# High-Resolution Sequence Stratigraphy of Early Transgressive Deposits, Viking Formation, Joffre Field, Alberta, Canada[1]

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## ABSTRACT

The Lower Cretaceous Viking Formation of the Joffre field is characterized by complex reservoir architecture. Deposits of three discrete sequences were delineated using high-resolution sequence stratigraphy. The coarse-grained deposits of sequence 3, lying between BD-2 and an overlying open marine flooding surface, comprise the main reservoir interval within the Viking Formation of the Joffre field. This succession has previously been interpreted as an incised conglomeratic shoreface, stranded in a basinal position during transgression; however, sequence 3 displays characteristics difficult to reconcile with a shoreface interpretation, including an abundance of brackish mudstone interbeds and rip-up clasts, dominance of trough cross-stratification in the coarse clastics, and large-scale interfingering of the coarse clastics with fine-grained marginal-marine deposits. Despite the incised basal contact and brackish-water characteristics of the deposits, the succession does not reflect an estuarine incised valley complex, as conventional sequence stratigraphic wisdom might suggest. The shore-parallel orientation of the deposit, the lack of a convincing valley margin to the northeast, and parasequence orientations lying parallel to the strike of the deposit are inconsistent with an incised valley interpretation. Instead, the succession is interpreted as a broad brackish-water embayment of the shoreline, into which coarse-clastic bayhead delta and distributary channel complexes were deposited during incremental transgression. Such lagoonal or brackish bay complexes are ubiquitous in modern transgressive shorelines, but previously have been recognized only rarely in the ancient record.


## INTRODUCTION

The Viking Joffre field (Lower Cretaceous) constitutes part of an elongate trend of fields (including Gilby, Mikwan, Fenn, and Chain), which extends northwest-southeast for approximately 250 km in central Alberta (Figure 1). Joffre is the last oil field in a trend of fields that becomes gas prone southward onto land held by PanCanadian Petroleum Ltd. The exceptional database available in the Joffre area made it attractive to study and employ as an analog for similar deposits along trend. The main Viking Formation reservoir within the Joffre field consists of an anomalously coarse-grained, northwest-southeast–trending, narrow, linear, conglomeratic sandstone body interstratified at its distal (northeast) edge with dark mudstones. The combination of these features has resulted in its interpretation as an incised conglomeratic shoreface, stranded during transgression in an offshore to shelf setting (Downing and Walker, 1988), an interpretation now widely accepted. Many characteristics of the deposit are incompatible with a shoreface interpretation. The succession also superficially resembles an estuarine incised valley complex due to the apparent shape of the basal contact, the dominance of trough cross-bedded



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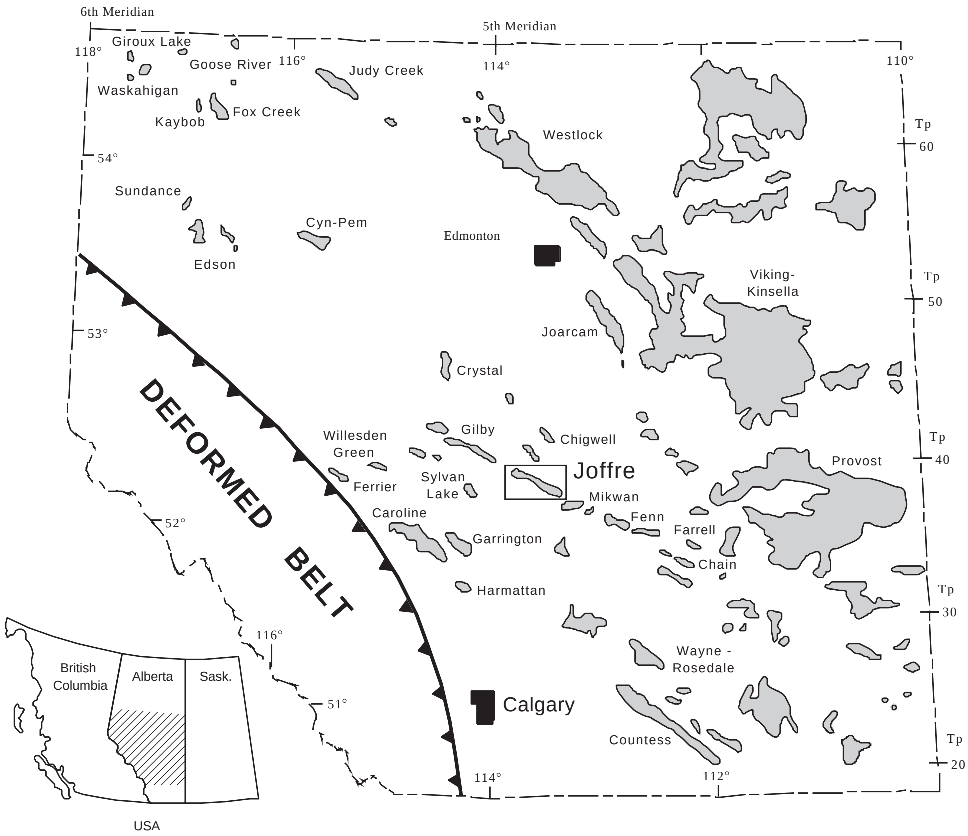
**Figure 1—Major Viking Formation field locations in Alberta, Canada. In central Alberta, the Joffre field forms part of an elongate (~250 km) trend of fields, including Gilby, Mikwan, Fenn, and Chain.**




coarse clastics, and the interstratification of conglomeratic sandstones with brackish water mudstones. The succession, however, contains features that cannot be easily attributed to estuarine incised valley deposition. For these reasons, the Joffre conglomeratic deposits of sequence 3 warranted a detailed facies and high-resolution sequence stratigraphic analysis to reevaluate the established model, present an alternative model, and resolve the reservoir architecture of the succession.

## STUDY AREA AND DATABASE

The Joffre field, located in Townships 37–39, Ranges 24–27W4, in central Alberta, Canada, was discovered in 1953, and extends for some 35 km along a northwest-southeast trend (Figure 2). The Viking Formation within the Joffre field contained some $14{,}830 \times 10^3$ m$^3$ of original oil in place over an area of 8210 ha and at an average depth of 1490 m (Alberta Energy and Utilities Board, 1997). Established reserves constituted $6451 \times 10^3$ m$^3$, reflecting $2481 \times 10^3$ m$^3$ from primary and $3970 \times 10^3$ m$^3$ from enhanced ($3087 \times 10^3$ m$^3$ waterflood and $883 \times 10^3$ m$^3$ solvent flood) recovery techniques. To date, cumulative production totals approximately $6044.1 \times 10^3$ m$^3$ ($38.0 \times 10^6$ barrels U.S.). As such, the field is generally regarded to be depleted.

The Lower Cretaceous Viking Formation consists predominantly of westerly derived siliciclastics, which prograded northward and eastward into the developing Alberta foreland basin in response to the progressive uplift of the cordillera. Subsidence within the basin has since resulted in a southwesterly dip for the Viking Formation. Closure in the field is a combination structural/stratigraphic trap.

The study area contains approximately 950 wells that penetrate the Viking Formation. Of these, about 280 wells contain core from the Viking. This study used data from 110 of these cores (Figure 2), which were logged in detail. Physical sedimentological, ichnological, and sequence stratigraphic analyses were all carefully integrated with one another. Selected core lithologs were used in the construction of six (five dip-oriented and one strike-oriented) stratigraphic facies cross sections. Samples also were collected for foraminiferal paleoecology. The core analyses from all logged cores were integrated into the study to characterize the porosity and permeability variations within each facies.

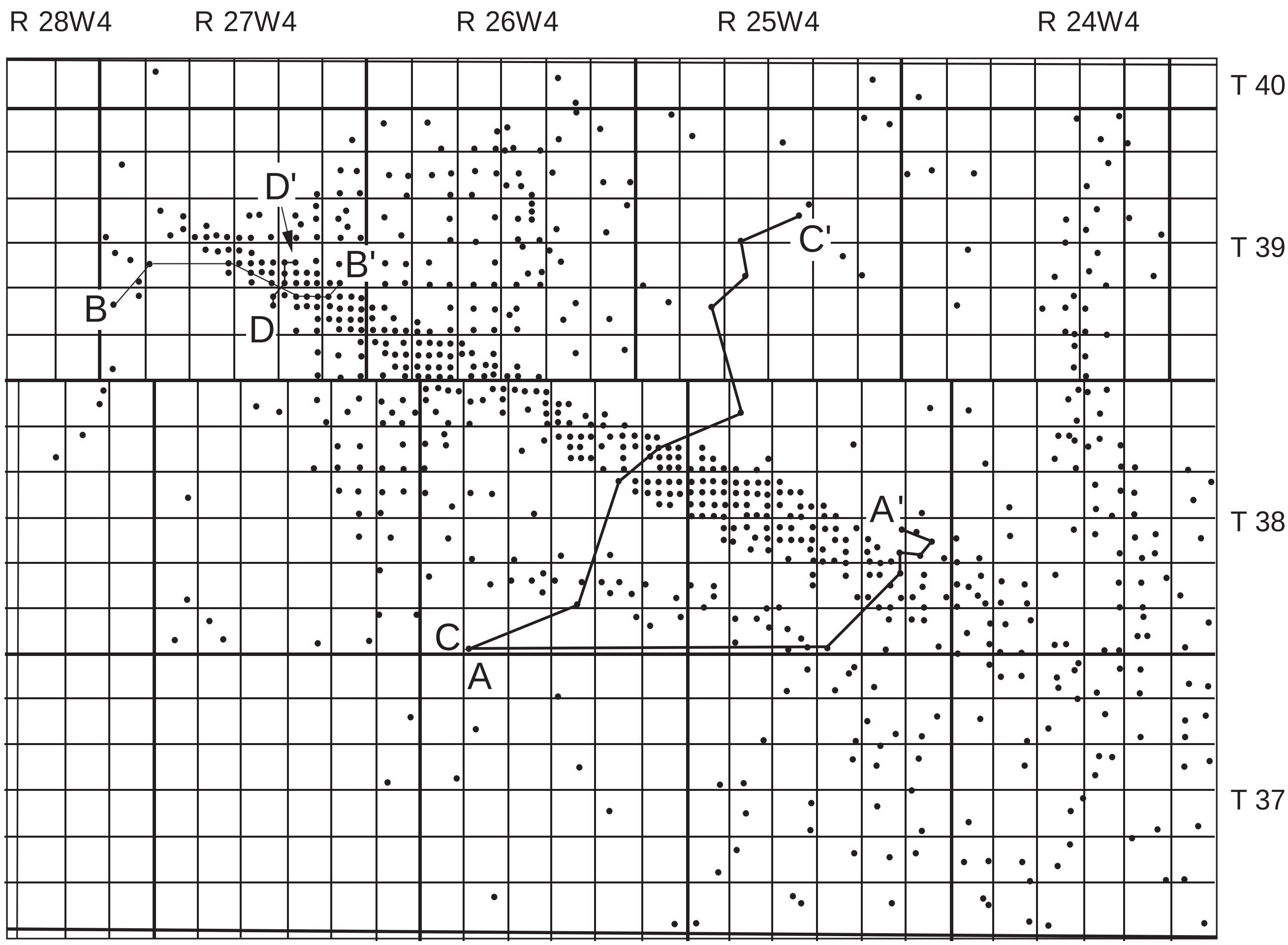



**Figure 2—Joffre field study area. The map shows core cross section lines AA′ and BB′, as well as well-log cross sections CC′ and DD′.**

In addition, 700 of the 950 geophysical well-log suites were analyzed to delineate the internal stratigraphic discontinuities. Picks from these wells were incorporated into a database used for all mapping. Selected gamma-ray and resistivity geophysical well-log responses were used to construct eight regional stratigraphic cross sections and thirteen local (field) stratigraphic cross sections. The local cross sections outlined the orientation and distributions of the parasequences.

## REGIONAL STRATIGRAPHIC RELATIONSHIPS

The Viking Formation is late Albian in age. It passes upward from marine shales of the Joli Fou Formation and is overlain by the transgressive marine shales of the Westgate Formation (Figure 3). The Joli Fou Formation unconformably overlies the Mannville Group and is roughly equivalent to the Skull Creek Shale of the Colorado Group in Montana and the Thermopolis Shale in Wyoming (McGookey et al., 1972; Weimer, 1984). The Viking Formation is roughly equivalent to the Paddy Member of the Peace River Formation (Stelck and Leckie, 1990), the upper part of the Bow Island Formation (Glaister, 1959), as well as the Muddy Sandstone, Newcastle Formation, and J-sandstone in Montana, Wyoming, and Colorado, respectively (McGookey et al., 1972; Weimer, 1984). The shales of the Westgate Formation are stratigraphically equivalent to the lower part of the Shaftesbury Formation (Stelck and Leckie, 1990; Bloch et al., 1993), and to part of the Hasler Formation in northeastern British Columbia (Stelck and Leckie, 1990). In the United States, the shales are equivalent to the Mowry Shale in Montana and North Dakota (McGookey et al., 1972).

The Viking Formation is highly complex and contains numerous discontinuities. Downing and Walker (1988), Boreen and Walker (1991) and Pattison (1991) Davies and Walker (1993), have all

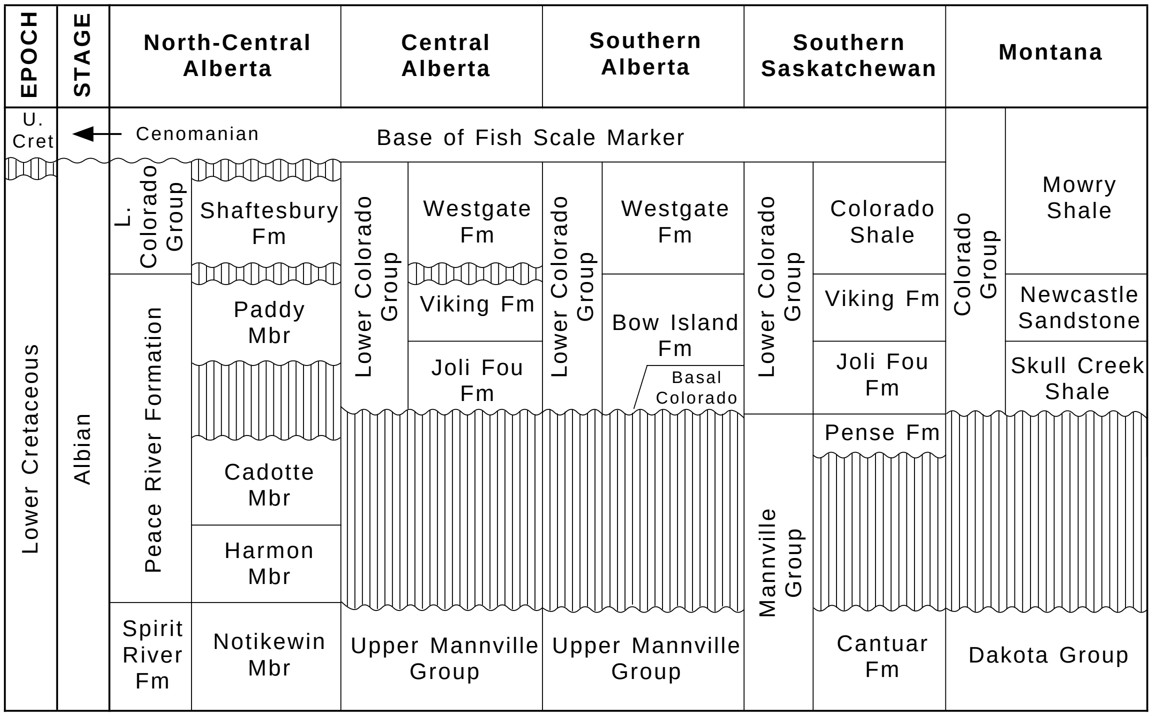



**Figure 3—Stratigraphic correlation chart for the Viking Formation.**

attempted to subdivide the interval into regionally correlative units. These attempts have sought to establish a formal allostratigraphic framework for the Viking Formation, according to the rules of the North American Code of Stratigraphic Nomenclature (North American Commission on Stratigraphic Nomenclature, 1983). Of these, the most notable and effective have been by Boreen and Walker (1991) (Figure 4) and Pattison (1991). Other workers have taken a sequence stratigraphic approach to the subdivision of the interval (e.g., Leckie and Reinson, 1993; Posamentier and 1993). To date, a paucity of good internal markers and lack of a precise biostratigraphic framework for the interval in central Alberta have limited the ability of researchers to carry their correlations reliably across the Western Canada sedimentary basin.

