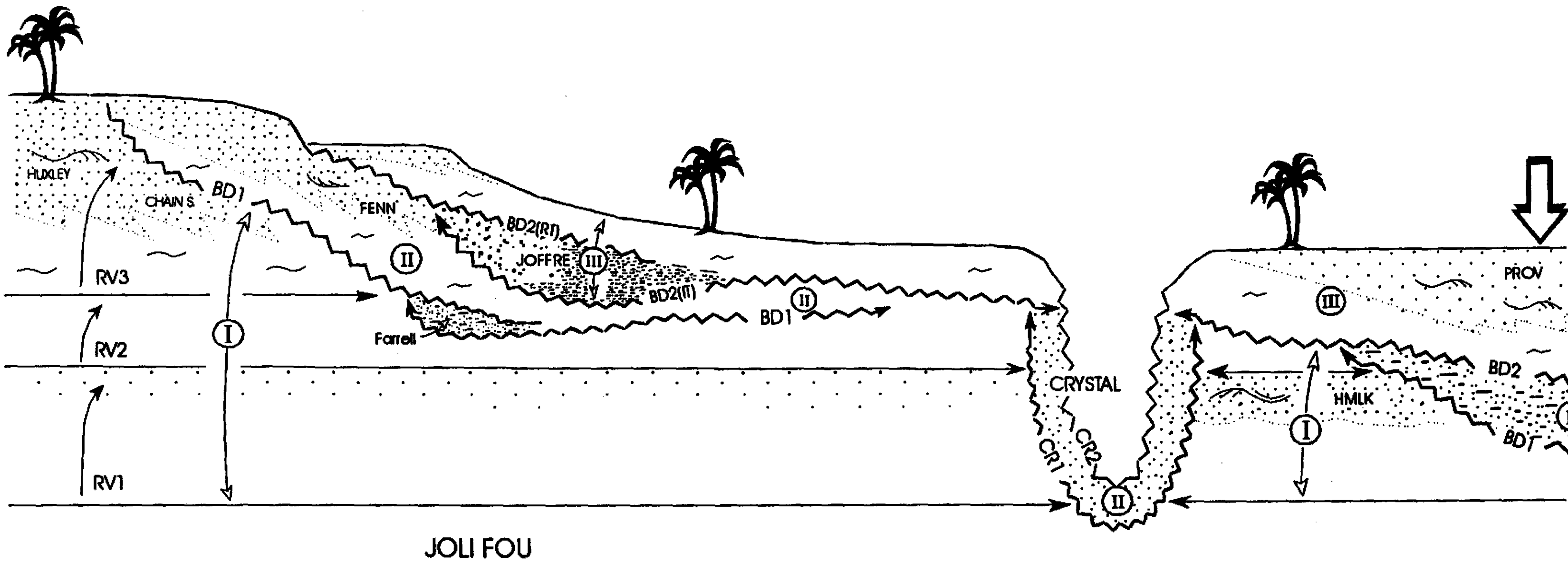
HUXLEY
CHAIN S.
FENN
JOFFRE
BD1(RT)
BD2(IT)-JOF
BD1
Farrell
(IT)
RV3
RV2
RV1
CRYSTAL
CR1
HMLK
BD2
BD1(IT)
JOLI FOU

