COARSE-GRAINED, SHORELINE-ATTACHED, MARGINAL MARINE PARASEQUENCES OF THE VIKING FORMATION, JOFFRE FIELD, ALBERTA, CANADA

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ABSTRACT: The Viking Formation of the Joffre Field area comprises parts of three discrete sequences. The reservoir facies lies within the lower part of Sequence 3, interpreted to reflect shoreline-attached, marginal marine deposits. Sequence 3 was initiated by a fall of relative sea level with associated subaerial exposure and erosional scour, generating a sequence boundary. This sequence boundary was erosionally modified by ravinement during the ensuing transgression, to form a broad NW-SE trending asymmetric incision at Joffre, referred to as basal discontinuity 2 (BD-2).

BD-2 is mantled by conglomeratic lags and bioturbated, glauconitic transgressive sand sheets (Facies A). These are overlain by moderately burrowed, trough and low angle planar cross-stratified sandstone, pebbly sandstone and conglomerate, concentrated along the southern (landward) margin of BD-2, and interpreted to reflect distributary channels (Facies B/C/D). These channels fed sediment to prograding bay-head delta fronts, which coalesced to form broad, NW-SE trending coarse clastic aprons (Facies B/C/D and F). Each bay-head delta apron progressively interfingers with, and ultimately passes into weakly burrowed interbedded sandstone and mudstone (Facies E). These fine-grained deposits contain oscillation ripples, storm-generated wavy parallel laminations, and low diversity trace fossil suites, and are interpreted as brackish-water bay deposits.

Fluctuations in the rate of transgression resulted in the shifting of brackish-water bay deposits over channel/bay-head delta complexes, delineating three discrete marginal marine parasequences. Each parasequence trends northwest-southeast, onlaps relief on BD-2 along its landward (southwestern) margin, and offlaps/downlaps to the northeast. Resumed regional transgression generated a flooding surface (FS) with associated ravinement, that terminated brackish-water deposition and returned the study area to fully marine, offshore conditions.

INTRODUCTION

The Viking Joffre Field (Lower Cretaceous) is part of an elongate trend of fields, including Gilby, Mikwan, Fenn and Chain, extending NW-SE for approximately 250 km in central Alberta (Fig. 1). Joffre is the southeastern-most oil field in a trend that becomes gas-prone to the south. MacEachern et al. (1998) summarized the Viking Formation succession in the Joffre area, integrating ichnology with sedimentology and high resolution sequence stratigraphy to identify three discrete sequences. The reservoir interval corresponds to the lower portion of Sequence 3 and consists of three stacked, anomalously coarse-grained, NW-SE trending, narrow, linear conglomeratic sandstone bodies, interstratified at their distal (NE) edges with dark, weakly burrowed mudstone. The mapped distribution of Lower Sequence 3 and the basinward limits of the reservoir facies are shown in Figure 2. This paper concentrates on the characteristics, paleoenvironments, stacking, and distribution of the three parasequences that comprise the reservoir interval of Sequence 3.

The reservoir succession at Joffre was previously interpreted as a single incised conglomeratic shoreface, stranded during transgression in an offshore to shelf setting (Downing and Walker, 1988), an interpretation now widely accepted. Further work by Burton and Walker (this volume) refines this model to account for the interstratification of mudstone-dominated facies with conglomerate, by introducing two high-order lowstand events during an overall transgression. Their model now proposes two stacked lowstand or forced regressive conglomeratic shorefaces generated by high frequency relative falls in sea level during an overall transgression. Many characteristics of the reservoir succession, however, are incompatible with a shoreface interpretation in our opinion. These characteristics have been discussed in detail in MacEachern et al. (1998), and are outlined here in the "Interpretation of Lower Sequence 3" section of the present paper.

Additionally, the succession superficially resembles an estuarine incised valley complex, due to the apparent shape of the basal contact, the dominance of trough cross-bedded coarse clastics, and the interstratification of conglomeratic sandstones with brackish-water mudstones. Again, MacEachern et al. (1998) have outlined the incompatibilities with this model, which are also summarized here in the "Interpretation of Lower Sequence 3" section of the present paper.

STUDY AREA AND DATA BASE

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 NW-SE trend (Fig. 2). The Viking Formation within the Joffre Field contained some 14831 x 10^3m^3 (93 x 10^6 barrels US) of original oil in place (ERCB, 1994). Established reserves constituted 6451 x 10^3m^3, reflecting 2481 x 10^3m^3 from primary and 3970 x 10^3m^3 from enhanced (3087 x 10^3m^3 water flood and 883 x 10^3m^3 solvent flood) recovery techniques. To date, cumulative production totals approximately 5982.5 x 10^3m^3 (37.6 x 10^6 barrels US).

The Lower Cretaceous Viking Formation consists predominantly of westerly derived siliciclastics, and reflects northeastward progradation of sediment 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

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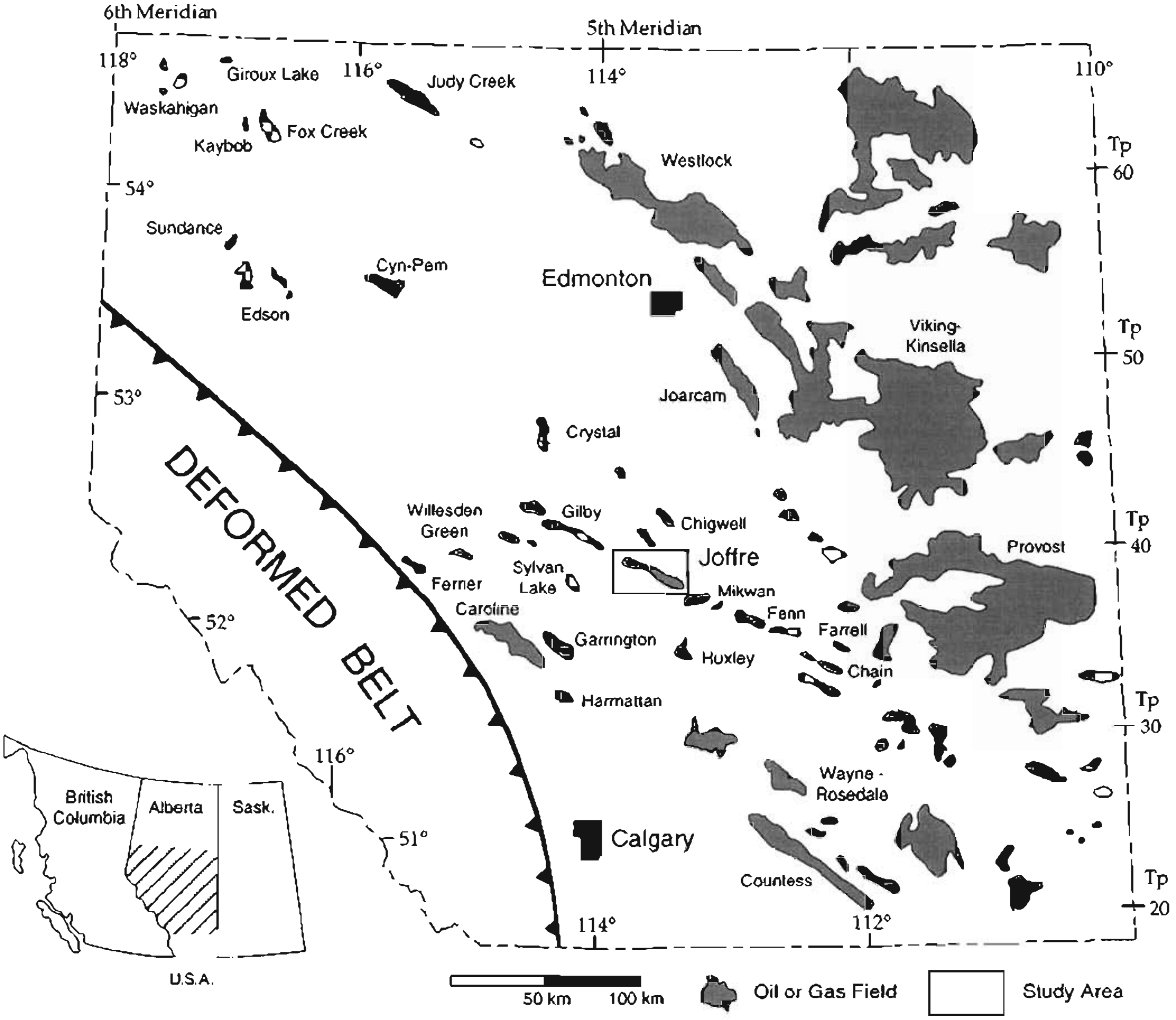

Fig. 1.—Major Viking Formation hydrocarbon field locations in Alberta, Canada.

the field is therefore a combination structural/stratigraphic trap, reflecting structurally high distal edges of coarse-grained parasequences that interfinger basinward with mudstone.

The study area contains approximately 950 wells that penetrate the Viking Formation, of which approximately 280 contain core from the interval. This study used data from 110 cores (Fig 2), which were logged in detail to integrate physical sedimentological, ichnological, and sequence stratigraphic data. Selected core lithologs were used in the construction of 9 (6 dip-oriented and 3 strike-oriented) stratigraphic facies cross sections.

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 8 regional stratigraphic cross-sections and 17 local (field-scale) stratigraphic cross-sections. The regional cross-sections and large-scale mapping delineated the distributions, geometries and thickness variations of the discontinuity-bound sequences employed in development of the general model (MacEachern et al., 1998). The field-scale well log and litholog facies cross-sections were used to determine the orientation, distribution, and geometry of the three parasequences comprising the lower part of Sequence 3.