## VIKING STRATIGRAPHY OF THE JOFFRE AREA

The Viking Formation, as preserved within the Joffre field area, contains parts of three discrete sequences separated by two regionally extensive, transgressively modified sequence boundaries (Figure 5). These major stratigraphic breaks were accurately delineated by Downing and Walker (1988) and constitute the fundamental bounding discontinuities of their allostratigraphic units. Boreen and Walker (1991) correlated the lower of the two surfaces to their VE3a surface. The Viking allostratigraphic paradigm is currently being modified by researchers at McMaster University (J. A. Burton and R. G Walker, 1997, personal communication). The nomenclature employed in this paper for the bounding discontinuities follows that of the developing allostratigraphic framework, although interpretations regarding the genesis of the discontinuities may differ.

### Sequence 1: Regional Viking Parasequences

The basal sequence, informally referred to as the "regional Viking," consists of stacked, northwest-southeast–trending, regionally extensive marine parasequences. These parasequences correspond to allomembers A and B of Boreen and Walker (1991). Across the study area, six parasequences are identified and form the depositional platform into which the later Viking sequences incise (Figure 6). The flooding surfaces at the top of each parasequence form distinctive markers on resistivity and gamma-ray logs; consequently, removal of these markers highlights the presence of an erosional discontinuity. The parasequences are arranged in a progradational parasequence set, which downlaps onto the transgressive marine shales of the Joli Fou Formation. The basal

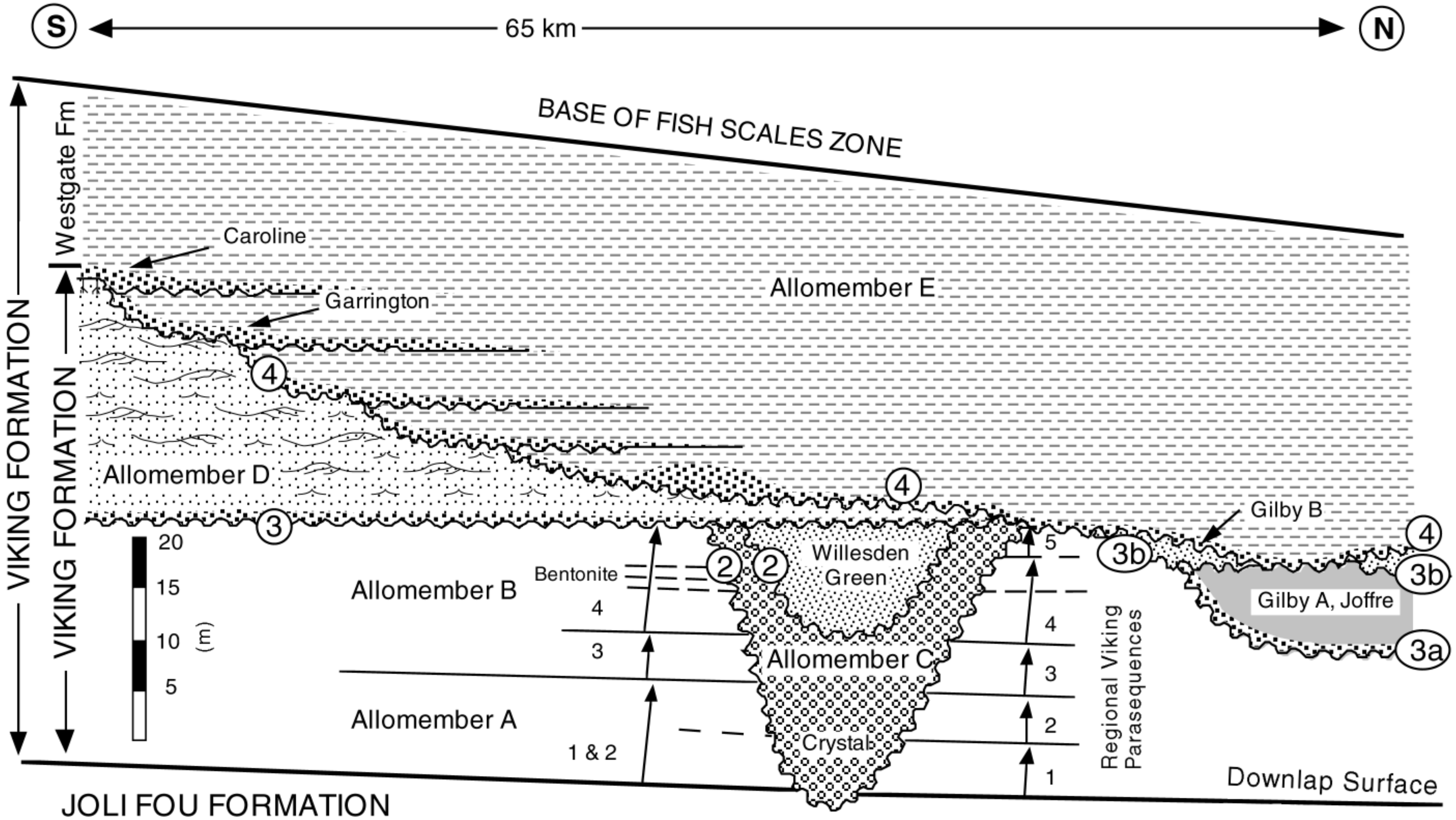



**Figure 4—Allostratigraphic framework of the Viking Formation. The Viking Formation is internally complex and has been subdivided into five genetic stratigraphic packages (allomembers A–E) bounded by regional discontinuities (figure modified after Boreen and Walker, 1991).**

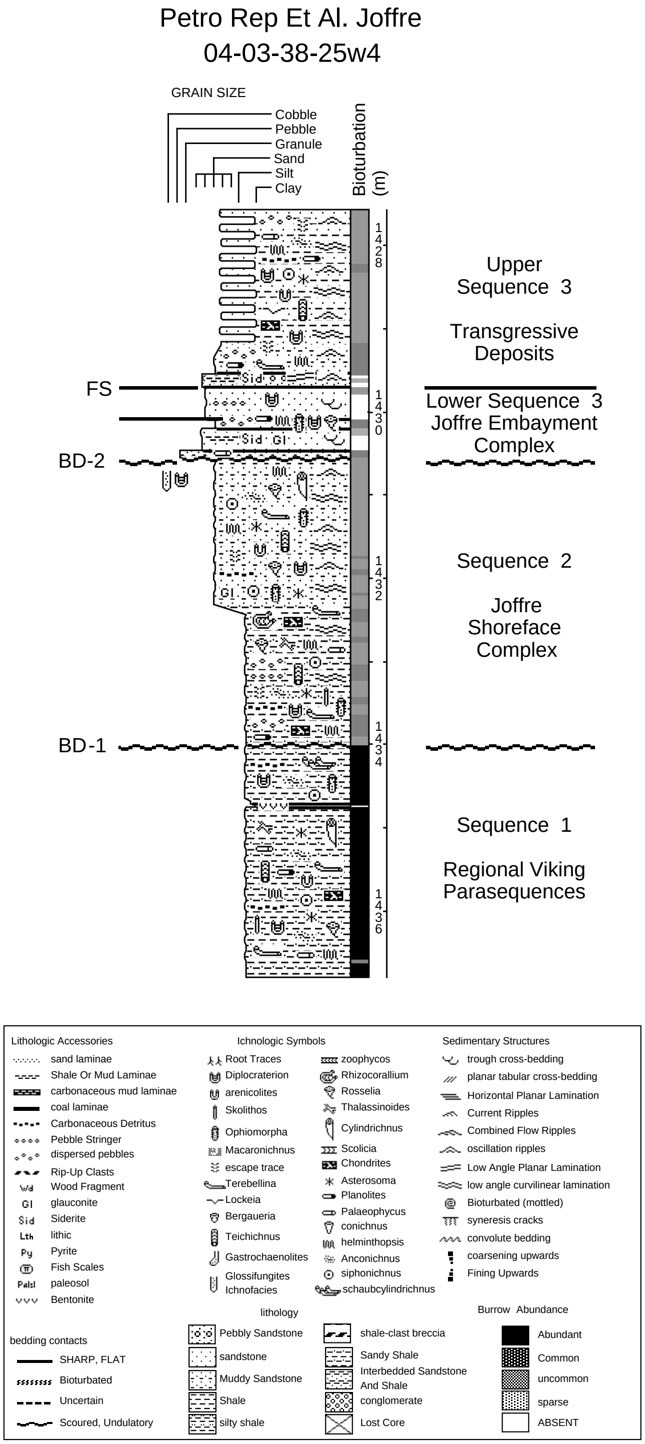



**Figure 5—Representative litholog of the Viking Formation at Joffre field. This Viking succession in the Petro Rep et al. Joffre 04-03-38-25W4 well illustrates three discrete sequences separated by transgressively modified sequence boundaries.**

sequence is interpreted to reflect part of a highstand systems tract (Pattison, 1991; MacEachern et al., 1995a, b).

### *Sequence 1 Facies Descriptions*

The parasequences coarsen upward. A complete vertical succession of facies within a single parasequence, from bottom to top, consists of marine shales, bioturbated silty mudstones, bioturbated sandy mudstones, and bioturbated to laminated muddy sandstones. In the Joffre area, few parasequences pass upward into the muddy sandstone facies, and in most cases the parasequences are terminated by a flooding surface capping the sandy mudstone facies. The most complete parasequence preserved in the area occurs near the top of sequence 1, where it is erosionally incised into by one or both of the overlying discontinuities. Within the parasequences, burrowing is intense, uniformly distributed, and diverse in character, reflecting slow, largely continuous deposition under fully marine conditions. The silty mudstone and sandy mudstone facies locally contain partially bioturbated, thin, sharp-based, fine-grained sandstone beds and lenses. These thin sandstones contain wavy parallel lamination and rare oscillation ripple lamination. The silty mudstones are dominated by grazing and deposit-feeding trace fossils of the distal *Cruziana* ichnofacies (MacEachern and Pemberton, 1992). The sandy mudstone facies locally contains thicker laminated sandstone beds, although they tend to be biogenically disrupted to a greater extent. The sandy mudstones are dominated by deposit-feeding structures with subordinate numbers of grazing and suspension-feeding/dwelling structures, which tend to be more robust and deeply penetrate the substrate. This suite is characteristic of the archetypal *Cruziana* ichnofacies. The muddy sandstone facies contains partially bioturbated, laminated sandstone beds displaying remnant oscillation-ripple lamination, combined flow-ripple lamination, and hummocky cross-stratification. The thickness and numbers of laminated beds increase upward, particularly in the uppermost parasequence that is well preserved landward of the Joffre field. The muddy sandstones are dominated by a mixture of deposit-feeding and suspension-feeding/dwelling structures, with a low proportion of grazing structures, reflecting the proximal *Cruziana* ichnofacies. Where the laminated beds within the muddy sandstone facies are more abundant, the increase in suspension-feeding structures, alternating with the deposit-feeding structures, generates a mixed *Skolithos-Cruziana* suite, consistent with a higher energy setting.

The reservoir quality of all facies within the parasequences is exceedingly poor. Sandstones possess porosities ranging from 1.1 to 9.4% and averaging 5.8%; permeabilities range from 0.01 to 1.03 md and average 0.09 md ($K_{max}$). No production is associated with this sequence.

### *Interpretation of Sequence 1*

Where parasequences consist of all four facies, the complete vertical succession is interpreted to reflect deposition of shelf shales, which progressively grade through lower offshore silty mudstones, upper offshore sandy mudstones, and, locally, into lower shoreface muddy sandstones. In the shelf and offshore deposits, wavy parallel lamination is largely confined to ragged, discontinuous sandstone stringers reflecting partially bioturbated remnants of distal tempestites. The shales and silty mudstones are interpreted to have been deposited in the shelf and lower offshore. In such low-energy settings, storm beds typically are thin and subject to partial or complete bioturbation. The presence of a distal *Cruziana* suite is characteristic of such settings. The sandy mudstones are interpreted to reflect upper offshore deposition, where tempestites are thicker, but also more intensely burrowed by the more robust and penetrative biogenic structures of the infauna (MacEachern, 1994; Pemberton and MacEachern, 1997). The presence of a fully diverse *Cruziana* assemblage is typical of the upper offshore. In the lower shoreface deposits, the tempestites are more proximal and, locally, are erosionally amalgamated into thicker bedsets. The bioturbated muddy sandstone facies is interpreted to reflect lower shoreface deposition. Where the storm-generated laminated sandstone beds are more abundant within the uppermost parasequence, we interpret a transition toward the middle shoreface (MacEachern and Pemberton, 1992). This interpretation is supported by the presence of the mixed *Skolithos-Cruziana* ichnofacies.