H

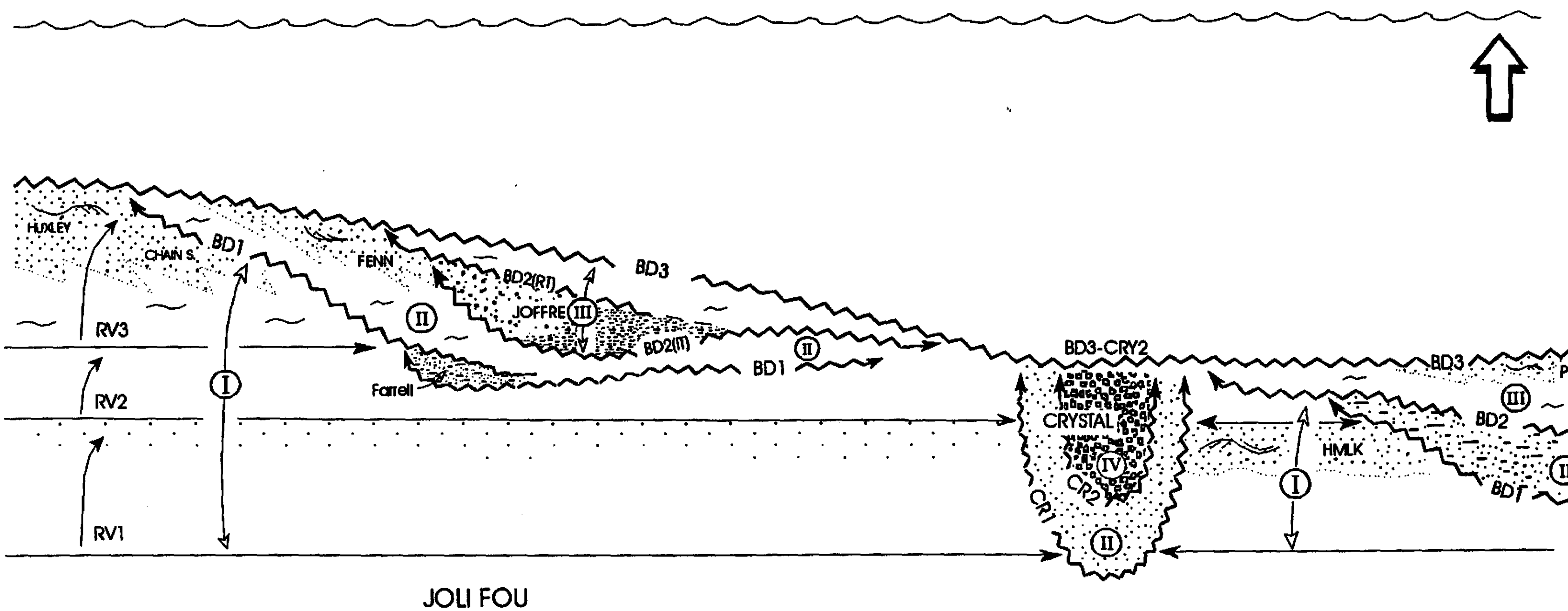


HUXLEY
CHAIN S.
BD1
FENN
BD2(RT)
JOFFRE
BD2(IT)
BD1
Farrell
RV3
RV2
RV1
PROV
CRYSTAL
CR1
HMLK
BD2
BD1
JOLI FOU

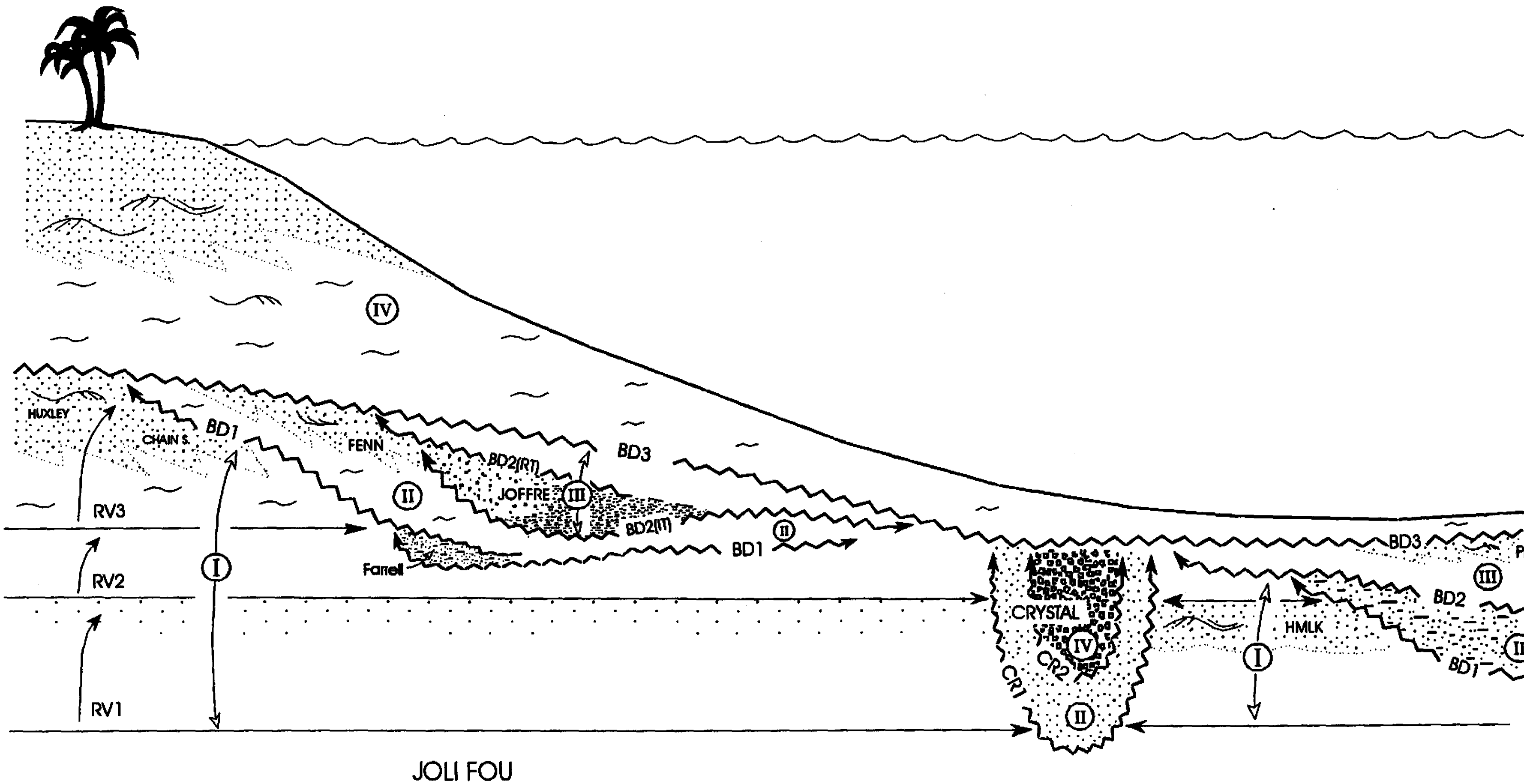
I


HUXLEY
CHAIN S.
BD1
FENN
BD2(RT)
JOFFRE
III
BD2(IT)
II