REGIONAL STRATIGRAPHIC RELATIONSHIPS

The Viking Formation is Late Albian in age. It passes upward from marine shale of the Joli Fou Formation and is overlain by the transgressive marine shale of the Westgate Formation (Fig. 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

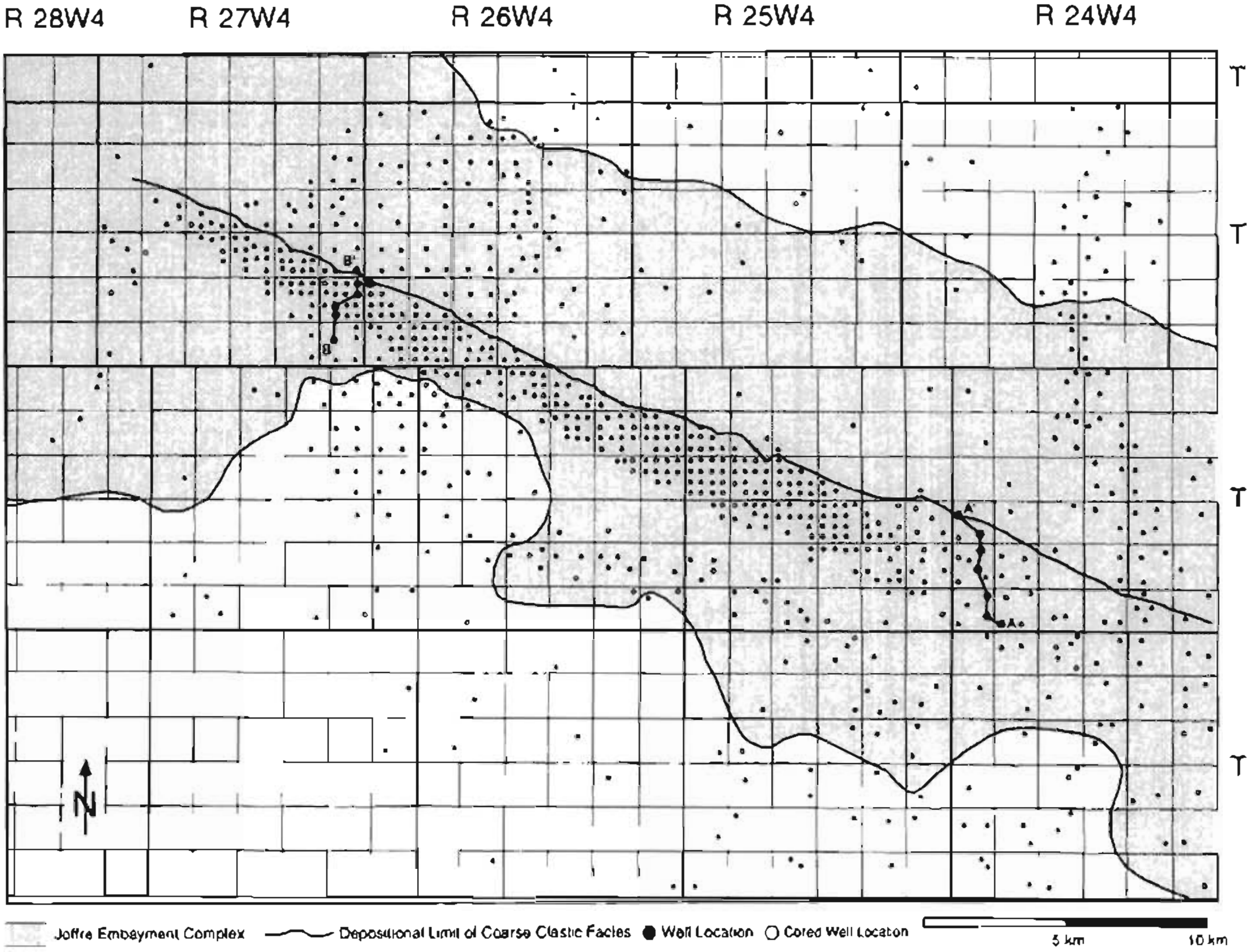

Fig. 2.—Joffre Field study area. The map shows the depositional limit of coarse clastic reservoir facies as well as cross-section lines A-A' and B-B'.

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 N.E. British Columbia (Stelck and Leckie, 1990). In the United States, these shales are equivalent to the Shell Creek (Caldwell et al., 1993; Obradovich, 1993). The Mowry shale in Montana and Wyoming is regarded to be Cenomanian in age (Cobban and Kennedy, 1989) and is equivalent to the Base of Fish Scales Marker and the overlying shale.

The Viking Formation is highly complex and contains numerous stratigraphic discontinuities. Attempts to subdivide the interval into regionally correlative genetic units have been undertaken by Boreen and Walker (1991), Pattison (1991), Davies and Walker (1993) and most recently by Burton and Walker (this volume). These attempts have sought to establish a formal allostratigraphic framework for the Viking Formation that conforms to the rules of the North American Code of Stratigraphic Nomenclature (NACSN, 1983). Others have taken a sequence stratigraphic approach to the subdivision of the interval (e.g., Posamentier and Chamberlain, 1993; Leckie and Reinson, 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 (Fig. 4), contains parts of three discrete sequences separated by two regionally extensive, transgressively modified sequence boundaries (MacEachern et al., 1998). These major stratigraphic breaks were accurately delineated by Downing and Walker, (1988) and constituted the fundamental bounding discontinuities of their allostratigraphic units. Boreen and Walker (1991) correlated the lower of the two surfaces to their VE3a surface. These discontinuities are referred to as BD-1 and BD-2, employing the terminology of Burton and Walker (this volume), although our interpretations regarding the specific details of their genesis differ somewhat.

The basal sequence (Sequence 1) consists of stacked, NW-SE trending, regionally extensive, coarsening-upward shelf

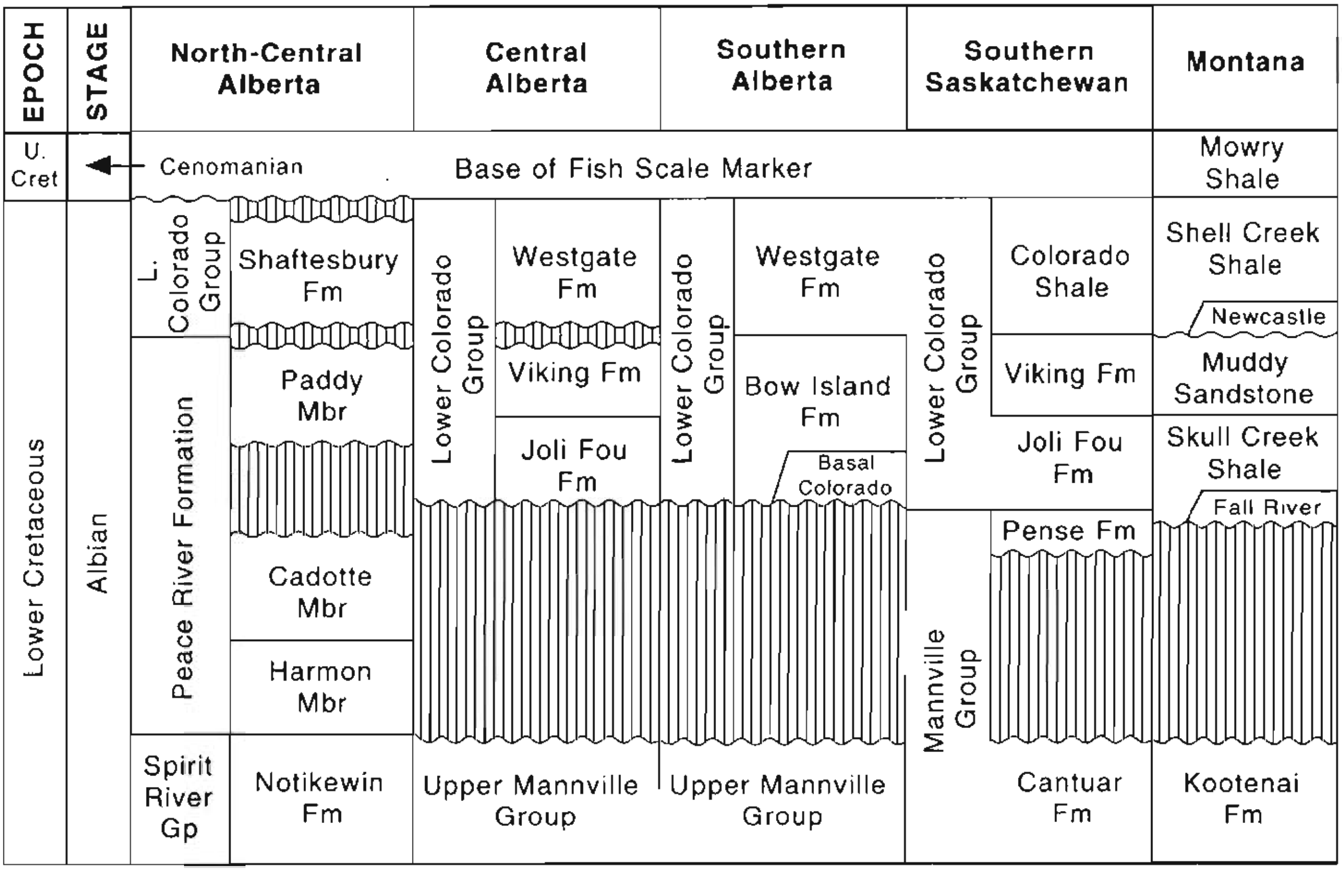

Fig. 3.—Stratigraphic correlation chart for the Viking Formation.

to lower shoreface parasequences informally referred to as the Regional Viking. The succession records progressive development of distal, through archetypal, and into proximal *Cruziana* ichnofacies. The facies are characterized by intense and uniformly distributed burrowing, as well as a diverse assemblage of ichnogenera (Fig. 5), reflecting slow, continuous, fully marine deposition with minimal influence of storm events. These parasequences downlap onto transgressive marine shales of the Joli Fou Formation, and constitute a progradational parasequence set of a highstand systems tract.