Identification of lower shoreface deposits within some of the regional Viking parasequences, and therefore the implication that these cycles were part of a shoreline system, is problematic given the general absence of identifiable middle and upper shoreface deposits lying landward of the muddy sandstone facies. Strong support for a lower shoreface interpretation for the muddy sandstones lies with the lithologic characteristics. All sedimentary structures within the facies attest to wave and storm-wave depositional processes. Within a marine succession, this indicates that deposition occurred above storm-weather wave base. The facies is not dominated by storm beds; rather, they are few in number and typically burrowed. The style of burrowing associated with storm beds, however, is quite different from the burrowing associated with fair-weather sedimentation (MacEachern and Pemberton, 1992;

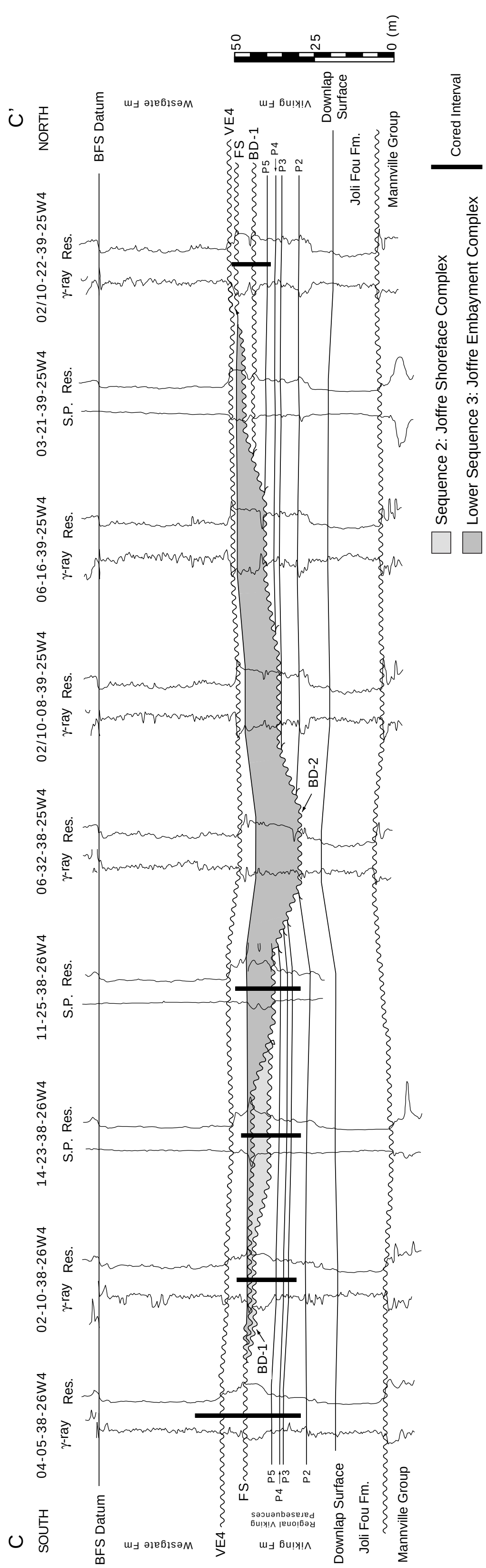



**Figure 6—Regional stratigraphic well-log cross section CC′. The Base of Fish Scales (BFS) marker is used as the datum. The cross section shows stacked parasequences of the regional Viking Formation, truncated initially by BD-1 and later by BD-2. BD-1 is overlain by sequence 2 (Joffre shoreface complex). Sequence 2 is incised into and locally removed by BD-2, which displays an apparent trough-like morphology. BD-2 is overlain by sequence 3 (Joffre embayment complex). A regionally extensive flooding surface (FS) truncates the top of the embayment deposits. The line of section is shown in Figure 2.**

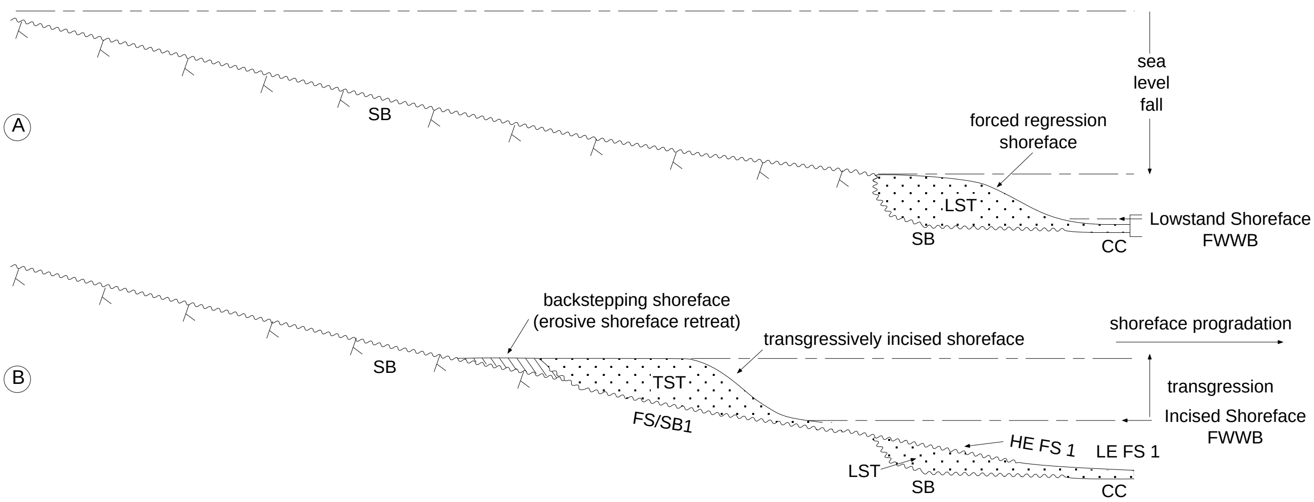



**Figure 7—Differentiation of forced regression shorefaces and transgressively incised shorefaces. Sharp-based, discontinuity-bounded (incised) shoreface successions can be ascribed to one of two main sequence stratigraphic settings. Model 1 corresponds to forced regression, reflecting allocyclic shoreface progradation during conditions of falling relative sea level. In this scenario, the shoreface sits directly on the sequence boundary (SB) and its correlative conformity (CC). In model 2, rising relative sea level causes the ravinement of the forced regression shoreface and development of a transgressively incised shoreface landward of the lowstand shoreline position. In this scenario, the sequence boundary is transgressively modified (BD-1), and shoreface progradation across this surface occurs during a pause in the rate of transgression. The characteristics of sequence 2 suggest that it best fits the transgressively incised shoreface interpretation. FS = flooding surface, LST = lowstand systems tract, FWWB = fair-weather wave base, HE = high energy, LE = low energy.**

Pemberton et al., 1992; Pemberton and MacEachern, 1997). A careful analysis of the ichnology attests to a paucity of suites attributable to tempestite colonization, and a dominance of suites generated under fair-weather conditions. This indicates that most of the muddy sandstone accumulated in response to persistent wave agitation at the bed, demonstrating that deposition occurred at or near fair-weather wave base.

The absence of identifiable middle and upper shoreface deposits can be accounted for in a number of ways. Low gradient systems, applicable to the Western Interior seaway in Alberta, may have very broad but thin shorefaces (Howard and Reineck, 1981); thus, contemporaneous shallow-water deposits might lie considerably landward. In many of the lower parasequences, nonerosional flooding surfaces cap upper offshore and lower offshore deposits, suggesting that the shoreface complexes never prograded that far basinward. In the case of the uppermost parasequence within the Joffre area, multiple incisions and subsequent transgressive ravinement have been responsible for removal of the shallow-water portion of the system. The presence of remnant middle shoreface deposits near the top of this succession indicates that the parasequence was attached to a shoreline complex.

## Sequence 2: The Joffre Shoreface Complex

### *Basal Discontinuity 1*

The regional Viking parasequences are erosionally truncated by an amalgamated sequence boundary and flooding surface, referred to as basal discontinuity 1 (BD-1) (Figure 5). BD-1 incises into underlying parasequences along the southwest edge of the Joffre field (Figure 6). The surface slopes steeply along the southwestern (landward) edge and flattens out to the northeast, forming an asymmetric scarplike geometry, originally termed E1 by Downing (1986) and Downing and Walker (1988). In proximal (southwestern) positions, the surface is locally overlain by a chert pebble lag or by muddy sandstones containing dispersed chert pebbles and granules. In distal (northeast) positions, the erosion surface lacks a discrete pebble lag, but overlying facies display a marked increase in the grain size of interstitial sand and, locally, dispersed chert granules and pebbles. In both proximal and distal positions, the surface is marked by the *Glossifungites* ichnofacies. The characteristics and implications of the *Glossifungites* ichnofacies are outlined in the discussion of sequence 3.

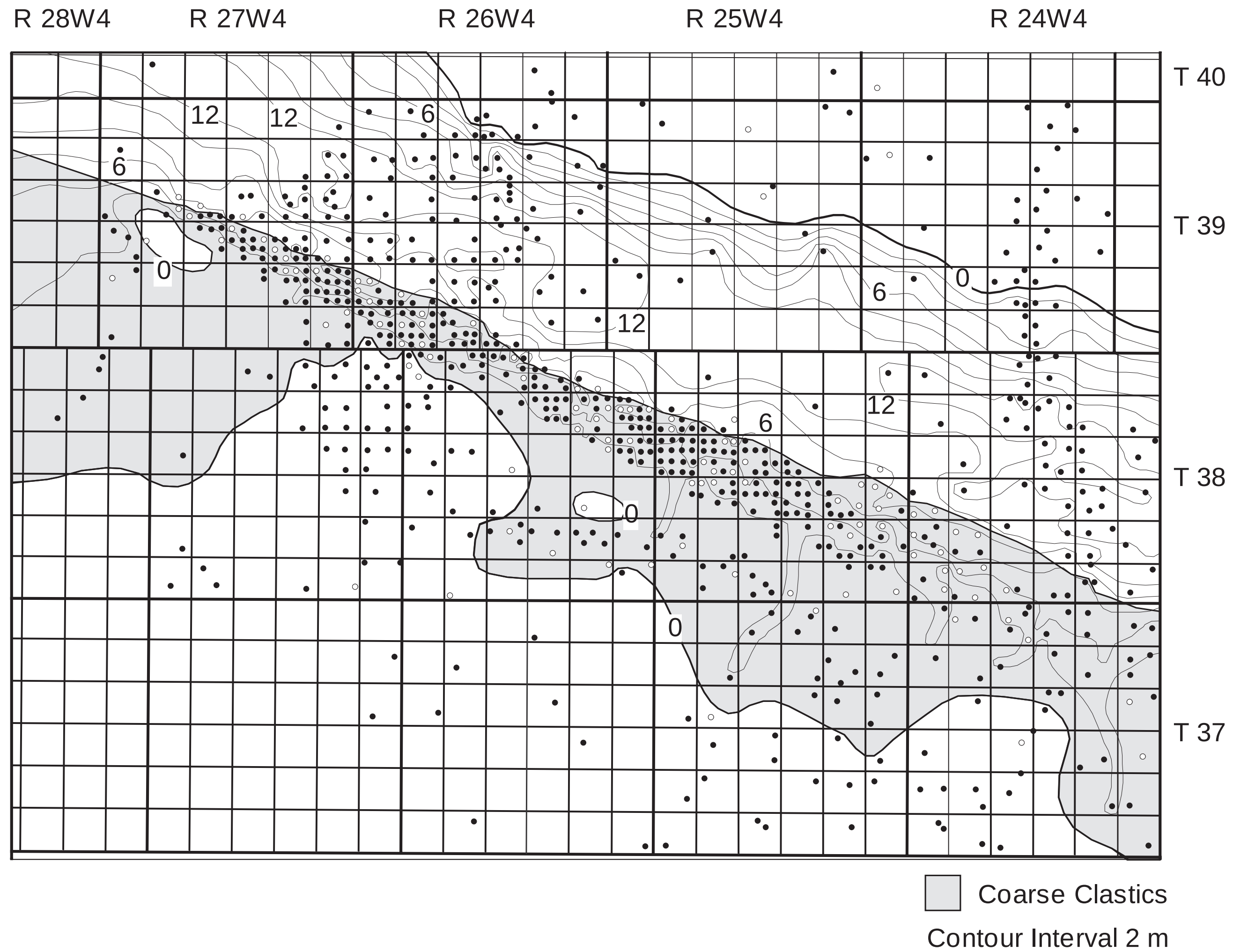



**Figure 8—Isopach of the embayment deposits of lower sequence 3 showing two erosional edges, related to truncation by the overlying regional flooding surface. The stippled area along the southern edge of the map defines the zone of coarse clastic deposition within the embayment. Open circles = cored wells.**

### *Facies Succession of Sequence 2*

Sequence 2 directly overlies BD-1 and is preserved as an erosional remnant in the Joffre field area (Figure 6). The sequence consists of three facies comprising an overall coarsening-upward succession. A complete facies succession consists of a thin granule to pebble lag mantling the discontinuity, grading upward into gritty sandy mudstones, through muddy sandstones, and into interstratified wavy parallel-laminated to burrowed sandstones.

The granule to pebble lag capping the discontinuity is typically thin, contains sideritized mudstone intraclasts, and is generally structureless. The gritty sandy mudstones at the base of the succession contain dispersed chert pebbles, granules, and very coarse grained chert and quartz sand. Discontinuous lenses of sharp-based, parallel-laminated sandstone are commonly intercalated. The sandy shales are moderately to thoroughly burrowed by a diverse, uniformly distributed trace fossil suite corresponding to a fully marine, archetypal *Cruziana* assemblage.

This facies grades upward into a bioturbated, upper fine-grained to lower medium-grained, muddy sandstone facies containing dispersed chert granules, rare pebbles, and thin pebble stringers. Remnant, sharp-based, parallel-laminated sandstone beds are intercalated, but uncommon and typically biogenically disrupted. The bulk of the facies is intensely bioturbated by a diverse and uniformly distributed trace fossil assemblage representing a fully marine, proximal *Cruziana* suite.

Toward the southwest portion of the study area, the bioturbated muddy sandstone facies grade upward into the laminated to burrowed, upper fine-grained to lower medium-grained sandstone facies. The facies consists of composite bedsets of wavy parallel-laminated sandstone beds interstratified with moderately to intensely burrowed muddy sandstone beds. This facies contains a trace fossil suite similar to that of the muddy sandstone facies from which it grades.

The sandstones of sequence 2 constitute a marginal reservoir and produce gas south of the Joffre field. Core analyses of the 216 samples reveal porosities ranging from 0.6 to 20.5% and averaging 8.7%. Permeabilities range from 0.01 to 172 md ($K_{max}$) and average only 7.17 md ($K_{max}$).

### *Interpretation of Sequence 2*

The facies succession of sequence 2 is interpreted to reflect a weakly storm-influenced shoreface; this interpretation is based on the coarsening-upward character of the succession, the presence of distal storm beds, and the diverse *Cruziana* assemblages (MacEachern and Pemberton, 1992). The granule to pebble layer mantling the transgressively modified sequence boundary (BD-1) corresponds to the transgressive lag. The *Glossifungites* ichnofacies associated with the discontinuity attests to colonization of the firm substrate during or immediately after transgressive ravinement (MacEachern et al., 1992). The gritty sandy mudstones above the lag are interpreted to reflect upper offshore deposition, primarily on the basis of the diverse, fully marine *Cruziana* suites. The intercalated, thin, parallel-laminated sandstones correspond to infrequent distal storm beds that accumulated below fair-weather wave base.

The muddy sandstones are interpreted to reflect lower shoreface deposition. The paucity of storm beds in this facies demonstrates a weak storm influence on the setting and implies that most of the sands accumulated under persistent wave agitation at or near fair-weather wave base. This scenario is further supported by the diverse, abundant, and uniformly distributed proximal *Cruziana* assemblage, reflecting slow, continuous deposition of sand under moderate energy conditions (MacEachern and Pemberton, 1992; Pemberton and MacEachern, 1997). The laminated to burrowed sandstone facies is interpreted to reflect proximal lower shoreface to middle shoreface conditions. The thicker and greater number of storm beds corresponds to progressive shallowing along the shoreface depositional profile (MacEachern and Pemberton, 1992).