BD1
Farrell
RV3
RV2
RV1
I
CRYSTAL
CR1
CR2
PROV
BD2
HMLK
BD1
JOLI FOU

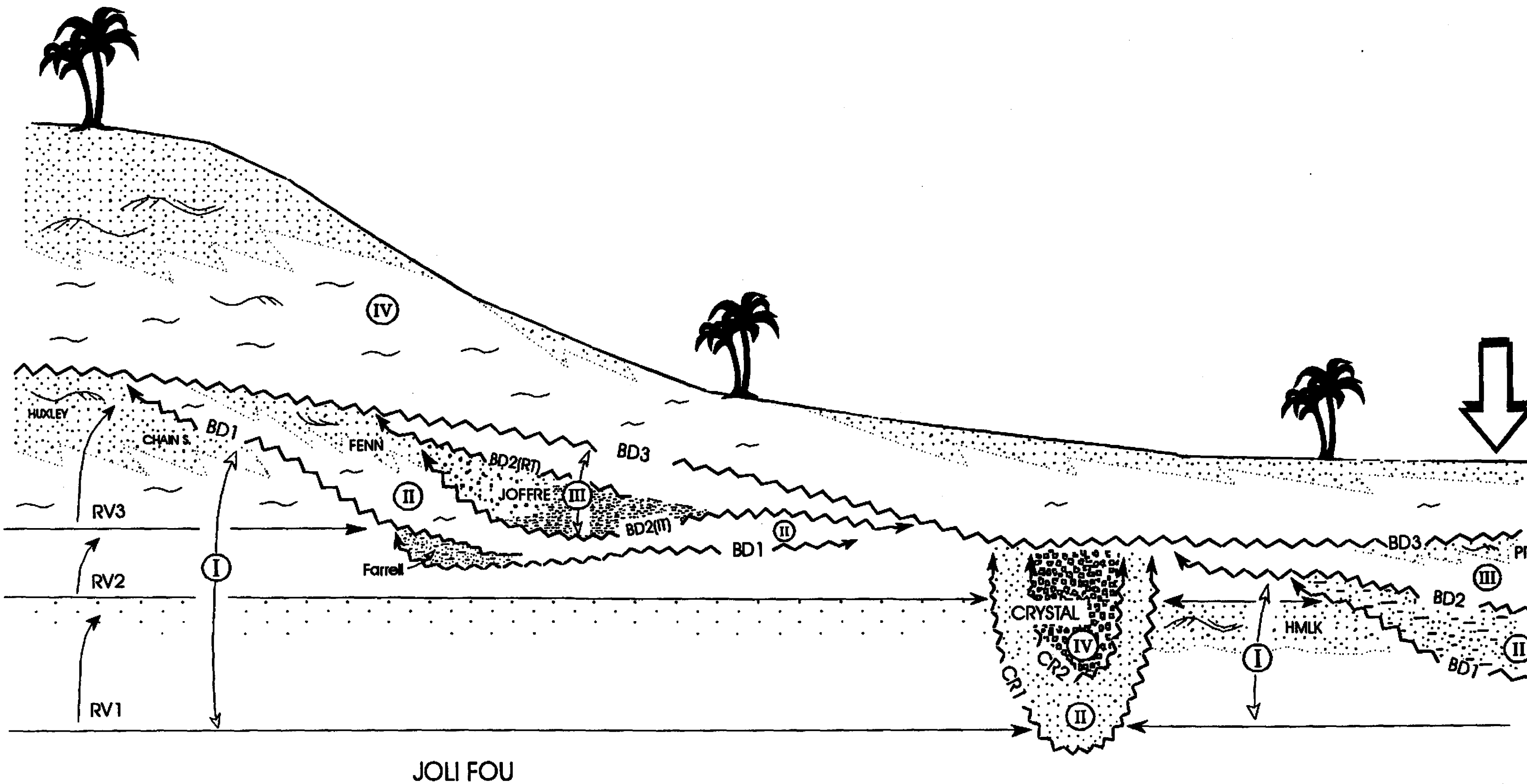
J


HUXLEY
CHAIN S.
BD1
FENN
BD2(RT)
JOFFRE
III
BD3
BD2(IT)
II
BD1
Farrell
RV3
RV2
RV1
I
BD3-CRY2
CRYSTAL
IV
CR2
CR1
BD3
PROV
BD2
HMLK
BD1
JOLI FOU