This marine parasequence set is erosionally truncated by an amalgamated sequence boundary and flooding surface (BD-1) typically demarcated by the *Glossifungites* ichnofacies. The discontinuity slopes steeply along the southwestern (landward) edge, and flattens out to the northeast, forming an asymmetric, scarp-like geometry. BD-1 is overlain by thoroughly bioturbated, fully marine, gritty sandy mudstone and muddy sandstone of Sequence 2, and is interpreted as an incised, early transgressive shoreface that prograded northward during a pause in the rate of relative sea level rise. Sequence 2 is truncated by the overlying BD-2 discontinuity, and near the southeastern end of Joffre, this succession is preserved as an erosional remnant. Toward the northwestern end, Sequence 2 is largely removed, and BD-2 typically rests directly on the highstand marine parasequences of Sequence 1.

The deposits of Sequence 2 are incised by BD-2, which forms a NW-SE trending trough, locally demarcated by the *Glossifungites* ichnofacies. The deposits overlying BD-2 constitute part of Sequence 3 and contrast markedly with the fully marine deposits of Sequence 1 and Sequence 2. The lower part of Sequence 3 consists of three stacked, coarse-grained parasequences, separated by marginal marine flooding surfaces (Fig. 4). The lower part of Sequence 3 is overlain and locally truncated by a regionally extensive flooding surface, designated as FS. Facies deposited above FS reflect a return to fully marine offshore conditions in the study area.

LOWER SEQUENCE 3

The lower part of Sequence 3, lying between BD-2 and FS, constitutes the Viking Formation reservoir interval in the Joffre Field. The map of lower Sequence 3 (Fig. 2) shows two erosional "zero" edges, related to erosional truncation by the overlying regional flooding surface FS. The map also demarcates the northern limit of lower Sequence 3 conglomeratic facies in the Joffre area, and constitutes the maximum progradational limits of the three parasequences. Northward of these coarser deposits, the succession is dominated by muddy facies, and internal parasequences cannot easily be delineated in core or on geophysical well logs. For this reason, detailed cross-sections are restricted to the southern (landward) margin of the deposit.

Lower Sequence 3 consists of three stacked parasequences (Fig. 4). Each parasequence overlies an erosional surface in the landward direction that passes northward and northeastward into a nonerosional and locally gradational downlap surface. The basal surface is regarded as a progradational/depositional surface of autocyclic origin, based on the facies relations discussed below. Coarse grained facies of Parasequence 1 rest on P1, those of Parasequence 2 rest on P2, and equivalent facies of Parasequence 3 rest on P3. Each parasequence is terminated by a *marginal marine* flooding surface overlain by weakly burrowed mudstone-dominated facies. Parasequence 1 is terminated by F2, Parasequence 2 is capped by F3, and Parasequence 3 is truncated by the regional flooding surface FS that marks the return to fully marine conditions in the study area. F1 constitutes the initial flooding and transgressive modification of the sequence boundary that generated BD-2. F1 can be easily identified in core and on well logs where mudstone directly overlies BD-2. In landward positions, however, the facies above F1 are sandy and difficult to differentiate from the progradational elements lying above P1. In these positions, it is unreliable to differentiate between the sandy transgressive elements and the sandy progradational elements particularly using geophysical well logs. For this reason, the F1 surface is defined by the limit of the mudstone component. The sandstone/conglomerate body of Parasequence 1 is regarded to overlie P1 in its entirety, although the body actually consists of both a thin transgressive component that should lie below P1, and an overlying progradational component lying above P1 (Fig. 4).

Parasequence 1

Basal Discontinuity 2 (BD-2)

BD-2 is an amalgamated sequence boundary and flooding surface with a scarp-like geometry, that truncates the early transgressive shoreface deposits of Sequence 2. The surface shows evidence of erosion in all cored intervals. Although geophysical well log mapping of the surface shows it to be a broad, asymmetrical U-shaped trough. MacEachern et al. (1998) demonstrated that this shape was an artifact of stratigraphic pull-up imparted by the necessity of using an originally seaward-inclined stratigraphic surface as the datum horizon.

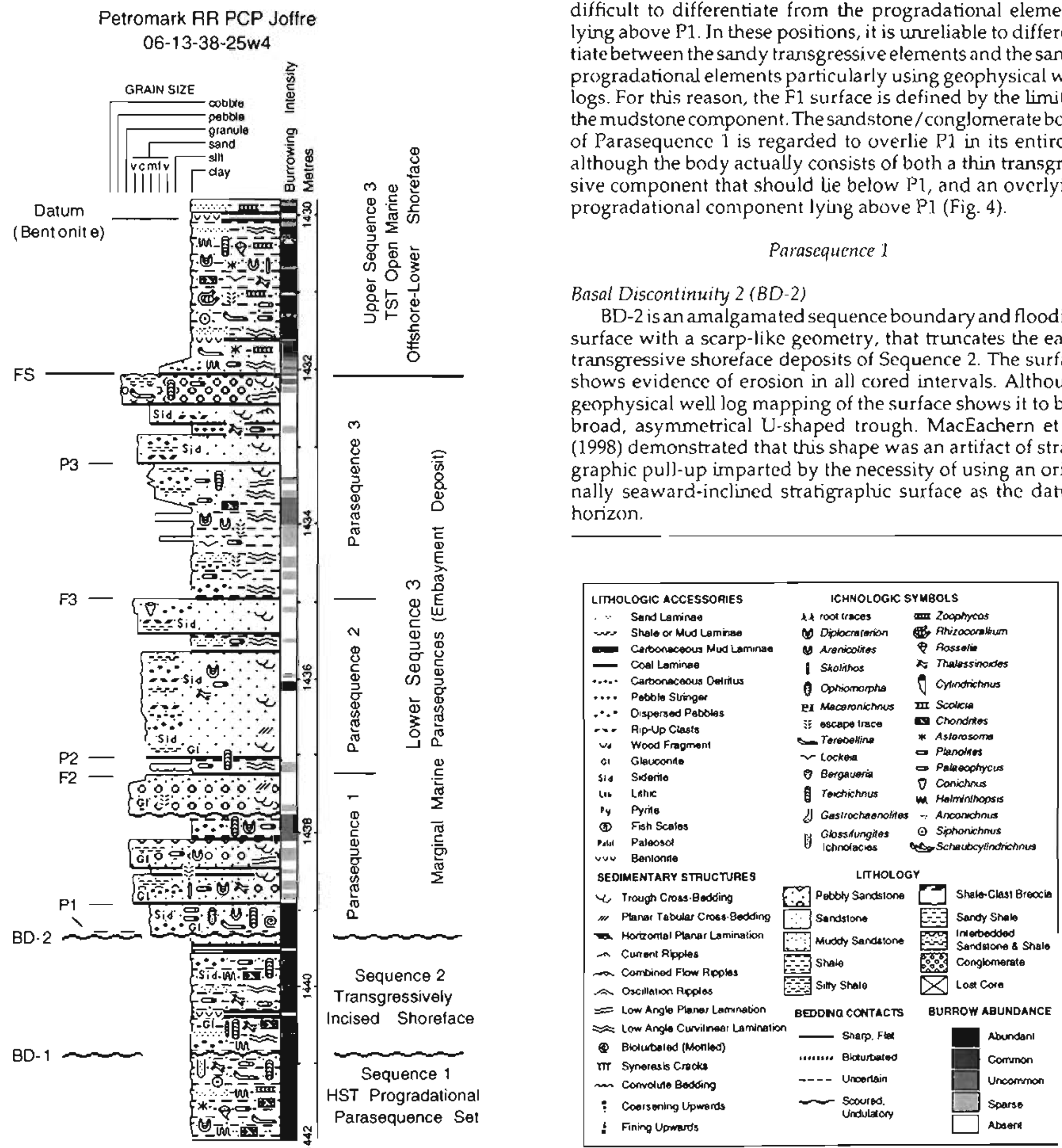

Fig. 4.—Representative core litholog for the Viking Formation of the Joffre area, showing the discontinuities. The dashed line below P1 represents the most practical selection for P1. The gray line represents the actual position of P1. Refer to the text for further discussion.