Sharp-based shoreface sand bodies may reflect progradation of late highstand successions (Van Wagoner, 1995), lowstand-incised forced regression systems (Posamentier et al., 1992; Posamentier and Chamberlain, 1993), and transgressively incised backstepping complexes (Downing and Walker, 1988; Raychaudhuri et al., 1992; Walker and Wiseman, 1995). The late highstand successions correspond to autocyclic progradation, and thus demonstrate a genetic affinity with the underlying facies. In contrast, the forced regression and transgressive shoreface successions correspond to allocyclic progradation, and overlie stratigraphic discontinuities incised into the underlying facies (Figure 7). The forced regression shoreface overlies a sequence boundary cut by wave erosion during the fall of relative sea level. In contrast, the transgressively incised shoreface overlies a wave ravinement surface incised into and amalgamated with the sequence boundary; this surface reflects shoreline progradation during a pause in the rate of transgression.

The sharp-based incised shoreface of sequence 2 is interpreted to reflect a transgressively incised shoreface rather than a forced regression shoreface. The erosional nature of BD-1 in seaward positions, particularly where it is directly overlain by deposits that accumulated below fair-weather wave base (i.e., offshore sandy mudstones), is inconsistent with a forced regression model. In a forced regression scenario, the sequence boundary passes into a nonerosional correlative conformity seaward of fair-weather wave base. If a forced regression model were appropriate, one would expect BD-1 to be represented by the correlative conformity and not an erosional discontinuity. Consequently, a *Glossifungites* assemblage would not be expected to be associated with this surface. If the surface were cut by storm action below fair-weather wave base, the scour surface should be mantled by a tempestite, and would not be available to colonizers of the *Glossifungites* ichnofacies. In an early transgressive scenario, however, wave ravinement of the sequence boundary during erosional shoreface retreat produces an erosional discontinuity that ultimately would lie below the fair-weather wave base of an overlying prograding shoreface, because the modified surface was cut prior to shoreface progradation and while sea level lay at a stratigraphically lower position (Figure 7). As a result, this amalgamated surface has great erosional extent and can be demarcated by the *Glossifungites* ichnofacies, even in these basinal positions.

## Lower Sequence 3: The Joffre Embayment Complex

### *Basal Discontinuity 2 (BD-2)*

The early transgressive shoreface deposits of sequence 2 are truncated by a second amalgamated

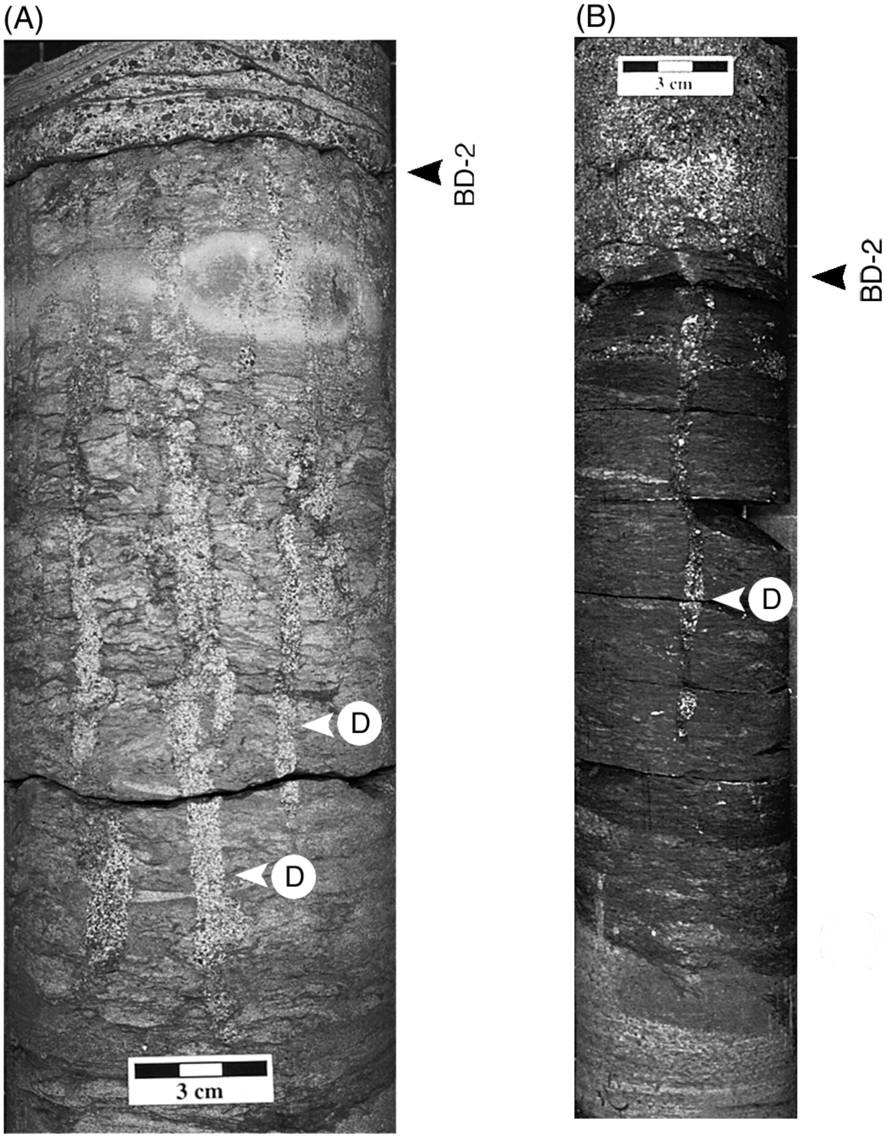



**Figure 9**—***Glossifungites*-demarcated BD-2 surface. (A) In positions to the south, BD-2 is incised into bioturbated muddy sandstones of sequence 2. The surface is ichnologically demarcated by sharp-walled, unlined *Diplocraterion* (D) of the *Glossifungites* ichnofacies. Note that the top of the Joffre shoreface complex is siderite cemented (well 16-34-37-25W4, 1434.0 m). (B) In positions to the north and east, BD-2 is incised into mudstones of the regional Viking parasequences. The surface is demarcated by sharp-walled, unlined *Diplocraterion* (D) of the *Glossifungites* ichnofacies (well 08-20-39-27W4, 1610.1 m).**

sequence boundary and flooding surface with a similar scarplike geometry, referred to as BD-2 (Figure 5). The surface shows evidence of erosion throughout its cored extent. The mapping of the surface shows a broad, asymmetrical u-shaped trough geometry (Figures 6, 8). BD-2 is incised into an erosional remnant of the Joffre shoreface complex (sequence 2) near the southeastern end of the Joffre field (Figure 9A). Toward the northwestern end of the field, however, BD-2 rests directly on the regional Viking parasequences, and the Joffre shoreface complex is largely removed (Figure 9B). The BD-2 surface is locally mantled by a thin (1–5 cm thick) chert pebble lag and, similar to BD-1, is commonly demarcated by a G*lossifungites* assemblage. The suite is dominated by firmground *Diplocraterion*, with relatively few firmground *Thalassinoides* and *Skolithos*.

The *Glossifungites* ichnofacies is a substrate-controlled recurring assemblage of trace fossils that corresponds to the colonization of a firmground. The suite encompasses ichnogenera that are "pseudo-bored" into an underlying, semilithified substrate. Ichnogenera of the firmground assemblage are typically unlined, sharp-walled (and locally scratch marked), vertical to subvertical dwelling structures that crosscut the original resident softground trace fossil community and generally are passively infilled with sediment overlying the discontinuity.

The significance of the *Glossifungites* ichnofacies to the identification and interpretation of stratigraphic discontinuities has been discussed by

Saunders and Pemberton (1986), Savrda (1991), MacEachern et al. (1992), Pemberton et al. (1992), and Pemberton and MacEachern (1995). The salient elements of the *Glossifungites* ichnofacies are that (1) it is substrate controlled and reflects conditions postdating deposition of the host deposit, (2) the substrate reflects either subaerial exposure (typically with erosion) or burial followed by erosional exhumation, (3) most pre-Tertiary assemblages reflect colonization of the substrate under marine or marginal-marine conditions, and (4) colonization of the substrate occurs during a depositional hiatus between a period of erosion and subsequent deposition. The exhumed substrate must be exposed to permit colonization, and therefore the erosion responsible for its exhumation cannot be directly responsible for deposition.

The isopach map of sequence 3 (Figure 8) shows two erosional "zero" edges related to truncation by the overlying regional flooding surface (FS in Figure 10). The stippled area along the southern edge of the isopach trend defines the zone of coarse clastic accumulation lying between BD-2 and Fs.

### *Facies Succession of Lower Sequence 3*

Sequence 3 overlies BD-2. The succession lying between BD-2 and the overlying regional wave ravinement/flooding surface is referred to as lower sequence 3, and consists of coarse clastic facies that grade northeastward via interbedding into fine-grained facies. The preserved deposits of lower sequence 3 are oriented northwest-southeast and comprise a stratigraphic body at least 35 km long and 8.5–9.0 km wide (Figures 6, 8). The coarse clastics are dominated by trough cross-stratified and low-angle planar-stratified sandstones, pebbly sandstones, and conglomerates concentrated along the southern margin of the BD-2 erosional escarpment (Figure 10). These coarse clastics progressively interfinger with, and ultimately pass into, interbedded mudstones, fine-grained sandstones, and rare, thin conglomeratic bands in a northward and eastward direction. The coarse clastics of sequence 3 constitute the Viking Formation reservoir in the Joffre field.

Detailed analyses demonstrate that the succession comprises at least three parasequences (Figure 10). These parasequences onlap relief on the southwest margin of BD-2 and interfinger with mudstones to the northeast. Along the southwest margin of BD-2 and toward the north end of the field, erosional amalgamation of coarse clastics is more pronounced, and parasequence boundaries cannot be delineated easily (cf. Figures 10, 11). Cross section BB′ illustrates that northeastward (dip-oriented) transitions from a succession entirely composed of coarse clastics to a succession consisting entirely of mudstone can occur over distances of 400 m or less (Figure 11). Well-log cross section DD′ demonstrates that even these abrupt transitions reflect facies changes via interbedding, rather than an erosional contact (Figure 12).

In most locations, BD-2 is directly overlain by moderately burrowed and highly glauconitic (glaucony) pebbly sandstones, comprising facies A. Facies A is particularly well developed toward the southeast end of the field (Township 38, Range 25W4). These coarse clastics contain abundant, thin, and locally siderite-cemented mudstone interbeds, as well as mud laminae and mudstone rip-up clasts (Figure 13). Sand sizes range from lower medium to lower coarse, and typically contain very coarse sand and granule stringers. Primary physical sedimentary structures are dominated by 3.0–5.0-cm-thick, current ripple-laminated beds and 5.0–10.0-cm-thick, small-scale trough cross-stratified beds. Locally, low angle (<15°), planar stratified sandstone beds are intercalated.

Facies A displays moderate to low degrees of burrowing, sporadically distributed and diminishing in intensity upward. Within the sandstone beds, the trace fossil suite is dominated by *Diplocraterion, Skolithos, Conichnus, Ophiomorpha, Palaeophycus*, and *Rosselia*, with variable numbers of escape structures. The mudstone interbeds typically contain small numbers of *Planolites, Teichichnus*, and *Chondrites*. *Terebellina, Bergaueria, Siphonichnus, Asterosoma, Arenicolites*, and *Helminthopsis* are very rare components of the assemblage. The overall trace fossil suite corresponds to the mixed *Skolithos-Cruziana* ichnofacies. The sandstones contain a *Skolithos* ichnofacies, whereas the interstratified mudstones possess a proximal *Cruziana* suite.

Upward, the facies succession is dominated by well-sorted, unidirectional trough cross-stratified and low-angle, planar-stratified sandstones (facies B, Figure 14), pebbly sandstones (facies C), and rarer granule-rich conglomerates (facies D). Sand sizes range from lower medium to lower coarse, with variable concentrations of very coarse sand, granules, and small pebbles consisting predominantly of quartz and chert. Beds range from 5 to 25 cm in thickness, locally amalgamated into bedsets up to 3.5 m thick. The coarse clastics occur in multistory fining-upward cycles with scoured bases and contain granule and pebble stringers, as well as mudstone rip-up clasts and thin mudstone interbeds (Figure 15). These facies extend along the entire length of the Joffre trend, but are confined to the southwestern margin (Figure 8) where they onlap BD-2. The thickest amalgamation of these facies occurs near the north end of the field (Figure 11).

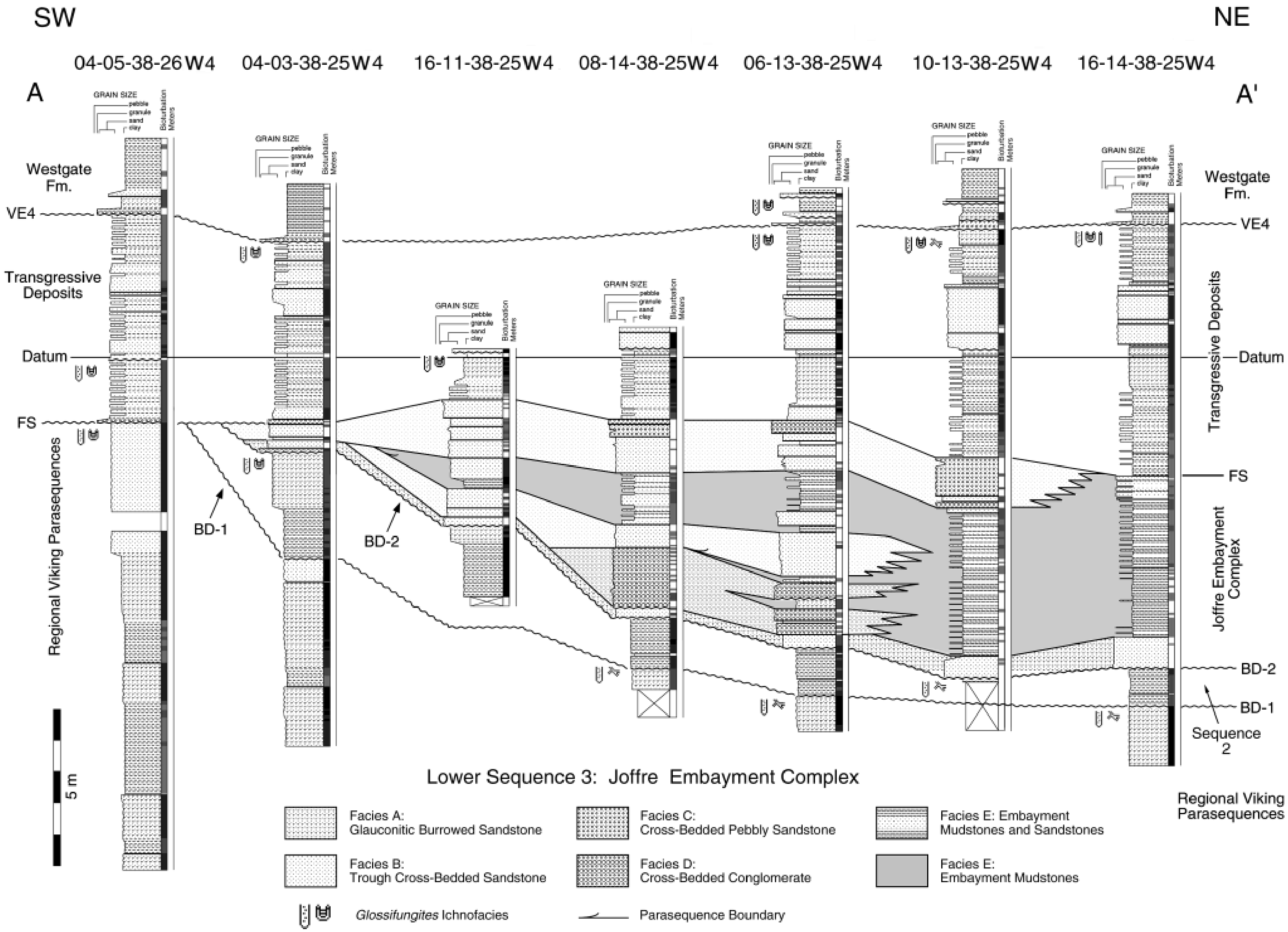



**Figure 10**—Stratigraphic facies cross section AA′. The stratigraphic datum is a bentonite horizon encased within overlying offshore marine mudstones. BD-2 is incised into sequence 2 and is mantled by a transgressive sand sheet/lag. Coarse clastics interfinger with bay mudstones in a northeastern direction, comprising the embayment deposits of sequence 3. The conglomerates and sandstones onlap relief on the southwest margin of BD-2. Deposits along this margin of the embayment complex are interpreted to reflect bayhead delta progradation into a marginal marine bay. A major parasequence boundary partitions the field, reflecting a period of transgression within the embayment. A regional flooding surface (FS) terminates embayment deposition. The line of section is shown in Figure 2.