K

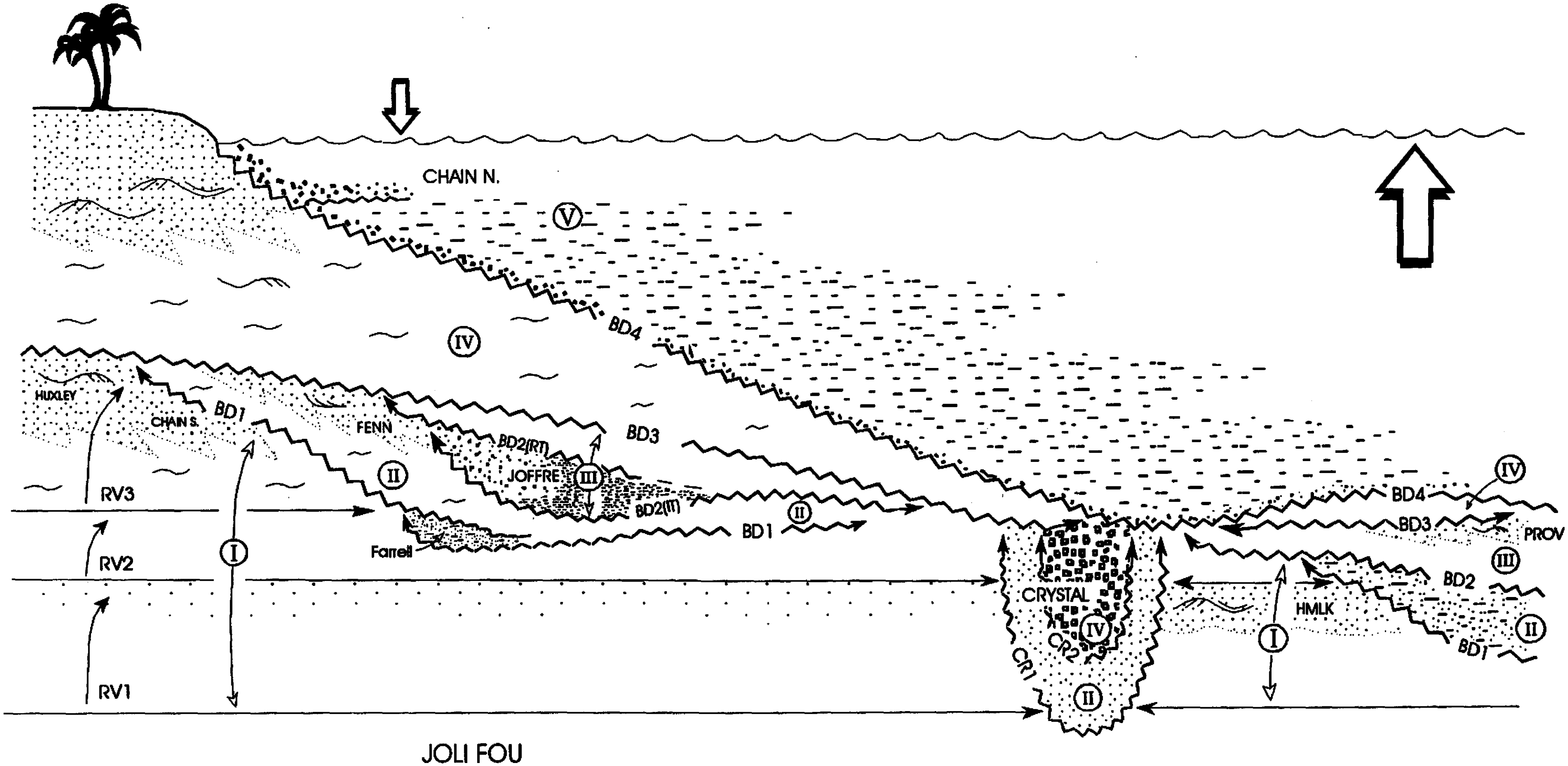

IV
HUXLEY
CHAIN S.
BD1
FENN
BD2(RT)
JOFFRE
III
BD3
II
RV3
RV2
RV1
I
Farrell
BD2(IT)
BD1
II
CRYSTAL
IV
CR2
CR1
II
BD3
PROV
III
BD2
HMLK
I
II
BD1
JOLI FOU