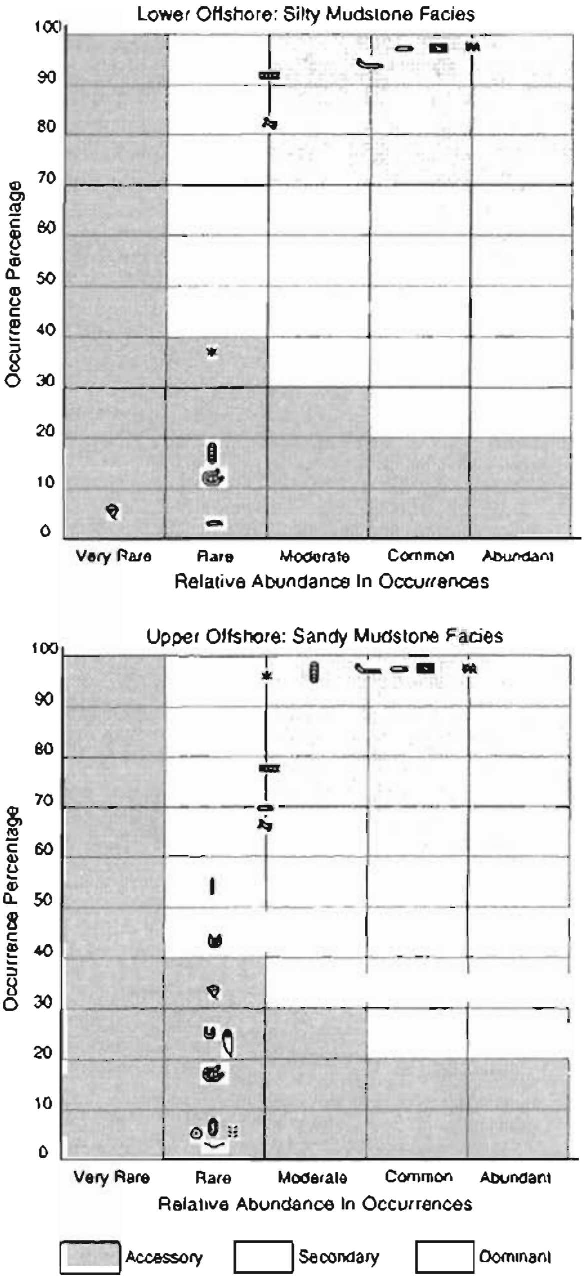

Fig. 5.—Cross-plots, showing ichnogenera occurrence percentage *vs.* abundance percentage for highstand marine offshore deposits of the regional Viking Formation (modified after MacEachern and Pemberton, 1994). Refer to Figure 4 for the legend of trace fossil symbols.

The BD-2 surface is locally mantled by a thin (1-5 cm thick) chert pebble lag and is commonly demarcated by a *Glossifungites* assemblage, dominated by firmground *Diplocraterion*, with local development of firmground *Thalassinoides* and *Skolithos*. The *Glossifungites* ichnofacies is a recurring, substrate-controlled assemblage of trace fossils that reflects the colonization of a firmground. The suite encompasses ichnogenera which are "pseudo-bored" into an underlying, semi-lithified substrate. Ichnogenera of the firmground assemblage are typically unlined, sharp-walled (and locally scratch marked), vertical to subvertical dwelling structures. The structures cross-cut the original resident softground trace fossil community, and are generally passively infilled with sediment overlying the discontinuity (Saunders and Pemberton, 1986; Savrda, 1991; MacEachern et al., 1992; Pemberton et al., 1992; Pemberton and MacEachern, 1995).

Facies Association Overlying Flooding Surface 1 (F1)

The transgressive limit of the fine-grained facies associated with F1 generally lies basinward of all other flooding surfaces (Fig. 6). In reality, however, the sandstone component of this initial transgression (mainly Facies A, described below) probably persists nearly to the base of the escarpment on BD-2 (Fig. 7). Fine-grained deposits associated with F1 mantle BD-2 in only six cored intervals and lie outboard of the Viking reservoir. In each of the six cases, the interval associated with F1 is quite thin, ranging from 0.1-0.6m, and averaging 0.4 m. Most cored intervals lie in the northwestern part of the field.

The facies has been designated Facies E (MacEachern et al., 1998; cf., Fig. 8), and is characterized by interbedded mudstone and sandstone that typically contain dispersed pebbles and granules of chert, glaucony, pyrite and carbonaceous detritus. Sandstone beds range from 1.0-5.0 cm in thickness and comprise between 5% and 15% of the facies. Individual sandstone beds tend to be well sorted, but may range in grain size from lower fine to lower medium. Sandstone beds are sharp based and are oscillation rippled, combined flow rippled, or contain wavy parallel laminations. Mudstone beds range from 1.0-20.0 cm in thickness, are typically silt and sand poor, and contain considerable carbonaceous detritus that imparts a dark color. Mudstone beds are locally siderite cemented or display displacive siderite nodule development.

Facies E is generally weakly burrowed with a sporadically distributed and low diversity trace fossil suite (Fig. 9). It is unlikely, however, that a complete trace fossil assemblage is known from this facies in light of the limited number of intervals and reduced thicknesses encountered. *Helminthopsis* occurs in only two of the six intervals and in very rare numbers. Ichnogenera with an occurrence of approximately 17% reflect only a single interval in which they were encountered. Most intervals only contain between 3 and 4 ichnogenera. Thus, although the assemblage contains a total of 13 ichnogenera, only *Planolites*, *Teichichnus*, *Diplocraterion*, and *Thalassinoides* can be considered as recurring elements of the suite. This constitutes a low diversity, low abundance assemblage, generated by facies-crossing (opportunistic) organisms. Such suites are typical of stressed environments

Facies Association Overlying Progradational/ Depositional Surface 1 (P1)

The facies association overlying progradational/depositional surface 1 (P1) occurs in 49 cored intervals, and consists of 3 main facies. In most landward locations, P1 is regarded to directly overlie BD-2 (Fig. 4). The basal facies corresponds to Facies A of MacEachern et al. (1998), and comprises highly glauconitic, muddy and pebbly burrowed sandstone. These pass upward into trough cross-stratified, variably glauconitic and pebbly sandstones, corresponding to Facies B, C, and D of MacEachern et al. (1998). Locally, Facies B/C/D may be capped by a variably burrowed, interstratified conglomerate, pebbly sandstone and mudstone facies, herein referred to as Facies F. More commonly, however, Facies F occurs basinward (northeastward) of the trough cross-stratified coarse clastics, suggesting that there is a proximal-distal relationship between the two.

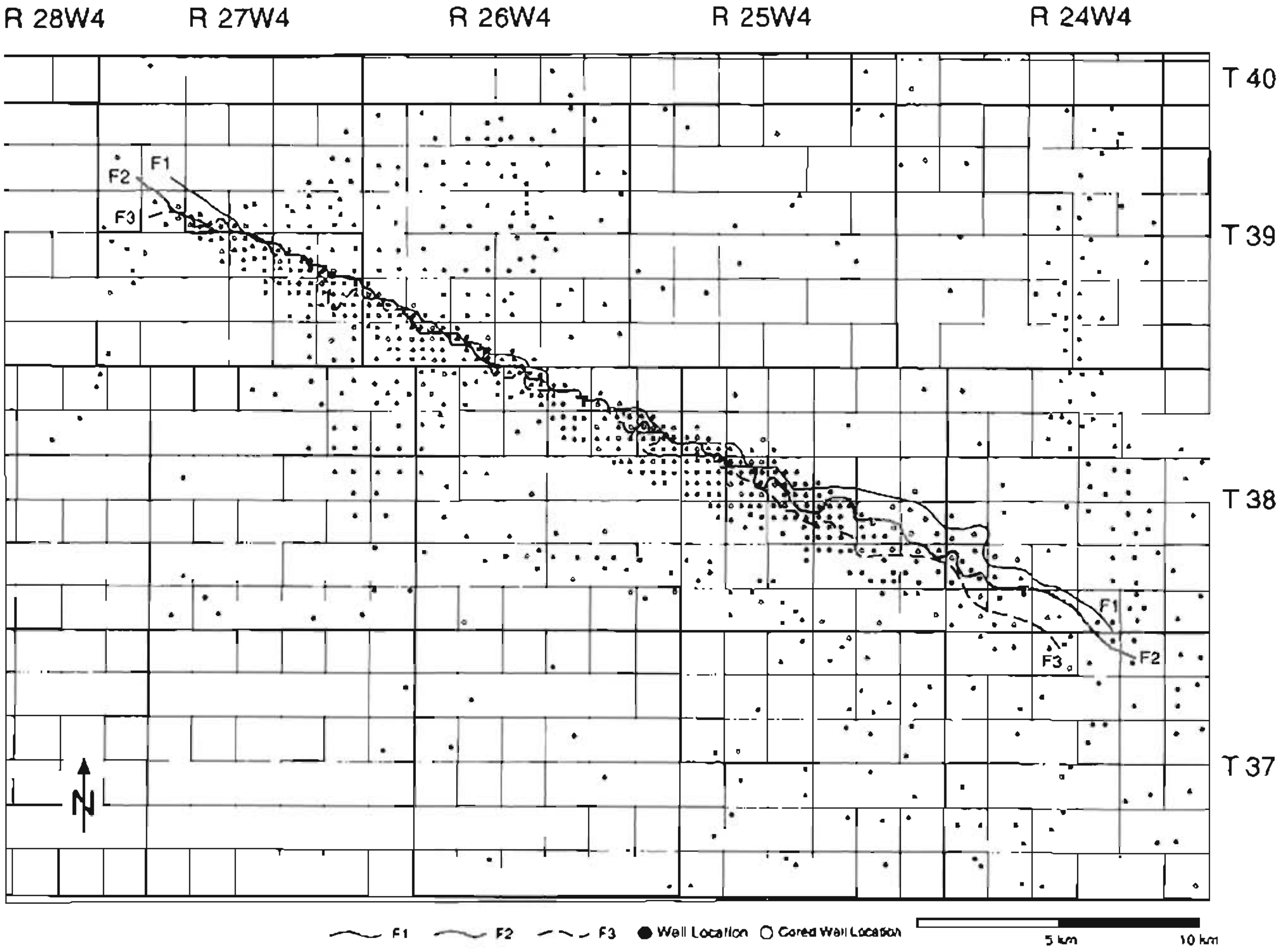

Fig. 6.—Landward transgressive limits of the marginal marine (bay) flooding surfaces F1, F2 and F3