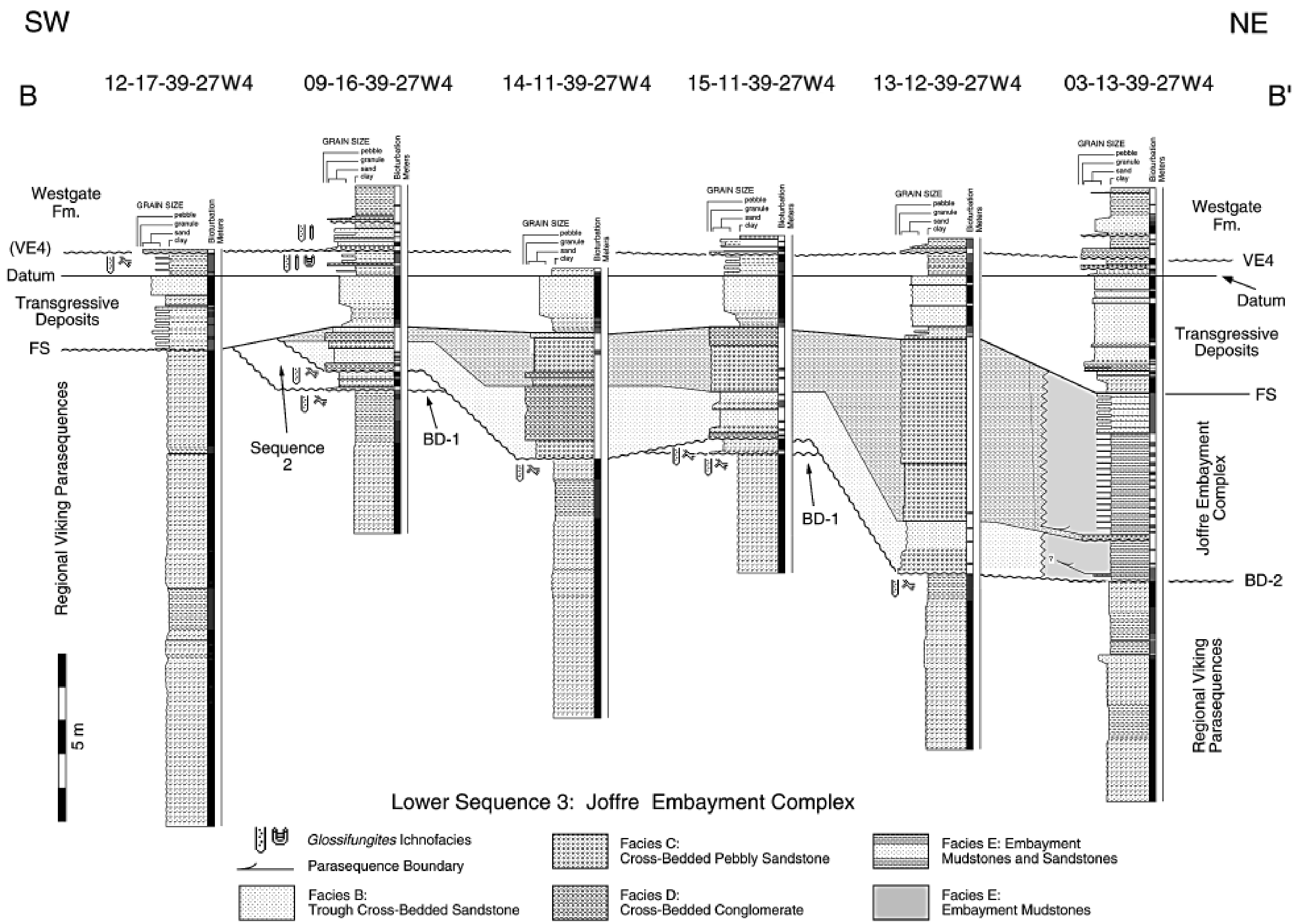



**Figure 11**—Stratigraphic facies cross section BB′. The stratigraphic datum is the top of a thin bioturbated transgressive sand sheet. BD-2 is largely incised through sequence 2 and typically rests on the regional Viking parasequences. Coarse clastics pass abruptly (over a distance of only 400 m) into bay mudstones constituting the embayment deposits of sequence 3. This portion of the embayment complex of sequence 3 is interpreted to reflect stacked channel environments cut into and laterally interfingering with penecontemporaneous marginal-marine bay mudstones. A regional flooding surface (FS) terminates embayment deposition. The line of section is shown in Figure 2.

Burrowing, although present, is sporadically distributed, of low intensity, and generally of reduced diversity. Trace fossils are far more common within the sandstone and pebbly sandstone facies than they are in the conglomeratic facies. Nonetheless, mudstone interbeds within conglomeratic units typically display evidence of biogenic reworking, attesting to their marine or marginal marine origin. Ichnogenera are characterized by low numbers of *Diplocraterion, Skolithos, Palaeophycus, Conichnus*, and *Ophiomorpha* within the coarse-grained beds, with *Teichichnus*, *Planolites*, and *Terebellina* largely restricted to the mudstone interbeds. The remainder of the suite is exceedingly rare and consists of small numbers of *Arenicolites, Bergaueria, Rosselia, Asterosoma, Cylindrichnus, Thalassinoides*, and escape traces. The overall suite comprises a *Skolithos* assemblage.

Facies E is characterized by interbedded mudstones and sandstones (Figure 16). The facies constitutes the low-energy component of the facies succession and progressively interfingers with the coarser facies in a northeast (basinward) direction (Figure 10). In thick sections, facies E demonstrates three coarsening-upward parasequences, ranging from 1 to 4 m in thickness. These parasequences can be traced southwestward into the field, where facies E is interstratified with the coarse clastics (Figure 12). Sandstone beds constitute as little as 5% of the succession near the base of a parasequence to as much as 75% toward the top, and range from 1.0 to 15.0 cm in thickness. Individual sandstone beds tend to be well sorted, but may range in grain size from lower fine to lower very coarse. Sandstones are sharp based and predominantly display oscillation ripples, combined flow ripples, and wavy parallel laminations. Mudstone beds range from 1.0 to 20.0 cm in thickness, are typically silt and sand poor, and contain considerable carbonaceous detritus, which imparts a dark color. Mudstone beds are locally siderite cemented or display displacive siderite nodule development. Pyrite content within the mudstone is variable.

Facies E is generally weakly burrowed, with a sporadically distributed and low-diversity trace fossil suite. Burrowing intensity and diversity of ichnogenera increase toward the top of the facies succession, as well as near the top of individual parasequences. In addition, muddier portions of the succession possess the lowest diversity, lowest degrees of burrowing, and the most diminutive forms. As sand content increases, trace fossils become more diverse, more abundant, and more robust. The facies is dominated by *Teichichnus*, *Planolites*, and *Terebellina*, with subordinate but moderate numbers of *Palaeophycus*, *Lockeia*, *Skolithos*, and *Thalassinoides*. Near the top of the succession, *Siphonichnus*, *Arenicolites*,

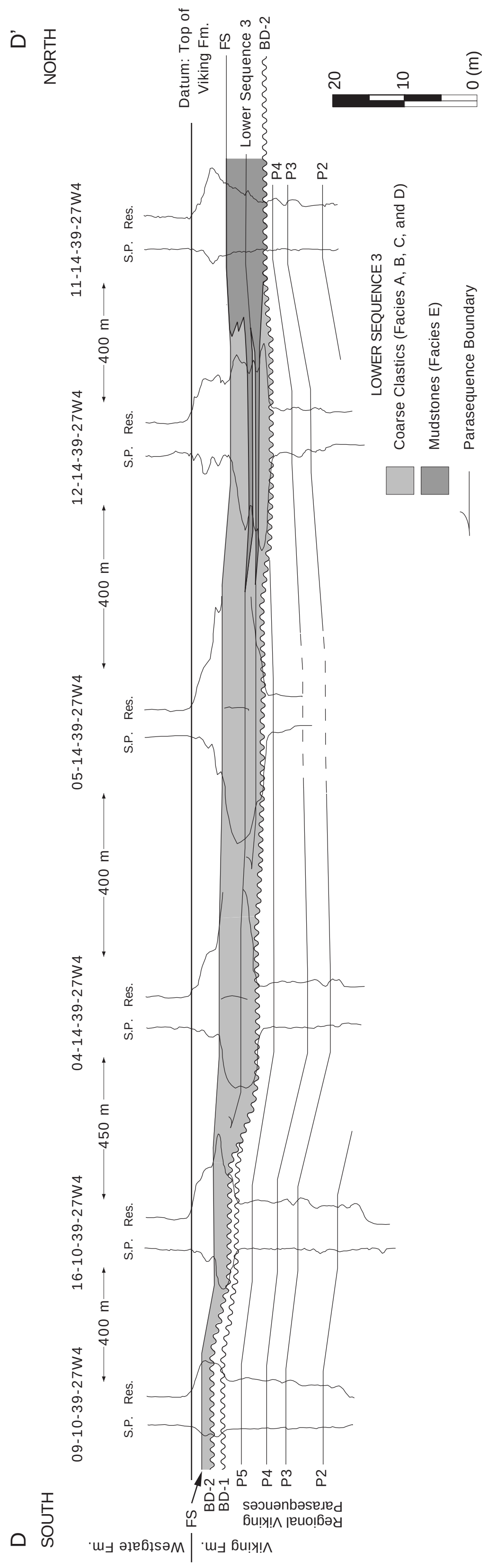



**Figure 12—Stratigraphic well-log cross section DD′. The section demonstrates that, even in localities characterized by rapid transition from thick, amalgamated coarse clastics to uninterrupted interstratified mudstones and sandstones, intervening wells show the successions to interfinger with one another, demonstrating a genetic relationship. The top of the Viking Formation is used as the datum. The line of section is shown in Figure 2.**

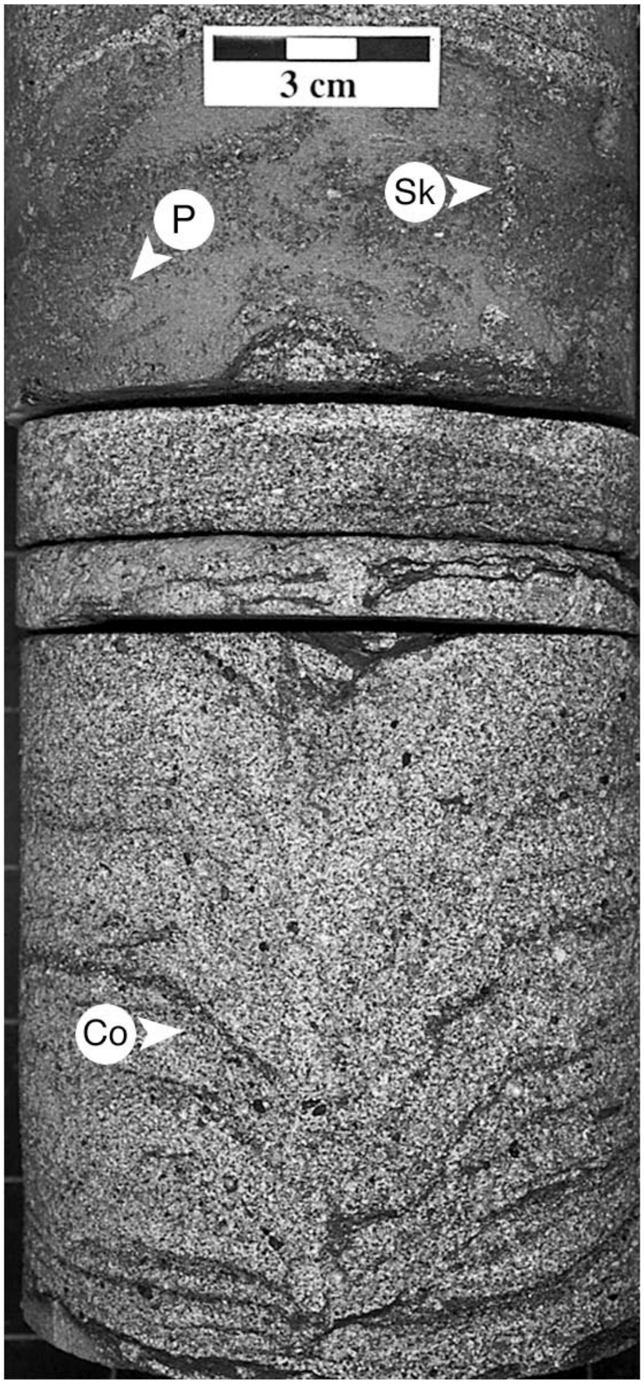



**Figure 13—Core showing facies A, which is a highly glauconitic, trough cross-stratified sandstone overlying BD-2. A robust *Conichnus* (Co) is present within the sandstone. Siderite-cemented zone toward the top of the photo contains *Planolites* (P) and *Skolithos* (Sk). This facies is interpreted to reflect transgressive sand sheets mantling BD-2 within the embayment (well 01-07-38-24W4, 1416.0 m).**

*Diplocraterion*, and escape structures become significant elements of the suite. *Chondrites*, *Asterosoma*, *Bergaueria*, *Rosselia*, *Anconichnus*, *Helminthopsis*, and *Zoophycos*, although present, are restricted to the top of the succession and are of exceedingly low abundance. The dominant expression of the trace fossil suite corresponds to a low-diversity, mixed *Skolithos-Cruziana* assemblage.