L

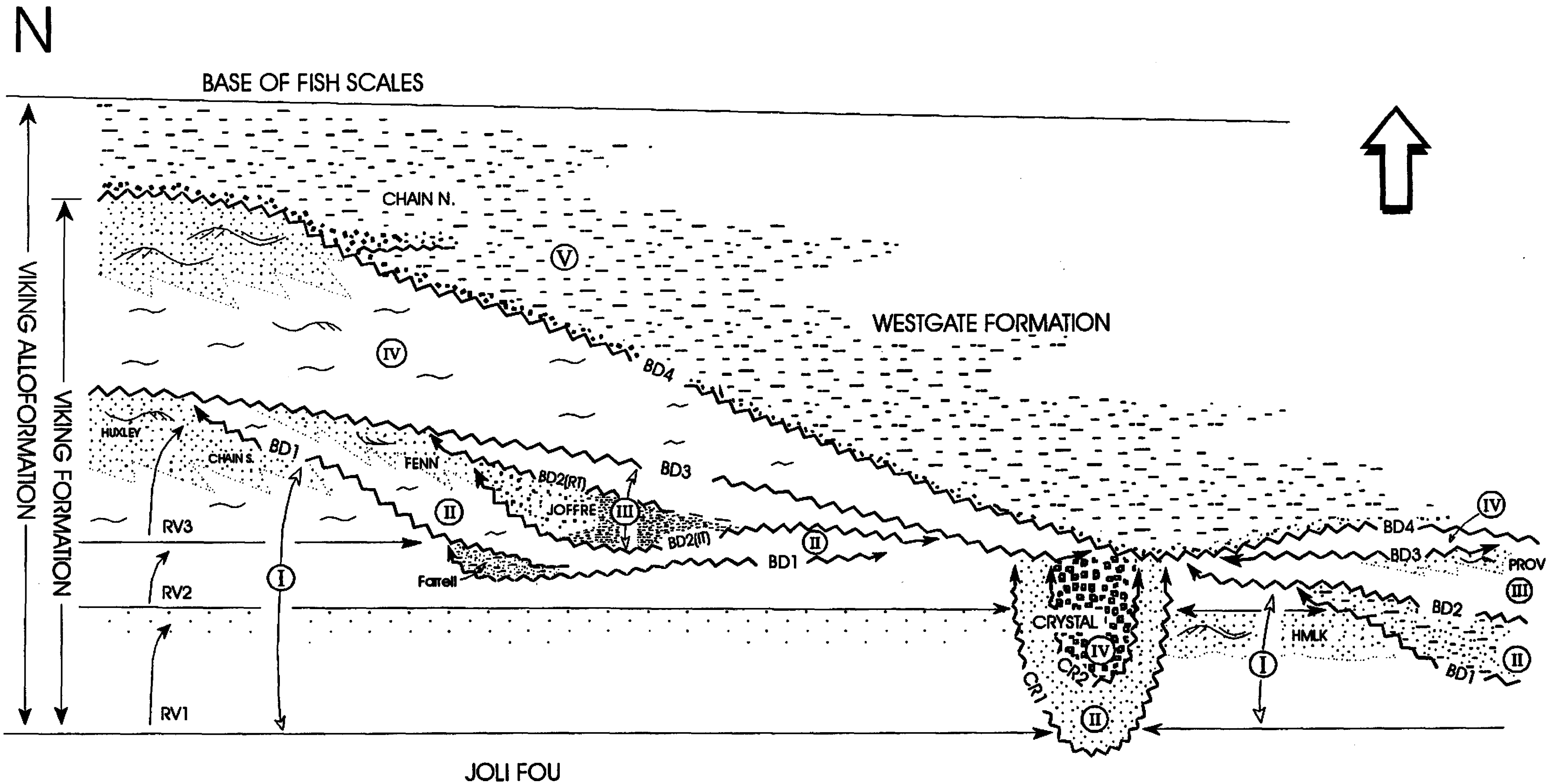


IV
HUXLEY
CHAIN S.
BD1
FENN
BD2(RT)
BD3
II
JOFFRE
III
BD2(IT)
RV3
RV2
RV1
I
Farrell
BD1
II
CRYSTAL
IV
CR1
CR2
II
BD3
PROV
III
BD2
HMLK
I
II
BD1
JOLI FOU

M



CHAIN N.
V
IV
BD4
HUXLEY
CHAIN S.
BD1
FENN
BD3
BD2(RT)
JOFFRE
III
BD2(IT)
II
BD1
Farrell
RV3
RV2
RV1
I
CRYSTAL
CR1
CR2
BD4
BD3
PROV
BD2
HMLK
JOLI FOU


N
BASE OF FISH SCALES
VIKING ALLOFORMATION
VIKING FORMATION
CHAIN N.
V
WESTGATE FORMATION
IV
BD4
HUXLEY
CHAIN S.
BD1
FENN
BD2(RT)
BD3
JOFFRE
III
BD2(IT)
II
RV3
RV2
RV1
I
Farrell
BD1
CRYSTAL
CR2
CR1
BD4
BD3
PROV
BD2
HMLK
BD1
JOLI FOU

6.7 Summary of Viking Sea Level Fluctuations

6.7.1 Introduction

The existence of four regional TSEs, identified within the Viking Formation of central Alberta (BD1-4), indicates that at least four significant fluctuations of RSL occurred during Viking time. From the interpreted depositional history, it is possible to construct a RSL curve for the Viking, and relate deposition of the various sandbodies within this study area to different positions on the curve (Fig. 6.2). The speculated positions of the two incised valleys at Crystal (Pattison and Walker, 1994) have been superimposed on this RSL curve. These valleys have been associated with the two greatest drops of RSL prior to formation of BD3 which truncates both valley fills.