Facies A—In most locations, BD-2 is directly overlain by Facies A, although locally, a thin (0.5-10 cm) pebble lag, commonly glauconitic, mantles the discontinuity. Facies A is particularly well developed toward the southeast end of the field (Township 38, Ranges 24-25W4). These coarse clastics contain abundant, thin and locally siderite-cemented mudstone interbeds, as well as mud laminae and mudstone rip-up clasts (Fig. 10). Sand sizes range from lower medium to lower coarse, and typically contain very coarse sand and chert granule stringers. Basal units may be quite conglomeratic. 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. Low angle (<15°), planar stratification and rarer oscillation

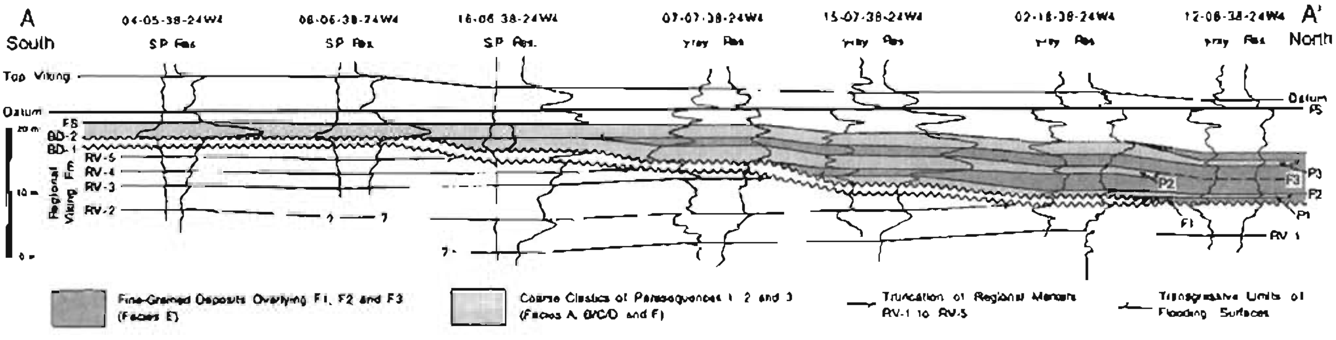

Fig. 7.—Cross-section A-A', showing the depositional onlap of Parasequences 1, 2 and 3 onto basal discontinuity BD-2, as well as their offlap to the northeast. The preserved transgressive limits of F1, F2 and F3 are also indicated. The line of section is displayed in the map of Figure 2.

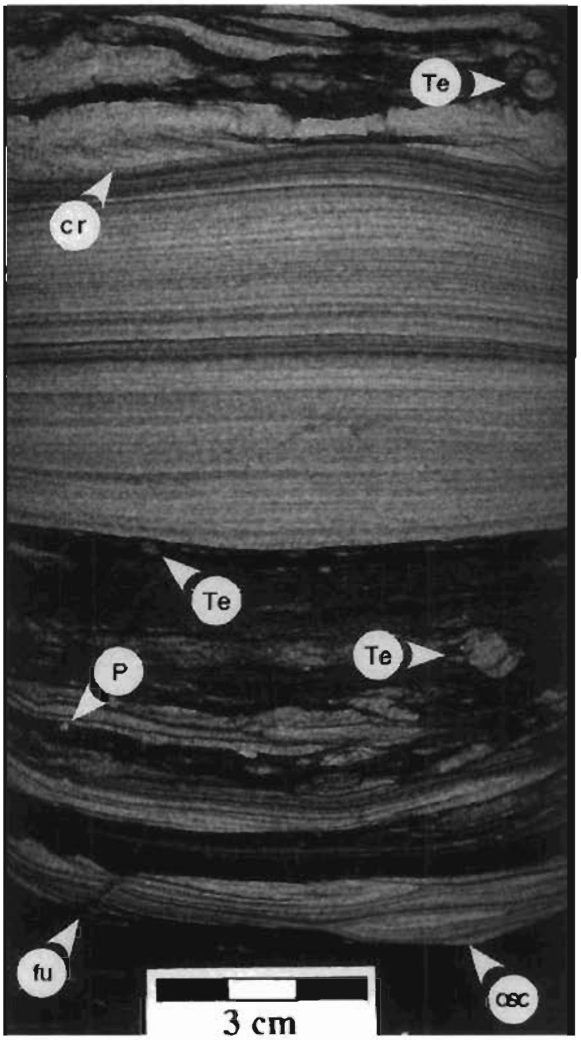

Fig. 8.—Photo of Facies E, consisting of interstratified mudstone and sandstone. Sandstone beds contain low angle wavy parallel lamination, oscillation ripple lamination (osc), and current ripple lamination (cr). Note the *Planolites* (P), *Teichichnus* (Te), and fugichnia (fu). Well 03-24-38-25W4; 1437.7m.

ripple lamination occur in some intercalated sandstone beds.

Facies A displays moderate to low degrees of burrowing, sporadically distributed and diminishing in intensity upward. Sandstone beds contain a trace fossil suite that is dominated by *Diplocraterion*, *Skolithos*, *Conichnus*, *Ophiomorpha*, *Palaeophycus* and *Rosselia*, with variable numbers of escape structures (fugichnia). 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 a somewhat impoverished mixed *Skolithos*-*Cruziana* assemblage. The sandstone contains the *Skolithos* ichnofacies, while the interstratified mudstone possesses a proximal *Cruziana* suite. The bulk of all bioturbation within Parasequence 1 occurs within this facies, such that the trace fossil assemblage cross-plot illustrated in Figure 11 largely reflects the assemblage of Facies A. Although the assemblage appears quite diverse (18 ichnogenera) only 7 genera can be considered "characteristic" of the suite. The remaining forms are encountered in only a few intervals. As well, many of the ichnogenera are likely associated with the more marine units, and correspond to proximal facies related to initial transgression across BD-2, rather than to the progradational portion of the succession. Differentiating between these two genetically discrete sandstones is problematic, due to the "sand-on-sand" contact, the widespread cannibalization or intense reworking of the earlier transgressive sandstone by overlying progradational units, and the poorly recovered and/or mis-ordered character of many of the older cores.

Facies B, C and D—Facies A is typically overlain by moderately well- to well-sorted, unidirectional trough cross-stratified and lesser low-angle, planar stratified sandstone (Facies B), pebbly sandstone (Facies C), and rarer granule-rich conglomerate (Facies D). Contacts vary from gradational (rare) to sharp and erosive. Sand grain sizes range from lower medium to lower coarse, with variable concentrations of very coarse sand, granules, and small pebbles consisting mainly of quartz and chert. Glaucony is mainly restricted to Facies B, particularly near the southeastern portion of the field. Carbonaceous detritus locally marks stratification, and wood fragments, coalified *in situ*, are intercalated. Beds range from 5 cm to 25 cm in thickness, locally amalgamated into bedsets up to 0.3-0.8 m thick. The coarse clastics contain granule and pebble stringers as well as mudstone rip-up clasts and thin mudstone interbeds (Figs. 4 and 12). Mudstone beds are typically 5-15 cm thick, dark in colour and locally siderite cemented.

Burrowing, though 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.

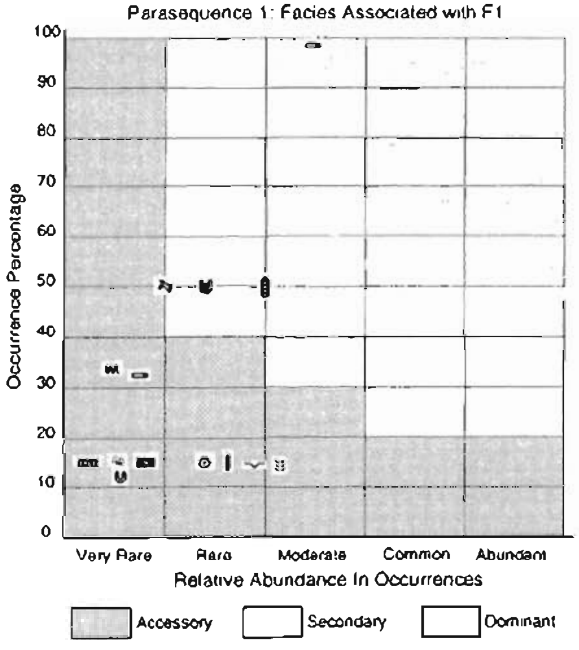

Fig 9.—Cross-plot, showing ichnogenera occurrence percentage *vs.* abundance percentage for interstratified mudstone and sandstone of Facies E overlying F1. Refer to Figure 4 for the legend of trace fossil symbols.