The parasequences consisting of facies A, B/C/D, and E are truncated by a regionally extensive wave ravinement surface (FS). This wave ravinement surface is locally demarcated by the *Glossifungites* ichnofacies, represented by firmground *Skolithos*, *Diplocraterion*, *Thalassinoides,* and rarer *Arenicolites*. Facies overlying this ravinement surface consist of transgressive pebble lags passing upward into bioturbated silty and sandy mudstones, muddy sandstones, and burrowed mudstones interstratified with storm-generated sandstones of upper sequence 3. These facies contain diverse and robust trace fossil suites of the archetypal *Cruziana* ichnofacies, reflecting fully marine conditions similar to those indicated by the facies of sequence 1 and sequence 2.

### *Reservoir Characteristics of Lower Sequence 3*

The coarse clastics of sequence 3 represent the main Viking Formation reservoir and produce both oil and gas along the southwest margin of the depositional trend. A study correlating depositional facies to reservoir character employed a total of 1054 samples, collected from the main facies groups described (facies A, facies B/C/D, and facies E; Figure 17). The glauconitic trough cross-bedded pebbly sandstones of facies A possess porosities ranging from 2.1 to 22.1% and averaging 11.8%. Permeabilities range from 0.01 to 1800 md ($K_{max}$) and average 144.8 md ($K_{max}$). Facies A constitutes a marginal reservoir sandstone, however, because it is typically thin, confined to the base of the succession where it is locally water wet, and is laterally heterogeneous due to the abundance of glauconite, mud laminae, and mudstone interbeds.

The well-sorted trough cross-stratified and planar-stratified sandstones, pebbly sandstones, and conglomerates of facies B, C, and D possess porosities ranging from 2.1 to 21.0% and averaging 12.8%. Permeabilities range from 0.01 to 4100 md ($K_{max}$) and average 435 md ($K_{max}$). These facies constitute the main Viking Formation reservoir at Joffre. Low porosities and permeabilities within this facies group tend to be associated with local zones of siderite cementation and the presence of mud laminae.

Coarser sandstones and thin conglomerate beds in the interbedded sandstones and mudstones of

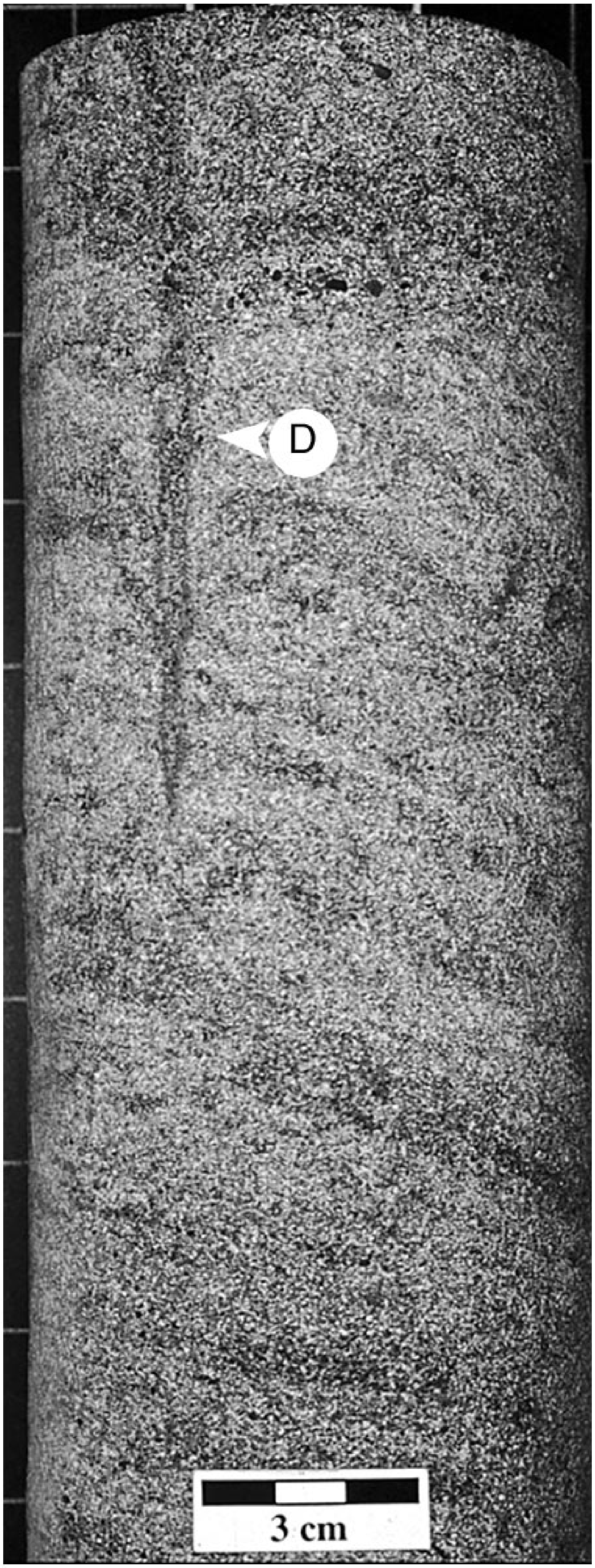



**Figure 14—Core showing facies B, a large-scale trough cross-stratified sandstone with a lined *Diplocraterion* (D) shaft. This facies is interpreted to reflect migrating dunes within marginal marine (brackish water) channels (well 02-05-39-26W4, 1573.3 m).**

facies E have porosities ranging from 0.6 to 20.4% and averaging 7.9%. Permeabilities range from 0.01 to 1040 md ($K_{max}$) and average 69.9 md ($K_{max}$). The higher porosity and permeability values are generally associated with beds thinner than 25 cm, which are unlikely to be laterally extensive.

Lower sequence 3 consists of three discrete parasequences that onlap relief on the southwest margin of BD-2 (Figures 10, 11). The parasequences are best developed, and the coarse clastics are both thinner and regularly interstratified with mudstones, toward the southern end of the field (T38, R25W4), which serves to partition the reservoir along its northeastern and structurally updip edge (Figure 10). These coarse clastics tend to form units 0.5–3.5 m in thickness. The southern portion of the field is structurally low and has a higher water cut than the northern end of the field. Cumulative production consequently tends to be poorer in the south. Despite this, the stacked coarse clastic bodies within the parasequences in the south tend to be broad in area and typically extend across two to three sections (3.2–4.8 km), making them an easier target than the narrower, amalgamated clastic bodies in the north end of the field.

In the north (T39, R27W4), erosional amalgamation of the coarse clastics is much more pronounced, and parasequence boundaries cannot be delineated easily. The coarse clastics are thicker (3–7 m) and less extensively interstratified with mudstones, producing a more homogeneous reservoir than in the south (Figure 11). The northern portion of the field is structurally higher than the southern portion and has virtually no water cut. Cumulative productions, therefore, tend to be significantly higher in the northern part of the field than in the southern part of the field. Unfortunately, these thicker amalgamated intervals also tend to occur in quite narrow bands, typically limited to 0.4–1.2 km in width, and locally may pass abruptly into bay mudstones over distances of only 0.4 km (Figure 11).

### *Interpretation of Lower Sequence 3*

The facies succession of lower sequence 3 is attributed to deposition within a marginal-marine bayhead delta/embayment complex, due to the genetic affinity between the burrowed, trough cross-stratified coarse clastics and the weakly burrowed, interstratified mudstones and sandstones.


**Figure 15—Core showing facies B and C, trough cross-bedded sandstone and pebbly sandstone. This unburrowed interval shows a dark mudstone interbed and mudstone rip-up clast within the cross-bedded coarse clastics (well 06-11-38-25W4, 1422.1 m).**

The glauconitic sandstones of facies A are interpreted as a transgressive marine sand sheet reworked along the base of the embayment by wave ravinement of the sequence boundary (BD-2), forming a discontinuity termed a bay ravinement surface (D. J. P. Swift, 1997, personal communication). Any lowstand deposits present were reworked during this early transgressive flooding. Facies A contains the most diverse ichnological suite of the succession, presumably reflecting largely marine conditions during ravinement.

The trough cross-stratified coarse clastics of facies B, C, and D are interpreted to reflect current-generated migrating dunes within channels. The trace fossil suite demonstrates that channel deposition occurred within marginal marine conditions. These channels are interpreted as tidal channels and creeks associated with the intertidal portions of the embayment. Locally, they also may correspond to marine-influenced distributary channels of bayhead delta systems prograding into the estuarine embayment. The distribution of facies B, C, and D, fringing the southwest edge of the embayment along the entire strike of the deposit, implies multiple point sources for clastic input, probably oriented perpendicular to the trend of the field. Although most of these shore-normal channel systems were probably removed by later erosion (Figures 6, 10, 11), localized north-south and northeast-southwest thick trends (e.g., T37-24W4 and T37-25W4; see Figure 8) may correspond to their remnants.

Facies E is interpreted to reflect marginal marine, sandy (proximal) and muddy (distal) bay deposits. The physical structures demonstrate a predominance of wave processes, with subordinate storm events and rare current processes. Upward increase in sandstone content is interpreted to indicate shallowing of the bay during fill, and locally, may indicate proximity to a bayhead delta. The trace fossil suite displays strong evidence of environmental stress near the base of the succession, but is progressively less stressed in character near the top of the succession, particularly as sandstone content increases. The trace fossil assemblage is consistent with a salinity-stressed setting (Pemberton et al., 1992; MacEachern and Pemberton, 1994), although the setting is characterized by pronounced fluctuations in salinity coupled with generally increasingly more normal-marine conditions upward. The suite generally shows less marked salinity reductions than comparable facies within Viking Formation estuarine incised valley complexes, such as in the Crystal and Willesden Green fields (MacEachern and Pemberton, 1994); however, the ichnological assemblage of facies E contrasts markedly with those of the underlying, unstressed, fully marine regional Viking parasequences and Joffre shoreface complex (Figure 5). The ichnological suites of the overlying transgressive deposits are also more diverse and abundant.

The lower sequence 3 facies succession has been interpreted previously as a conglomeratic, incised shoreface system, similar in origin to the Joffre shoreface complex (Downing and Walker, 1988); however, it displays features that are difficult to reconcile with a transgressively incised shoreface deposit. First, the only shoreface subenvironment that could accommodate the characteristics of facies B, C, and D is the upper shoreface. Upper shorefaces are typified by stacked, trough cross-stratified sandstones, pebbly sandstones, or conglomerates generated by wave-forced currents operating in the surf zone (Clifton et al., 1971; Davidson-Arnott and Greenwood, 1976; Hunter et al., 1979). In contrast, lower and middle shoreface deposits are dominated by oscillatory processes, which generate successions dominated by hummocky and swaley cross-stratification (Kumar and Sanders, 1976; Aigner and Reineck, 1982; Dott and Bourgeois, 1982; Swift et al., 1985). Longshore bars, which also contain trough cross-bedding, occur near the top of the middle shoreface within modern barred shoreface settings (Wright et al., 1979). These upper shoreface and longshore bar settings, however, are characterized by sustained, high-energy conditions (Davidson-Arnott and Greenwood, 1976; Davis, 1978; Hunter et al., 1979). The abundance of mudstone laminae, mudstone interbeds, and nonresistant mudstone rip-up clasts within facies B, C, and D (Figures 10, 11, 15) are inconsistent with the high-energy conditions of these environments, particularly a surf zone capable of mobilizing granules and pebbles into subaqueous dunes.

Second, if the trough cross-bedded coarse clastics reflect nearshore deposition, then they should grade seaward into contemporaneous middle and lower shoreface burrowed to hummocky/swaley cross-stratified sandstones. In contrast, the clastics pass into thinly interbedded oscillation rippled sandstones and dark mudstones of facies E, reflecting highly sheltered, lower energy settings (Figures 10, 11). The interbedded sandstones and mudstones of facies E are also untenable as the offshore or shelf component of a conglomeratic shoreface on three counts: (1) The abrupt transition from coarse clastics to fine-grained deposits (e.g., Figures 11, 12) over distances of only 400 m constitutes depositional gradients that are too steep for a transition from the upper shoreface to the offshore. (2) The interbedded sandstones and mudstones of facies E contain a stressed trace fossil suite consistent with reduced salinity settings. This suite is impoverished compared with the fully marine offshore deposits of the transgressive Joffre shoreface complex and highstand regional Viking parasequences. (3) Foraminiferal assemblages within the mudstones generally display a low diversity of forms and a paucity of environmentally intolerant genera (C. R. Stelck, 1997, personal communication), particularly when compared to the microfos-

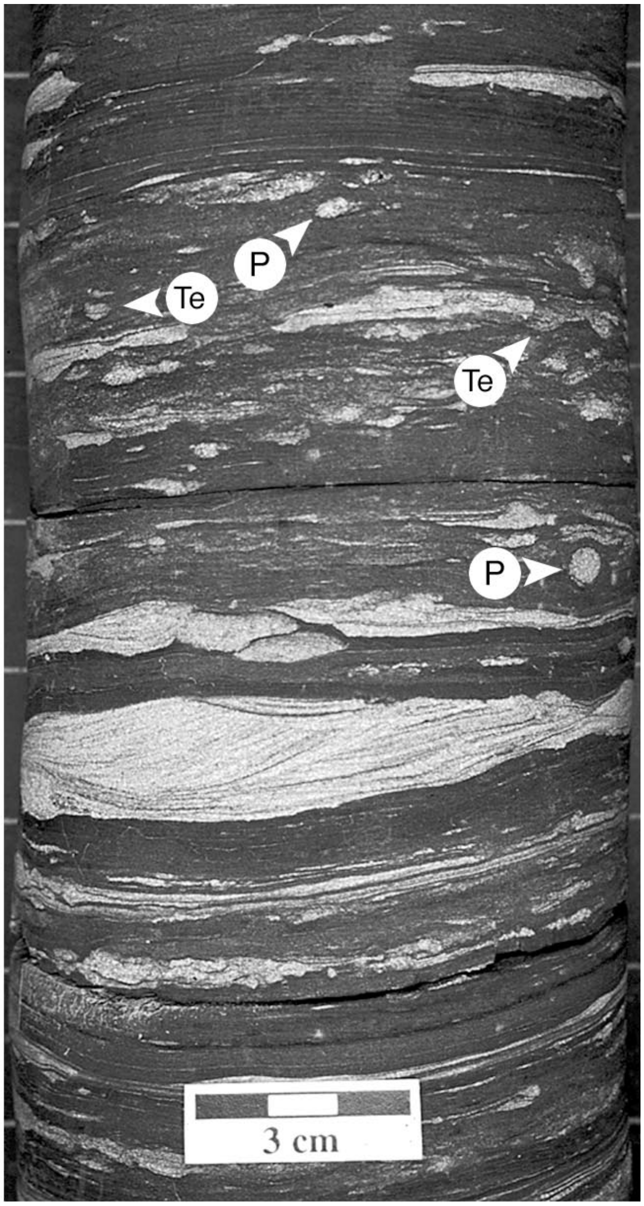



**Figure 16—Core showing facies E, oscillation rippled sandstones and mudstones. Note the interstratified fine-grained, oscillation rippled sandstones and weakly burrowed carbonaceous mudstones. *Teichichnus* (Te) and *Planolites* (P) are the dominant trace fossils (well 03-24-38-25W4, 1438.5 m). This facies is interpreted to reflect marginal-marine bay deposits.**

sil assemblages associated with sequence 1, sequence 2, and the overlying transgressive mudstones.