6.7.2 Magnitude of Relative Sea Level Fluctuations

The minimum magnitude of RSL fluctuations can only be determined directly from the depth of incision of valleys. The first incision at Crystal is approximately 30 m deep and cuts into regional Viking deposits which are interpreted to be deposited below fair weather wave base (5-15 m) (Pattison and Walker, 1994). This implies a drop of RSL of at least 35-50 m. If we also assume that the cutting and filling of Crystal 1 is related to the formation of BD1, then a rise of RSL of at least 35 m is responsible for the creation of the first extensive Viking TSE (BD1). The second incision at Crystal is also 30 m deep (Pattison and Walker, 1994). If we assume that the cutting and filling of Crystal 2 is related to the formation of BD3, then a rise of RSL of at least 30 m is responsible for the creation of the third extensive Viking TSE (BD3). BD2 appears to be less extensive than

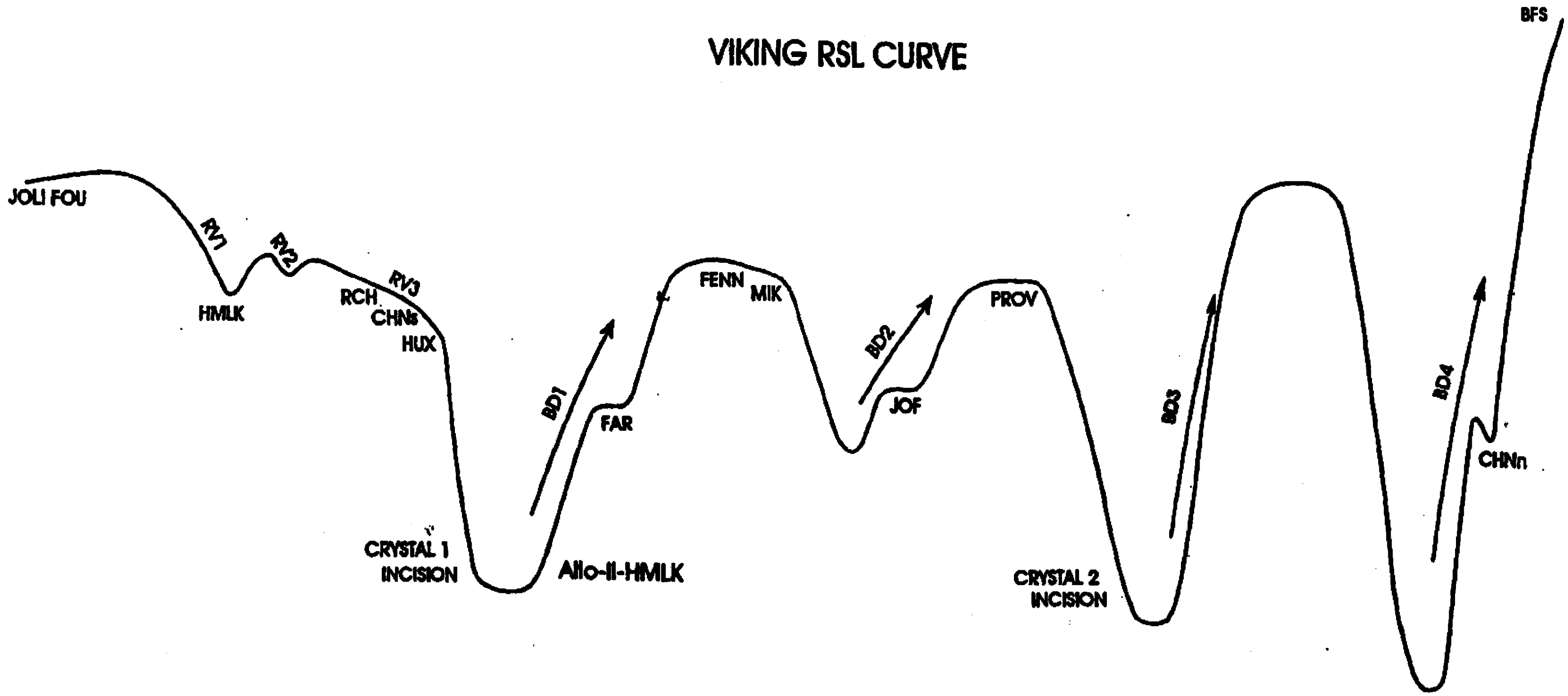


Figure 6.2 The proposed relative sea level curve for the Viking Formation in the study area. Position of Viking reservoirs are shown relative to the curve, with the two valley incisions at Crystal surperimposed. HMLK=Hamilton Lake, RCH=Richdale, CHNs=Chain South, HUX=Huxley, FAR=Farrell, MIK=Mikwan, JOF=Joffre, PROV=Provost, CHNn=Chain North, BFS=Base of Fish Scales. No Scale implied.