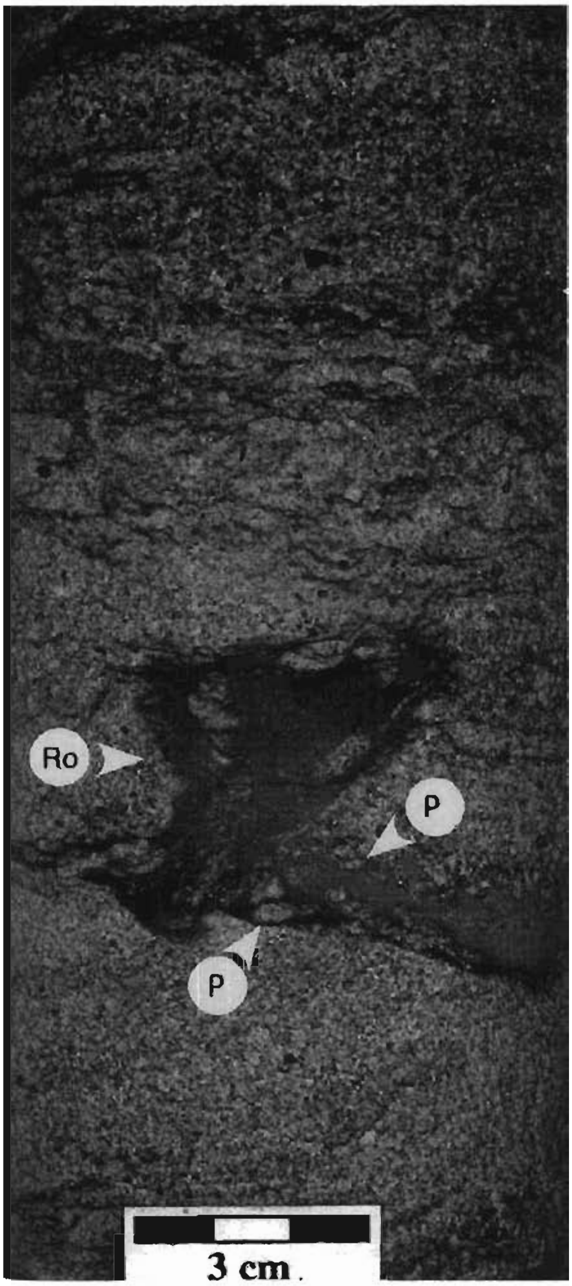

Fig. 10.—Photo of Facies A, consisting of glauconitic pebbly, muddy sandstone. Note the *Planolites* (P) and *Rosselia* (Ro). Well 14-05-38-24W4; 1372.3m.

Nonetheless, mudstone interbeds within conglomeratic units typically display evidence of biogenic reworking, attesting to their marginal marine origin. Ichnogenera are characterized by low numbers of *Diplocraterion*, *Skolithos*, *Palaeophycus*, and *Ophiomorpha* within the coarse-grained beds (cf., Fig. 13), 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*, *Asterosoma*, *Thalassinoides*, and escape traces. Again, although the overall suite contains 10 ichnogenera, individual intervals contain four or fewer ichnogenera.

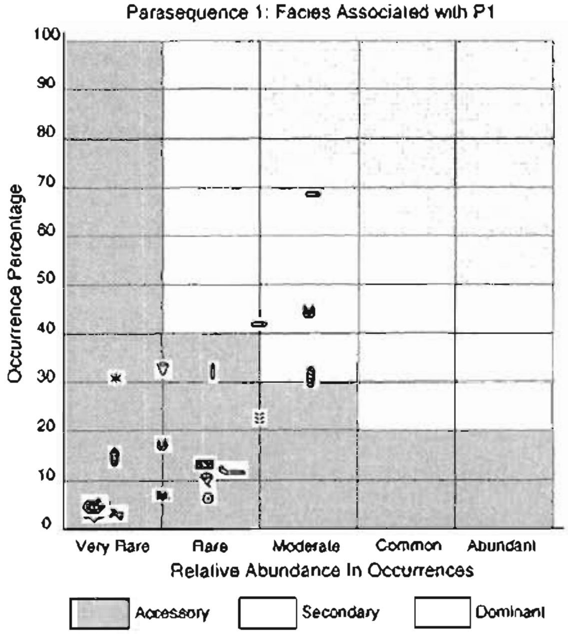

Fig. 11.—Cross-plot, showing ichnogenera occurrence percentage versus abundance percentage for facies overlying P1. Refer to Figure 4 for the legend of trace fossil symbols.

Facies F—Facies F overlies the trough cross-bedded facies in a few locations within Parasequence 1, but typically lies in a basinward position reflecting more distal depositional conditions. The facies consists of regularly interstratified granule conglomerate, sandstone and mudstone (cf., Fig. 14). In distal positions, Facies F grades upward out of the interstratified mudstone and sandstone of Facies E, and forms a depositional platform across which Facies B/C/D prograde. Facies F consists of beds 0.1-0.3 m thick. Glaucony is relatively uncommon, although carbonaceous detritus, mudstone rip-up clasts and thin mudstone interlaminae are locally abundant. Several mudstone beds are siderite cemented.

The sandstone and conglomerate are similar in character to beds in Facies B/C/D, but comprise beds less than 10 cm in thickness. Conglomerates are trough cross-stratified, but sandstone beds contain both current ripple lamination, trough cross-stratification, rare oscillation ripple lamination, combined flow ripple lamination and low angle, undulatory parallel lamination.

Facies F is characterized by rare to moderate bioturbation, and contains a trace fossil assemblage sporadically distributed and manifest by rare numbers of *Planolites*, *Teichichnus*, *Chondrites*, *Terebellina*, *Palaeophycus*, *Asterosoma*, *Diplocraterion*, *Skolithos*, *Arenicolites* and fugichnia. Although the suite encompasses a total of 9 ichnogenera, most intervals contain 4 or less. *Planolites*, *Teichichnus*, *Diplocraterion* and fugichnia comprise the recurring elements of the suite.

Geometry of Parasequence 1

The coarse clastic unit of Parasequence 1 displays a narrow, northwest to southeast trend (Fig. 15). The body preserves a depositional edge lying to the northeast (basinward), where it passes into interstratified mudstone and sandstone of Facies E. In the southwest (landward) direction, however, the surface varies from a depositional to

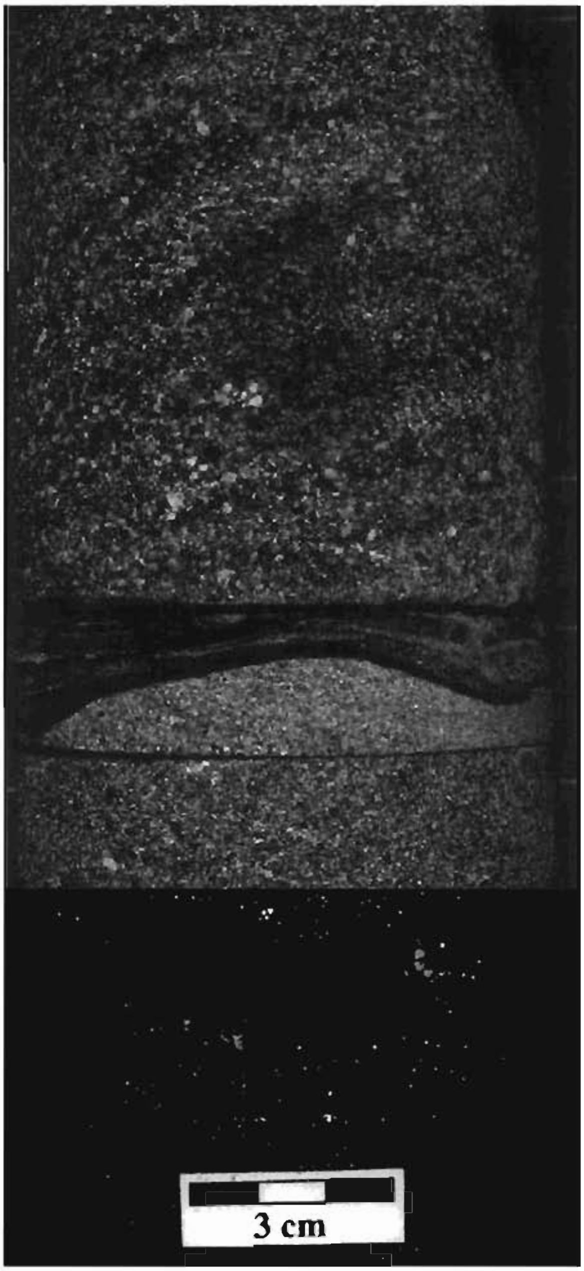

Fig. 12.—Photo of Facies B and C, consisting of trough cross-stratified sandstone and pebbly sandstone with mudstone interbed and mudstone rip-up clast. Well 06-14-38-25W4; 1422.1m.