Instead, the multiple scours, fining-upward, and uniformly oriented character of the trough cross-bedded intervals, coupled with the presence of mudstone laminae, interbeds, and nonresistant rip-up clasts, are more consistent with deposition in response to channelized flow. The mudstone interbeds and laminae attest to repeated fluctuations in flow strength, which may suggest some tidal modifications of flow. The mudstone rip-up clasts indicate that current flow was capable of scouring into the adjacent and underlying, penecontemporaneous, fine-grained deposits of facies E. The presence of burrowing within the coarse clastics demonstrates that channelized flow occurred in marine to marginal marine conditions. The trace fossil suite of facies E, with which the coarse clastics interfinger, indicates salinity-induced stress, suggesting that marginal marine conditions prevailed for much of lower sequence 3 deposition.

Given the marginal marine character of the succession and the apparent trough-shaped erosional discontinuity it rests upon, conventional sequence stratigraphic wisdom would suggest that these deposits constitute an incised valley complex. These deposits contain features, however, that are incompatible with an incised valley interpretation. The first inconsistency is related to the orientation of the deposit parallel to the inferred shoreline trends during Viking time. Although valleys may reorient themselves parallel to old shoreline trends during lowstand conditions (Suter et al., 1987; Thomas and Anderson, 1994; Sullivan et al., 1995), this does not appear to have been the case for any of the known incised valley complexes of Viking age in Alberta. All currently recognized Viking Formation valley complexes have an orientation perpendicular to paleoshoreline trends (Reinson et al., 1988; Boreen and Walker, 1991; Pattison, 1991).

A second incompatibility with a valley interpretation for lower sequence 3 is that no fluvial deposits or fluvially supplied deposits occur in the vicinity of the stratigraphically lowest position of BD-2. Isopach thicks (Figure 8) correspond to predominantly muddy intervals within the succession (Figures 6, 10, 11), and appear to consist of brackish-water facies E. If the proposed valley were cut by fluvial processes, it would require the system to have operated as a zone of total coarse sediment bypass not only during lowstand conditions, but also during early transgression and concomitant increasing accommodation space. Within valleys, increasing accommodation space is generally accompanied by fluvial aggradation. The succession cannot be accounted for within a terraced valley complex (cf., Blum, 1994) because cross sections demonstrate that the coarse-grained facies along the margins of the deposit interdigitate with the mudstones to the northeast (Figures 6, 10, 12).

The remaining problems with an incised valley interpretation are related to the distribution and orientation of the fill above BD-2. Most incised valley deposits are characterized by a tripartite zonation of facies, comprising (from landward to seaward) bayhead delta, central basin, and estuary mouth complexes (Dalrymple et al., 1992; Zaitlin et al., 1994). Although the former two complexes can be demonstrated to exist in sequence 3, the estuary mouth deposits, which should lie near the southeast end of Joffre or in the Mikwan field (Figure 1), cannot. Perhaps more importantly, the orientation of the three parasequences comprising this succession is inconsistent with a shore-parallel incised valley. In valleys, parasequences are oriented with strikes perpendicular to the valley trend, onlap upvalley, and downlap/offlap downvalley. If lower sequence 3 reflected an incised valley, the parasequences would be oriented northeast-southwest, and shift northwest in the upvalley direction or southeast in the downvalley direction. In contrast, the parasequences of sequence 3 strike parallel to the length of the deposit (northwest-southeast), while onlapping to the southwest and offlapping to the northeast (Figures 10, 12). This orientation is more characteristic of shoreline or intertidal parasequences.

The apparent valleylike morphology of BD-2 warrants addressing at this point. The isopach map of lower sequence 3 (Figure 8) illustrates a 12-m (or more) thick maximum along a northwest-southeast trend, thinning to a zero edge toward both the southwest and the northeast. In addition, the regional cross section CC′ (Figure 6) shows a broad, u-shaped (trough-like) morphology for BD-2. It is tempting, therefore, to accept this as conclusive proof of a valley geometry for BD-2. These features can be explained, however, without appealing to valley incision.

The stratigraphic rise of BD-2 toward the northeast (Figure 6) is an artifact of pull-up caused by using the Base of Fish Scales (BFS) marker as a datum. Marine markers, both depositional and erosional, dip gently in a seaward direction. Based on the regional paleogeography of the Western Interior seaway and the paleoshoreline trends during the Viking, markers are expected to dip toward the northeast (Posamentier et al., 1992; Posamentier and Chamberlain, 1993; Walker and Wiseman, 1995). A close appraisal of cross section CC′ (Figure 6), however, shows that the regional Viking parasequences of sequence 1 do not dip in a northeast direction, but rather remain horizontal. In addition, the base of the incised shoreface of

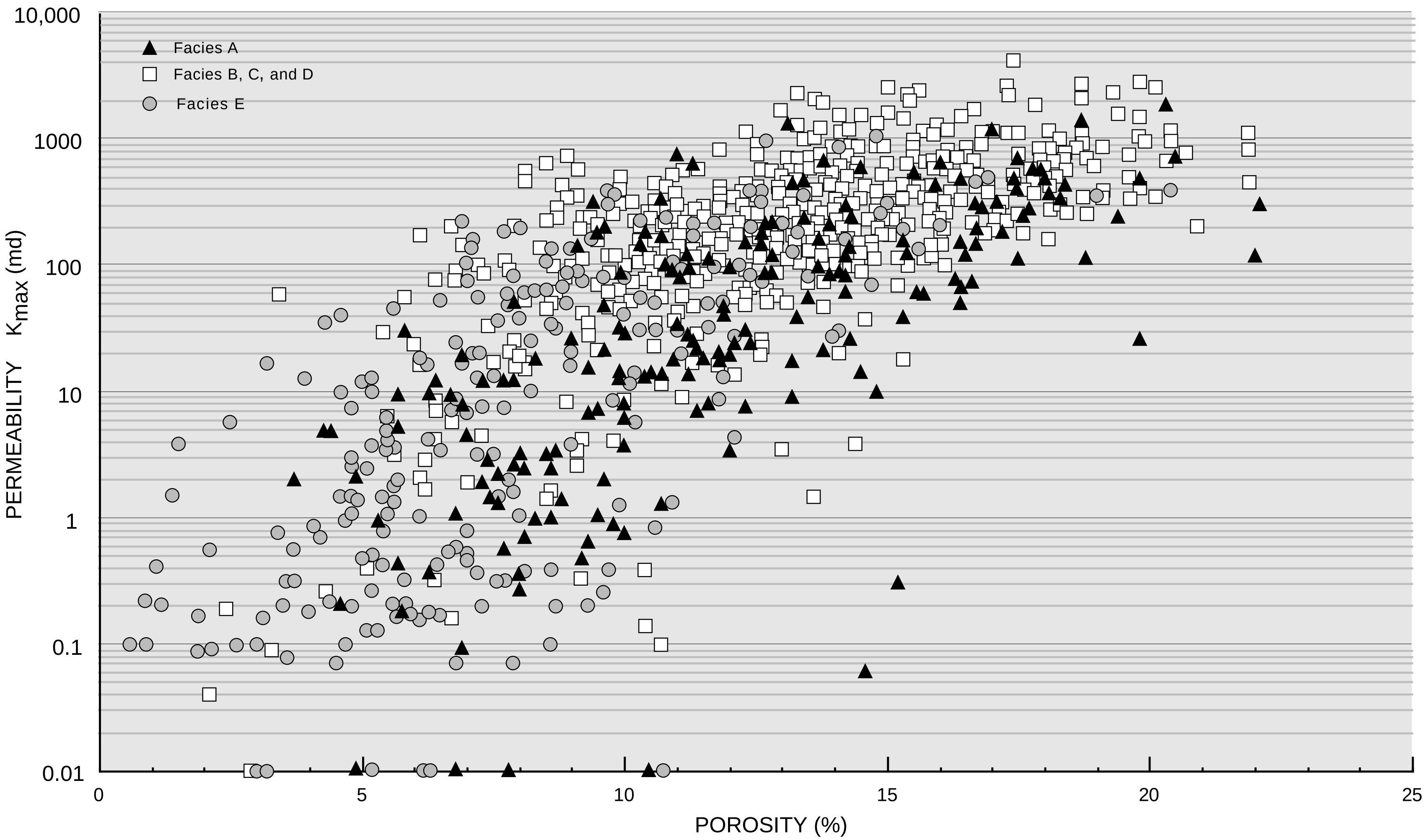



**Figure 17**—Porosity and permeability data for sequence 3 embayment deposits. The plot of core analyses is based on 1054 samples. Three main facies groups (A; B, C, and D; and E) are represented. Facies A is glauconitic, burrowed muddy sandstones interpreted as transgressive lag and transgressive sand sheet deposits. Porosity is 2.1–22.1%, averaging 11.8%, and permeability is 0.01–1800 md ($K_{max}$), averaging 144.8 md ($K_{max}$). Facies B, C, and D are trough cross-bedded sandstones, pebbly sandstones, and conglomerates interpreted as bayhead delta and tidal channel/distributary channel deposits. Porosity is 2.1–21%, averaging 12.8%, and permeability is 0.01–4100 md ($K_{max}$), averaging 435 md ($K_{max}$). Facies E is interbedded oscillation rippled sandstones and weakly burrowed mudstones interpreted as brackish water bay deposits. Porosity is 0.6–20.4%, averaging 7.9%, and permeability is 0.01–1080 md ($K_{max}$), averaging 69.9 md ($K_{max}$). Most hydrocarbon production is associated with facies B, C, and D.

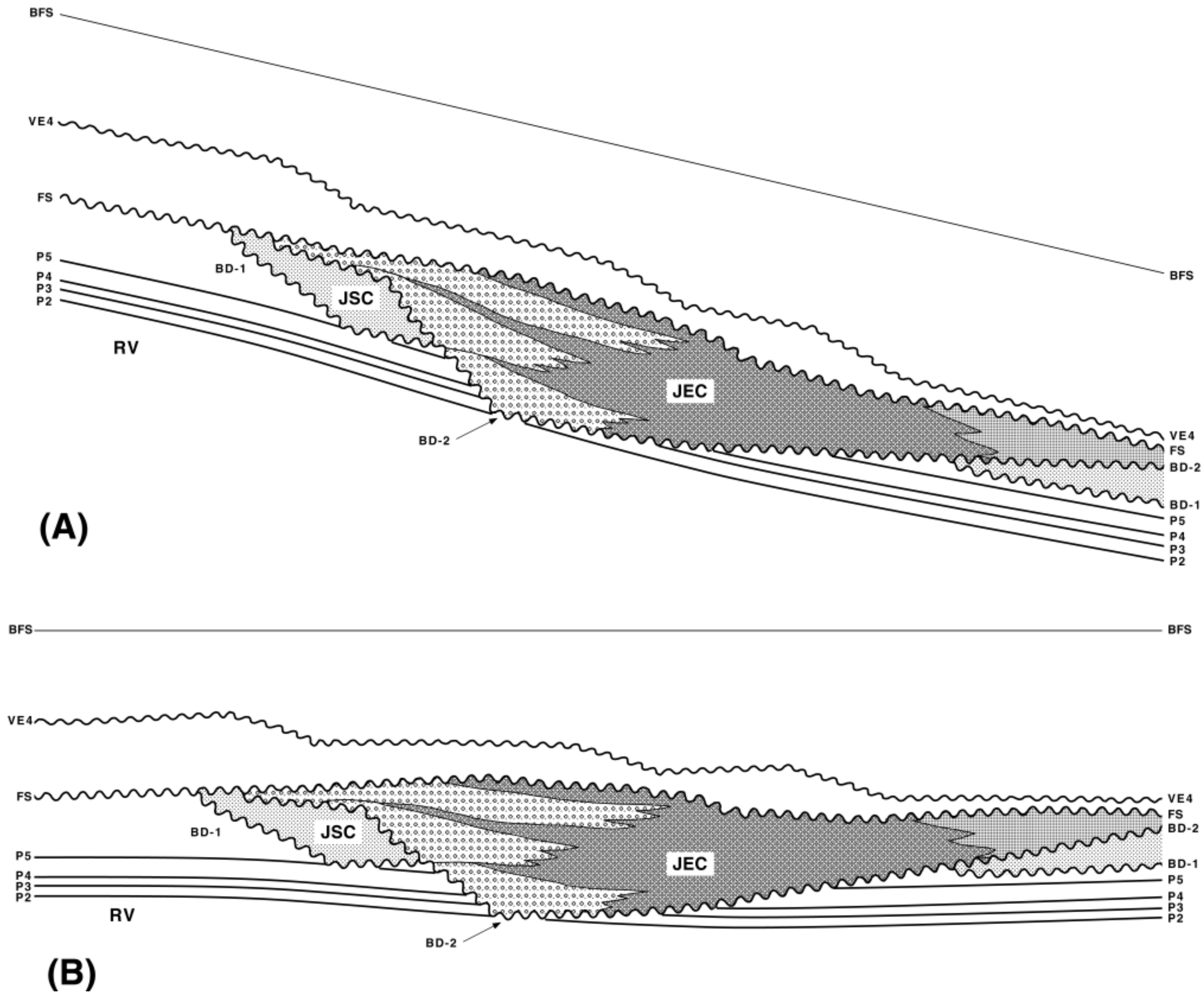



**Figure 18— Schematic model of the effects of stratigraphic pull-up. (A) Original paleodepositional relationships with the embayment deposits of sequence 3, assuming that the overlying datum BSF (Base of Fish Scales) had an original seaward dip. Note that the basal discontinuity BD-2 is represented by a gently seaward-dipping, asymmetrical scour. Preservation of sequence 2 and regional parasequences of sequence 1 is the result of having a steeper inclination than the overlying BD-2 surface. (B) The same schematic section rotated so that the BFS marker becomes a horizontal datum. Note that this has the effect of pulling up the seaward edge of BD-2, making it appear to have a valley morphology. RV = regional Viking parasequences, P1–P5 = regional Viking parasequences 1–5, respectively, JSC = Joffre shoreface complex, JEC = Joffre embayment complex.**

sequence 2 (BD-1) does not dip to the northeast, but actually sits 7.5 m stratigraphically higher than it does on the southwest (landward) side of the section. This anomalous relationship demonstrates that pull-up has occurred. A reasonable interpretation is that the overlying BFS marker originally dipped to the northeast. A dip of 0.14°, corresponding to a gradient of 1.9 m/km, is required in order to flatten BD-2, which also would yield the reasonable seaward dip of 0.09° (i.e., a gradient of 1.5 m/km) for the base of the incised shoreface in sequence 2 (BD-1). Posamentier and Chamberlain (1993) suggested that in the Joarcam area, the gradient of the erosion surface, upon which those Viking shoreface sandstones rest, dipped basinward as steeply as 0.11°.