either BD1 or BD3 and logically the magnitude of RSL change should therefore be less than those for BD1 and BD3. The extent of BD4 appears to be the greatest of all four TSEs. No lowstand or highstand shorelines have been discovered associated with BD4 and this may imply that the fluctuation of RSL which created BD4 was the greatest of Viking time, presumably greater than 35 m. Walker (1995) demonstrated 40 m of erosional relief on BD4 (VE4 in his terminology).

The only other way of determining magnitudes of RSL fluctuations is by a simple but indirect calculation based on the known distance of transgression, and an assumption about the gradient of the shelf across which the sea transgressed. The difficulty here lies in knowing the correct shelf gradient, which is unknown for the Viking. Approximating this gradient is possible by using the dip required to restore landward dipping erosion surfaces back to the horizontal. This value (0.015 - 0.08°) was calculated for BD1 between HMLK and Farrell, a distance of approximately 40 km. For the shoreline to transgress this distance over the estimated gradient, RSL must have risen 11 - 53 m.

6.7.3 Timing

The next fundamental question concerning the interpreted fluctuations of RSL concerns their frequency. Deposition of the entire Viking Formation is estimated to have taken about 1.5 Ma (see Chapter 2). When combined with the deposition of the underlying Joli Fou shales, the Viking makes up part of the Kiowa-Skull Creek cycle (Caldwell 1984), which would be considered a third order depositional cycle (1-5 m.y.) as defined by Van Wagoner et al. (1990). Haq et al. (1987, 1988) identify a prominent eustatic fall of sea level at 98 Ma which coincides relatively closely with the suspected age of the Viking.

In detail however, deposition of the Viking was controlled by at least four major fluctuations of RSL. If we arbitrarily assign an equal period of time for each depositional cycle over a period of 1.5 m.y., then the duration of each cycle works out to be 375,000 years. Because these four cycles would be superimposed on one third order cycle, they can be considered as fourth order cycles. Their estimated durations are compatible with those of fourth order cycles (Van Wagoner et al., 1990, p. 42).

6.7.4 Possible Controls on Fluctuations of RSL

The controls on fluctuations of RSL include the interplay of local tectonics, eustasy and sedimentation rates (Plint et al., 1992). The mechanism or mechanisms controlling sea level changes during Viking time must work at sufficiently fast geological rates (375, 000 yrs.) and be capable of causing fluctuations of a magnitude 35 m or greater.

There are numerous excellent reviews on the subject of RSL fluctuations and their controls (Miall, 1990; Hallam, 1992; Plint et al., 1992), and therefore an in depth discussion will not be presented here. In general most authors agree that neither tectono-eustasy nor tectonic movement of the basin floor operate rapidly enough to account for the frequency of RSL change observed within the Viking. Autocyclic mechanisms, such as delta switching, are not considered viable because of the regional extent of the Viking discontinuities. The most appealing mechanism for RSL fluctuations of this order is glacio-eustasy driven by Milankovitch cycles. The difficulty in applying this mechanism to the Viking depositional cycles lies in the fact that no direct evidence for continental glaciation exists in the period from the Triassic to the early Tertiary (Plint et al., 1992).

A growing body of evidence, albeit small, does exist which supports the possibility of climatically controlled high-frequency Cretaceous sea level fluctuations.

- Cooler Cretaceous polar temperatures suggested by General Circulation Models (Oglesby, 1989 *in* Plint, 1991), paleontological and oxygen isotope records (Pirrie and Marshall, 1990), and ice-rafted blocks in central Australia (Frakes and Francis, 1988).
- Rapid fluctuations in Cretaceous Strontium concentrations which coincide with fluctuations of $\delta^{18}O$ values and fluctuations of the Exxon sea level curve (Stoll and Schrag, 1996).
- Alternately filling and draining the pore space of sedimentary aquifers, caused by climatic variations, could result in major fluctuations of sea level (Hay and Leslie, 1990).

It is emphasized that the estimates of the duration of Viking cycles are only very rough, and specifying the controlling mechanism is not possible using data from the Viking alone.

CHAPTER 7: CONCLUSIONS AND SUGGESTED FUTURE WORK

7.1 Conclusions

1) The Viking Alloformation in the study area is made up of five allomembers (I-V), separated by four major bounding discontinuities (BD1-4). All allomembers are of shallow marine origin.

2) Four major fluctuations of RSL controlled deposition and erosion of Viking sandbodies.