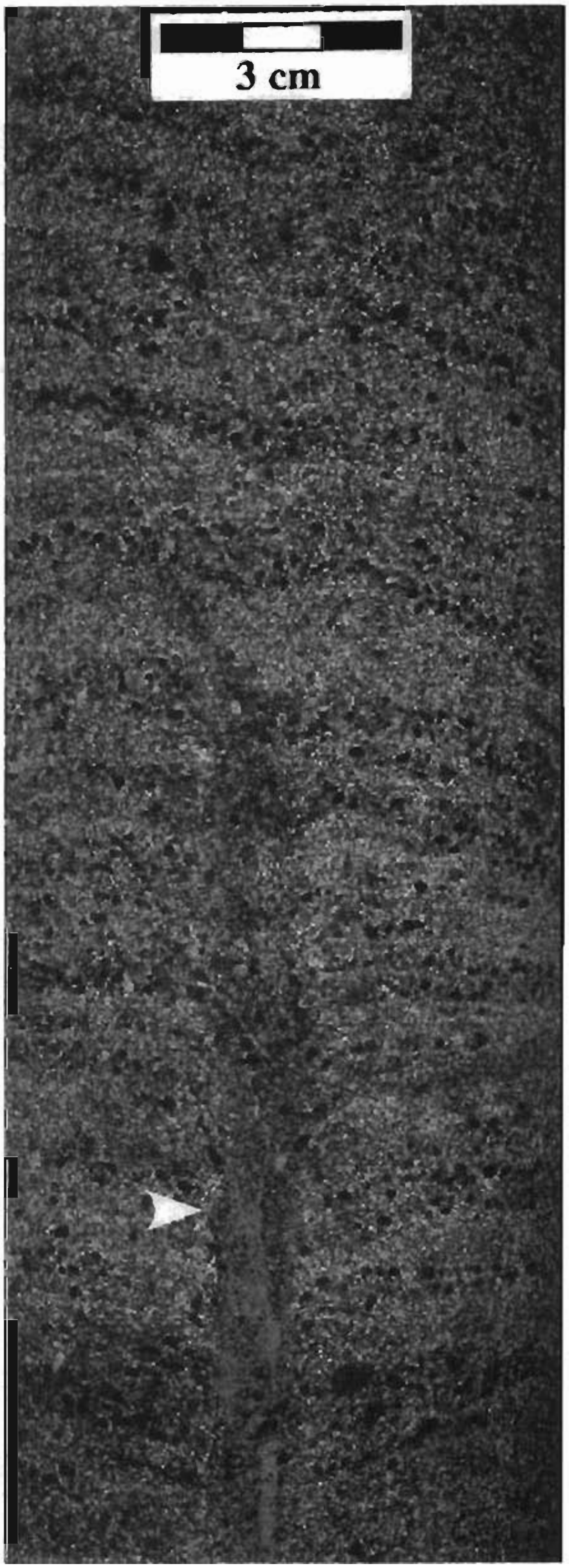

Fig. 13.—Photo of Facies B, consisting of trough cross-stratified sandstone with *Diplocraterion* (arrow). Well 11-07-39-26W4; 1348.1m.

an erosional edge. Preservation of the depositional edge is more common toward the southeastern end of the field, where Parasequence 1 onlaps relief on BD-2 (cross-section A-A'; Fig. 7). Although locally erosional throughout the entire study area, the landward edge is consistently erosional near the northwest end of the field where the parasequence has been truncated by coarse-grained deposits of Parasequence 2 (cross-section B-B', Fig. 16). The coarse-grained deposits of Parasequence 1 are quite thin, ranging from approximately 10 cm to 2.1 m, and likely reflect their preservation as an erosional remnant below Parasequence 2

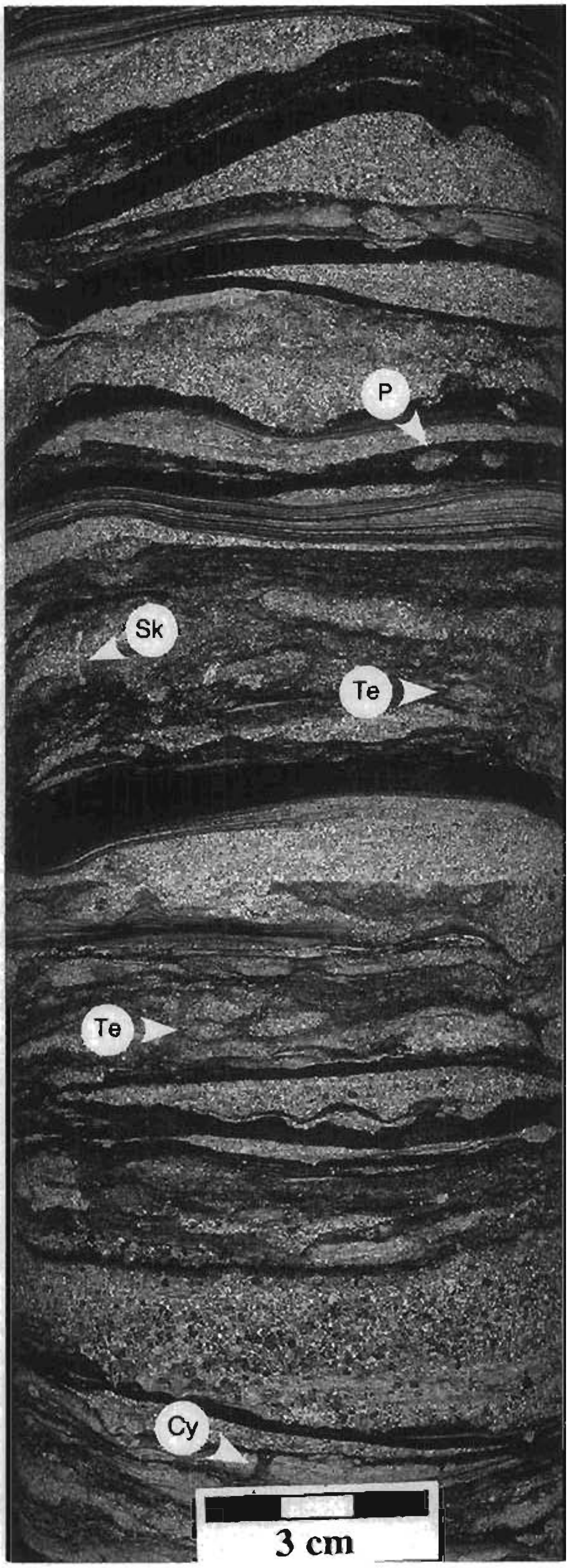

Fig. 14.—Photo of Facies F, consisting of interstratified, oscillation rippled, granule sandstone and mudstone. Note the sporadically distributed *Planolites* (P), *Teichichnus* (Te), *Skolithos* (Sk) and *Cylindrichnus* (Cy). Well 16-06-38-24W4; 1351.2m

Parasequence 2

Facies Overlying Flooding Surface 2 (F2)

The transgressive limit of the fine-grained facies associated with F2 generally lies landward of F1 and closely mimics the position of F3, except in the southeastern part of the Joffre Field (Fig. 6). Fine-grained facies associated with F2 drape Parasequence 1 in 23 cored intervals and correspond to Facies E. In most regards, the facies is identical to that associated with F1.

The facies is characterized by interbedded mudstone and sandstone (Fig. 8), typically with dispersed pebbles and granules of chert, glaucony, carbonaceous detritus and coalified wood fragments. Sandstone beds range from 2-10 cm in thickness and comprise between 5% and 20% of the facies. Individual sandstone beds tend to be well sorted, but may range in grain size from lower fine to lower medium. Sandstone beds are sharp based and display oscillation ripple, combined flow ripple, or wavy parallel lamination. Mudstone beds range from 1-10 cm in thickness, and are typically silt and sand poor. Mudstone beds are locally siderite cemented or display displacive siderite nodule development, and have variable pyrite contents.

Facies E in this interval is generally weakly burrowed with a sporadically distributed and low diversity trace fossil suite (Fig. 17). Although the facies contains a total of 14 ichnogenera, this serves to exaggerate the trace fossil diversity. Of the 23 intervals, only three contain very rare to rare numbers of *Helminthopsis* and *Palaeophycus*, and only single intervals contain *Anconichnus, Asterosoma, Thalassinoides, Terebellina, Arenicolites Diplocraterion, Skolithos, Ophiomorpha* and *Siphonichnus*. The suite is typified by *Planolites*, rarer *Teichichnus* and fugichnia. Only five ichnogenera occur in more than 10% of the intervals. Most intervals contain no more than 2-4 ichnogenera. This assemblage reflects a low diversity, low abundance suite generated by facies-crossing (opportunistic) organisms, typical of stressed depositional environments.

Facies Association Overlying Progradational/ Depositional Surface 2 (P2)

The facies association overlying P2 occurs in 55 cored intervals and is broadly similar to that overlying P1. The succession displays, however, significant variations in proximal, intermediate and distal positions. Burrowing diversity, as a whole, is lower than in the underlying parasequence (Fig. 18).

Facies A—In proximal and intermediate positions, Facies A directly overlies progradational/depositional surface P2. The facies is more common in the southeast portion of the field, in the vicinity of Township 38, Range 24W4 and Township 38, Range 25W4. The facies is broadly similar to those of Parasequence 1 (Fig. 10), but consists of beds 0.1-1.0 m thick, averaging 0.4 m thick. Locally, intervals are entirely cemented with siderite, or contain thin, siderite-cemented mudstone interbeds. Glaucony occurs in approximately 60% of the intervals.