Reconfiguring the BFS marker as a horizontal datum has served to distort the original paleodepositional relationships from those schematically illustrated in Figure 18A to those represented in the stratigraphic cross section CC′ (Figures 6, 18B). Along the southwest margin of the deposit, BD-2 slopes steeply toward the northeast, and pull-up has reduced the angle of slope on the discontinuity. Along the northeast margin, however, the same pull-up, acting on a more gently seaward sloping or horizontal portion of the surface, produces an artificial southwest inclination to the surface. The preservation of the underlying Joffre shoreface complex and regional Viking parasequences in a northeast direction (Figure 6) simply indicates that these underlying markers possessed a steeper seaward dip than BD-2, and does not necessitate BD-2 rising stratigraphically in that direction. The apparent southwest dip of BD-2 along the northeast margin of lower sequence 3 is purely an artifact of stratigraphic pull-up.

An alternative model for lower sequence 3 is presented in Figure 19, which better accounts for the problematic relationships previously discussed. The BD-2 surface reflects transgressive ravinement that erosively modified the sequence boundary at the base of sequence 3. The early stage of transgressive ravinement reworked available sediments to produce the basal, glauconitic, pebbly sandstones of facies A, and introduced a broad, shallow-water embayment in the Joffre area. The sequence 3 deposits lying between BD-2 and the flooding surface are interpreted to represent shore-normal and shore-parallel channels and creeks that fed coarse clastics to the elongate, shore-parallel estuarine embayment during the early stages of transgression. Elongate, isopach, thick trends oriented roughly north-south along the southwest margin of the deposit (Figure 8) may correspond to the remnants of shore-normal feeder channels partially removed during subsequent ravinement. The coarse clastics of facies B, C, and D mainly accumulated along the southwestern (landward) margin of the embayment in the form of channels and marginal marine deposits that coalesced to form a broad, shore-parallel (northwest-southeast oriented), coarse-grained bayhead delta apron. As the embayment filled, high sediment supply to the bayhead deltas permitted these systems to prograde northeastward into the bay during the overall transgression. Fluctuations in the rate of transgression allowed the brackish bay mudstones and interbedded sandstones and mudstones of facies E to onlap the bayhead delta/channel complexes along the entire length of the embayment. The onlap of these fine-grained bay deposits highlights the flooding surfaces of the three parasequences (Figure 10). The northeastward progradation of the bayhead delta along the length of the embayment resulted in parasequences with shore-parallel strikes, offlapping/downlapping to the northeast and onlapping to the southwest.

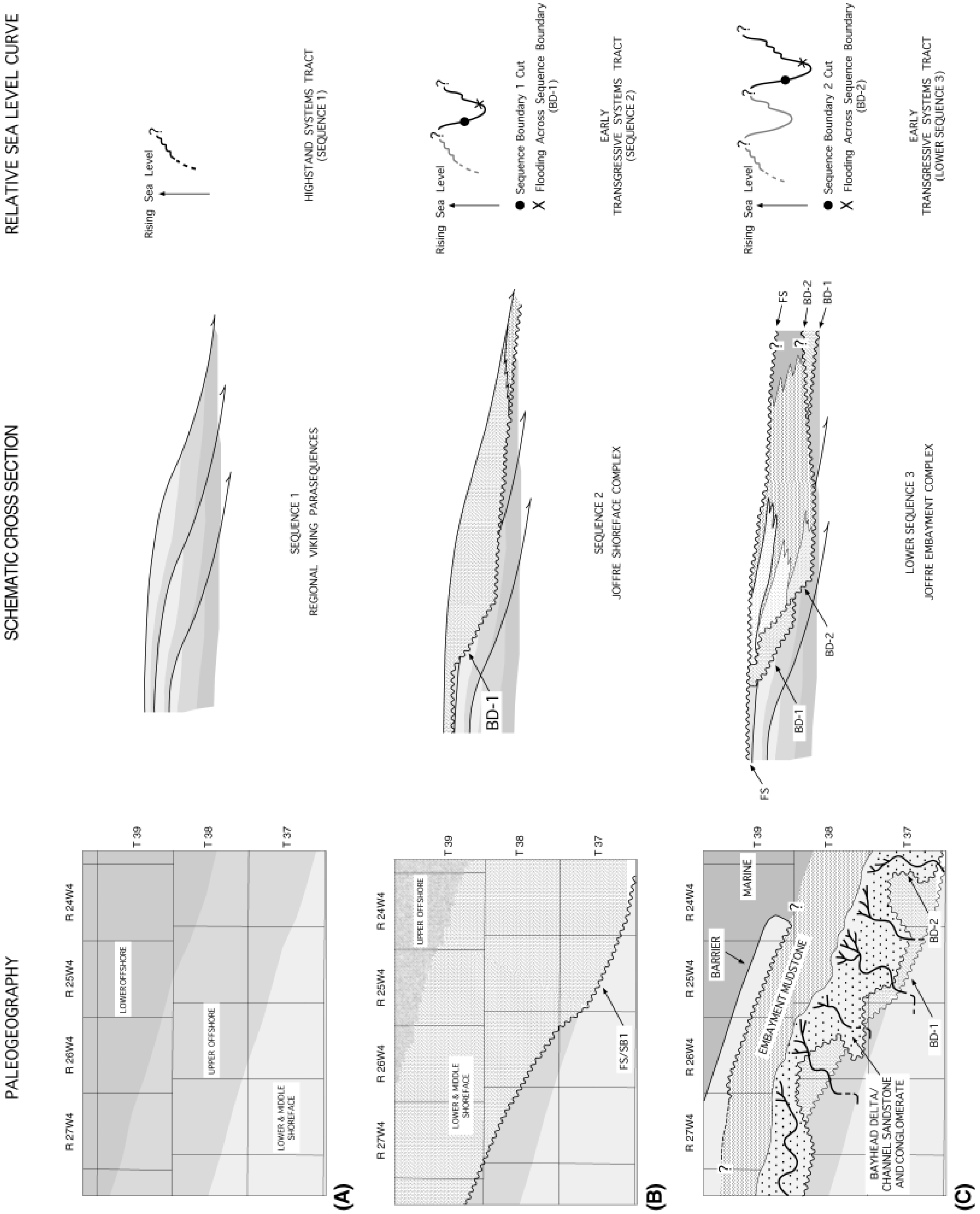
Facies E displays ichnological characteristics that indicate it was environmentally restricted, implying that the embayment was sheltered from open-marine conditions by a barrier system. Evidence of such a fronting barrier complex is lacking, although the preservation potential of barriers during transgression and associated ravinement is low (cf. Rampino and Sanders, 1980; Nummedal and Swift, 1987). The resumed transgression cut a ravinement surface across the top of the embayment deposits and is interpreted to have removed evidence of the barrier system. The transgression returned the study area to fully marine conditions and displaced the shoreline to the south and southwest. These deposits constitute the upper portion of sequence 3.

### *Implications of the Sequence 3 Model*

Generally, paleoshoreline-oriented coarse clastics engender a shoreline/shoreface interpretation. It is equally true that evidence of brackish conditions concomitant with coarse clastic deposition is typically regarded to reflect an estuarine incised valley. The Viking Formation at Joffre offers a third alternative, that of an embayment complex, which explains features difficult to reconcile with either shoreface or incised valley interpretations. Incremental transgression of coastal areas should be expected to generate abundant and widespread embayment complexes, making it an underrecognized hydrocarbon play type in the Cretaceous Western Interior seaway. The play comprises shore-parallel to shoreline-oblique coarse clastic parasequences, erosionally amalgamated and onlapping a basal stratigraphic discontinuity in the landward direction, and downlapping/offlapping seaward, where they rapidly interdigitate with brackish-water mudstones. Mellere and Steel (1995) described successions similar to lower sequence 3 at Joffre from the Campanian Haystack Mountains Formation of the Mesaverde Group, Wyoming. The embayment model proposed here may very well accommodate problematic features of the subsurface Shannon Sandstone, and ultimately resolve the controversy surrounding its interpretation in such fields as Hartzog Draw and Heldt Draw (Bergman, 1994; Bergman and Walker, 1995; Sullivan et al., 1995).

## SUMMARY

The Viking succession of the Joffre area comprises parts of three discrete sequences (Figure 19). Sequence 1 corresponds to the regional Viking, and consists of stacked, fully marine, shelf to lower/middle shoreface parasequences arranged in a progradational parasequence set, reflecting



PALEOGEOGRAPHY
SCHEMATIC CROSS SECTION
RELATIVE SEA LEVEL CURVE
(A)
R 27W4
R 26W4
R 25W4
R 24W4
T 39
T 38
T 37
LOWER OFFSHORE
UPPER OFFSHORE
LOWER & MIDDLE SHOREFACE
SEQUENCE 1
REGIONAL VIKING PARASEQUENCES
Rising Sea Level
HIGHSTAND SYSTEMS TRACT
(SEQUENCE 1)
(B)
UPPER OFFSHORE
LOWER & MIDDLE SHOREFACE
FS/SB1
BD-1
SEQUENCE 2
JOFFRE SHOREFACE COMPLEX
Sequence Boundary 1 Cut
Flooding Across Sequence Boundary
(BD-1)
EARLY
TRANSGRESSIVE SYSTEMS TRACT
(SEQUENCE 2)
(C)
MARINE
BARRIER
EMBAYMENT MUDSTONE
BAYHEAD DELTA/
CHANNEL SANDSTONE
AND CONGLOMERATE
BD-1
BD-2
FS
LOWER SEQUENCE 3
JOFFRE EMBAYMENT COMPLEX
Sequence Boundary 2 Cut
Flooding Across Sequence Boundary
(BD-2)
EARLY
TRANSGRESSIVE SYSTEMS TRACT
(LOWER SEQUENCE 3)

part of a highstand systems tract. These parasequences downlap onto the transgressive marine shales of the Joli Fou Formation (Figure 19A).

A relative fall in sea level permitted the widespread development of an erosional sequence boundary that incised into the underlying highstand systems tract and shifted the shoreline to the northeast. This sequence boundary was wave ravined during subsequent transgression, generating BD-1. Any overlying lowstand deposits were reworked during this transgression, which shifted the shoreline far to the south and southwest of the study area. A pause in the rate of transgression allowed the northeastward progradation of a shoreface across BD-1, depositing the transgressively incised Joffre shoreface complex of sequence 2 (Figure 19B).

A second relative fall of sea level permitted the excavation of a second sequence boundary, forming a broad northwest-southeast–trending incision at Joffre (Figure 19C). This sequence boundary dissected the underlying Joffre shoreface complex of sequence 2 and locally incised through it into the regional Viking parasequences of sequence 1. The shoreline was shifted north and northeast of the study area. The sequence boundary was subsequently ravined during ensuing transgression to form BD-2, and any overlying lowstand deposits were reworked to produce transgressive lags and glauconitic, transgressive sand sheets mantling the surface. This transgression generated a broad northwest-southeast embayment of the shoreline, probably separated from the open-marine seaway by a barrier complex lying in the northeastern portion of the study area. Pauses in the rate of flooding during the early stages of transgression permitted the northeastward progradation of conglomeratic bayhead deltas into the estuarine embayment from small, shore-normal and shore-parallel marginal marine channels. These coarse-grained deposits coalesced to form a broad, northwest-southeast–trending apron consisting of bayhead delta and distributary channel deposits along the southwestern margin of BD-2. Incremental transgressive fill of the embayment resulted in the shifting of bay deposits over bayhead delta/channel complexes, generating three discrete parasequences that onlap relief on BD-2 along its landward (southwestern) margin and offlap/downlap to the northeast (Figure 10). These interstratified coarse clastic and brackish bay mudstone deposits constitute the Joffre embayment complex of lower sequence 3. Resumed transgression cut a ravinement surface, termed FS, which terminated deposition within the Joffre embayment complex and returned the study area to fully marine, offshore conditions.

Successions characterized by coarse clastics regularly interstratified with marine or marginal-marine mudstones can be problematic to interpret because the facies indicate the juxtaposition of disparate energy conditions. These types of successions have been generally interpreted either as coarse-grained conglomeratic shoreface deposits or as incised valley complexes (Downing and Walker, 1988; Posamentier et al., 1992; Posamentier and Chamberlain, 1993; Walker and Bergman, 1993; Bergman, 1994; Bergman and Walker, 1995; Sullivan et al., 1995). Careful ichnological, sedimentological, and high-resolution sequence stratigraphic analyses indicate that neither model is appropriate for the Viking Formation deposits at Joffre, and provides an alternative model. Transgressions favor the development of shoreline embayments, typically fronted by barrier systems. During subsequent ravinement, these barrier complexes are probably destroyed or preserved only as offshore to lower shoreface remnants resting on transgressive surfaces of erosion. The back-barrier mudstones and coarse clastics feeding into the embayment, however, have a higher preservation potential during the transgression, because (1) they occupy a paleo-depositional depositional low, and (2) ravinement surfaces

**Figure 19—Schematic model of Viking deposition in the Joffre area. (A) The regional Viking parasequences reflect incremental northeastward progradation of offshore to lower/middle shoreface successions during slowly rising or possibly stable relative sea level, and constitute part of a highstand systems tract within sequence 1. (B) A subsequent fall in relative sea level permitted the cutting of a sequence boundary and displacement of the shoreline northeast of the study area. Ensuing transgression flooded across the sequence boundary, modifying it to form BD-1. A pause in the rate of transgression allowed the progradation of the Joffre shoreface complex, which is interpreted as the early transgressive systems tract of sequence 2. (C) Another major fall of relative sea level excavated a second sequence boundary, which incised into, and locally through, the Joffre shoreface complex, shifting the shoreline northeast of the study area. A resumption of transgression erosionally modified the sequence boundary to produce BD-2, and mantled it with a transgressive sand sheet. Coarse clastics, reflecting bayhead delta and distributary channel deposits, prograded northeast into a brackish embayment. Incremental pulses of transgression or variations in sediment supply resulted in the onlap of bay mudstones over coarse clastics, marking the marine flooding surfaces of three marginal marine parasequences. These deposits comprise the Joffre embayment complex interpreted to represent part of an early transgressive systems tract of lower sequence 3. Continued transgression truncated the upper part of the embayment complex and generated a regional flooding surface (FS).**

rise stratigraphically during landward translation of the shoreline. Despite the ubiquitous occurrence of brackish lagoonal and embayment environments in modern transgressive shoreline systems, interpretations of ancient transgressive successions appear to ignore, or fail to recognize, the deposits of these environments, making it a potentially underrecognized hydrocarbon play type.

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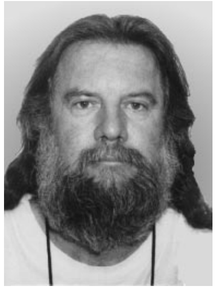

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