3) The linear incised shoreface sandbody identified at Joffre (Downing and Walker, 1988) does not continue as the main sandbody within the linear trend of fields to the southeast. In fact sandbodies within this linear trend exist at five stratigraphically distinct horizons.

4) Within the study area, hydrocarbon bearing sandbodies are producing from several sedimentologically distinct fields including 'regional Viking' offshore to shoreface sediments, transgressively-incised shoreface sediments, prograding highstand shoreface sediments, and forced regressive, onlapping shoreface 'tongues'.

5) Four of Downing and Walker's (1988) key surfaces can be traced regionally over most of the study area (E1=BD1, E2/CM4=BD2(IT)/(RT), CM5=BD3, E3=BD4).

6) Deposition of sandbodies during the 'regional Viking' highstand (Allomember I) is far more important than previously thought. Several hydrocarbon fields produce from this allomember:

I) **Hamilton Lake** field is a clean HCS sheet sandstone, deposited as the uppermost part of succession RV1.

ii) **Chain South**, **Richdale**, and **Huxley** all produce from the shoreface sandstones of RV3.

7) Allomember II was deposited during the transgression of BD1 and the ensuing highstand, and forms the main sandbody of several hydrocarbon fields:

I) **Farrell** produces from a transgressively incised shoreface deposit above BD1(IT) - FAR.

ii) The **Mikwan** and **Fenn** fields produce from prograding highstand shoreface deposits above BD1.

Early transgressively-incised shoreface deposits of Allomember II exist at HMLK, which truncate the HMLK sandstone (RV1), but are non-productive.

8) Allomember III was deposited during the transgression of BD2 and ensuing highstand, and contains the main sandbody of several hydrocarbon fields:

I) The coarsening upward incised shoreface deposits above BD2(IT) - FENN are somewhat shaly, but alongstrike at **Joffre**, these deposits are conglomeratic and very productive (Downing and Walker, 1988).

ii) **Provost**, **Maple Glen** and likely part of **Sullivan Lake** produce from prograding offshore-transition highstand deposits above BD2.

9) Allomember IV was mostly deposited during highstand progradation of a wave dominated offshore -shoreface system, and partly during early falling stage. No hydrocarbon bearing sandbodies are associated with these deposits.

10) Allomember V was deposited during transgression of BD4 and influenced by high-frequency forced regressions. **Chain North** field produces from an onlapping tongue of lower shoreface sandstone, deposited during one of these forced regressions.

11) Increasing thickness and sandstone content of succession RV1 (Allomember I) toward the southeast may indicate a source area to the southeast for early 'regional Viking' sedimentation in the HMLK area. This may suggest that sedimentation was influenced by the Sweetgrass (Bow Island) arch.

12) The identification of firmground *Zoophycos* and *Chondrites*, subtending BD4 in the HMLK area suggests the need to define a distal *Glossifungites* ichnofacies.

13) Transgressive-regressive cycles of each allomember have estimated durations of 375, 000 years. This may suggest climatically controlled fluctuations of RSL, caused by changes in the eccentricity of the earths orbit.

7.2 Suggested Future Work

1) *Investigation of a possible southeasterly source area for regional Viking successions, in particular the HMLK sandstone (RV1).* Isopach maps are needed to determine precise thickness trends. Extension of core and well log cross-sections into Sedalia and other sandbodies to the southeast of HMLK may help to understand the paleogeography at this time.

2) *Understanding the large areal extent of the Provost reservoir and its sharp northeastern edge.* Identification of sedimentary facies from core examination throughout Provost field will help to understand how such a large productive accumulation of offshore sandstones could be deposited. The sharp northeasterly edge, and the indentations forming the 'saddle shape' of Provost suggests dissection by overlying erosion surfaces, of which there are two (BD3 and BD4). The 'saddle shape' is reminiscent of the Pembina reservoir of the Cardium Formation which has been shown to be a sand sheet dissected by the overlying E5 erosion surface (Leggitt, 1987). The bevels which dissect the Cardium fields are commonly parallel to incised shoreface deposits (Walker and Eyles, 1988) such as the conglomerates at Carrot Creek (Bergman and

Walker, 1987). The sharp but slightly curved northeastern edge of Provost seems to line up quite well with the lowstand shoreface identified at Beaverhill Lake (Walker and Wiseman, 1995). Could a time equivalent, but non-productive, lowstand shoreface be truncating the northeastern edge of Provost? The possible existence of an incised valley within Provost (B. Zaitlin, pers. comm., 1996) should also be investigated.

3) *Investigating the Viking-Bow Island relationship.* The two prominent sandy marine successions preserved in the southwest of this study area are Allomembers I and IV. Allomember IV is already known to become non-marine at its top at Caroline (Davies and Walker, 1993). Allomember I displays upper shoreface conditions at Huxley and therefore one might expect to find non-marine conditions a little farther southwest. Correlating well logs and cores to the southwest of the study area might provide a link between the non-marine Bow Island Formation and these two allomembers of the Viking Alloformation.

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