Facies A units display moderate to low degrees of burrowing, consisting of a suite of 15 ichnogenera. The trace fossil suite is dominated by *Planolites, Palaeophycus* and *Diplocraterion*. Rare numbers of intervals contain uncommon *Terebellina, Teichichnus, Arenicolites, Asterosoma, Conichnus, Rosselia, Skolithos* and fugichnia. *Cylindrichnus, Thalassinoides, Ophiomorpha* and *Lockeia* occur in single intervals. Although some intervals contain up to six ichnogenera, most contain only three or four. The overall suite represents the stressed

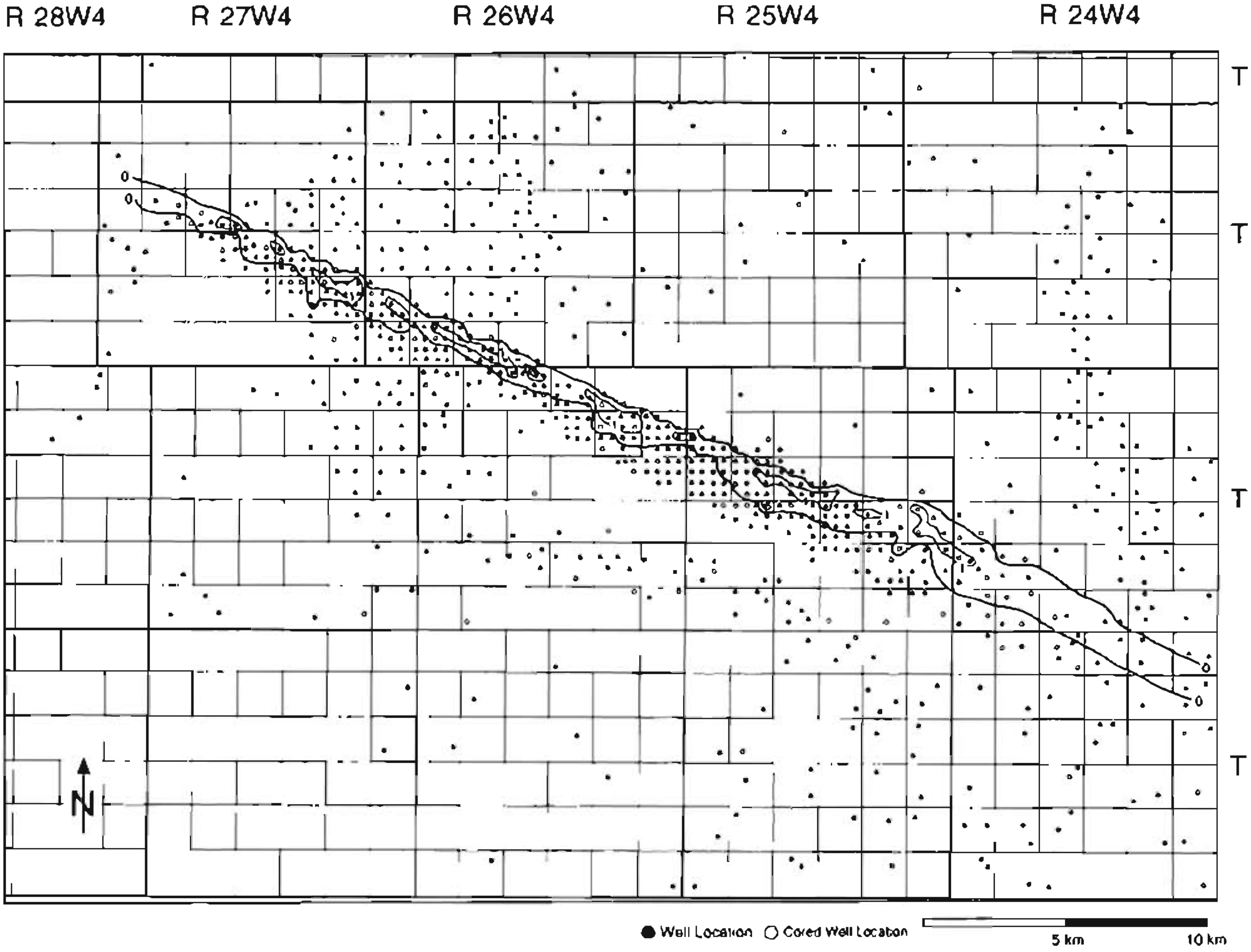

Fig. 15.—Isopach map of the coarse clastics of Parasequence 1. Contour interval is 1 m.

mixed *Skolithos-Cruziana* ichnofacies, characterized by facies crossing structures typical of opportunistic organisms.

Facies B, C and D—These facies are present in proximal, intermediate and distal positions, and comprise the dominant elements of Parasequence 2. The facies tend to be thinner in proximal positions, thickening in intermediate positions and thinning distally. In proximal positions, the facies range from 0.4-0.8 m, averaging 0.5 m. Intermediate intervals typically display intervals 0.6-1.8 m, averaging 0.7 m, while distal intervals are 0.2-0.5 m, averaging 0.3 m. Intervals are locally cut into Facies A units, or incised into mudstone of Facies E. In intermediate positions, the facies may be interstratified with Facies F. Facies B and C are generally more common in the southeast portion of the field, whereas Facies C and D dominate the northwestern end of the field.

In proximal positions, the facies are generally pebbly, with intercalated shale interbeds (locally siderite cemented), coalified wood fragments, rare glaucony, and minor carbonaceous detritus. Trough cross-beds tend to be small scale, with intercalated current ripple lamination. Bioturbation is rare to moderate in intensity but highly sporadic in distribution. A few intervals are completely unburrowed. The trace fossil assemblage is characterized by small numbers of *Diplocraterion, Skolithos, Conichnus, Palaeophycus, Ophiomorpha, Teichichnus*, and fugichnia. The bulk of the burrowing occurs in the southeastern portion of the field area, associated with Facies B. Most intervals contain only four ichnogenera.

In intermediate positions, the facies are characterized by larger scale trough cross-stratification, and contain dispersed granules and pebbles, pebble and granule stringers, and numerous mudstone rip-up clasts (Fig. 12). Burrowing intensity is low, sporadically distributed, and progressively weaker in a northwest direction. Trace fossils are more common in Facies B (Fig. 13) and become less abundant in Facies C and D, respectively. The suite consists of *Diplocraterion* (m-r), *Skolithos* (m-r), fugichnia (m-r), *Palaeophycus* (r), *Arenicolites* (r-vr), *Rosselia* (r), *Thalassinoides* (r), *Planolites* (r), *Teichichnus* (r), *Chondrites* (vr), *Terebellina* (vr), *Conichnus* (vr), *Ophiomorpha* (vr), *Lockeia* (vr), *Asterosoma* (vr). Eleven intervals, most lying northwest of Township 38, Range 25W4, do not contain trace fossils. Intervals rarely display more than four ichnogenera.

In distal positions, Facies B/C/D are relatively uncommon, occurring in only seven intervals. Like intermediate positions, they contain glaucony, sideritized mudstone interbeds and rip-up clasts, carbonaceous detritus, and chert granules or pebbles. Trace fossils are generally uncommon, with three of the intervals unburrowed. Trace fossils include *Diplocraterion* (r), *Planolites* (r), *Asterosoma*

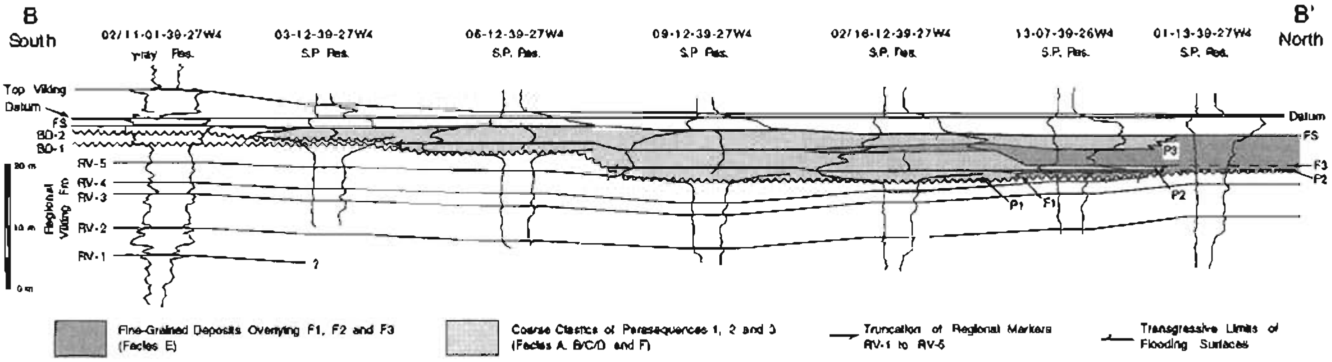

Fig. 16.—Cross-section B-B', showing the depositional onlap of Parasequences 1, 2 and 3 onto basal discontinuity BD-2, as well as their offlap to the northeast. The preserved transgressive limits of F1, F2 and F3 are also indicated. Note the greater degree of erosional amalgamation in this northwestern portion of the study area compared with the southeastern area shown in Figure 7. The line of section is located on the map of Figure 2.

(vr), *Skolithos* (vr), *Rhizocorallium* (vr), *Terebellina* (vr), and *Arenicolites* (vr). Intervals typically contain only two ichnogenera.

Facies F—Facies F (Fig. 14) occurs in only intermediate and distal positions. Units contain carbonaceous detritus, sideritized mudstone interbeds, glaucony, dispersed chert pebbles and granules, and coalified wood fragments. Mudstone rip-up clasts are exceedingly rare. Sandstone beds range from 0.2-1.3 m in thickness, averaging 0.5 m with intervening mudstone beds 0.5-5 cm thick. The facies group is rarely present northwest of Township 38, Range 25W4. Intervals consist of 30-40% sandstone beds with rare granule-rich beds, dominated by wavy parallel lamination and oscillation ripple lamination, with rarer combined flow ripple lamination and very rare current ripple lamination. Burrowing is typically rare to moderate in intensity and more uniformly distributed. The trace fossil assemblage is characterized by *Planolites* (a), *Teichichnus* (c), *Diplocraterion* (r), *Palaeophycus* (r), *Thalassinoides* (vr), *Chondrites* (vr), *Lockeia* (vr), *Skolithos* (vr), *Rosselia* (vr), *Arenicolites* (vr), fugichnia (vr), *Helminthopsis* (vr), *Conichnus* (vr), *Terebellina* (vr), *Siphonichnus* (vr), *Zoophycos* (vr) and *Anconichnus* (vr). Most intervals contain only 3-6 ichnogenera, although a single thick interval contained nine ichnogenera. *Zoophycos*,

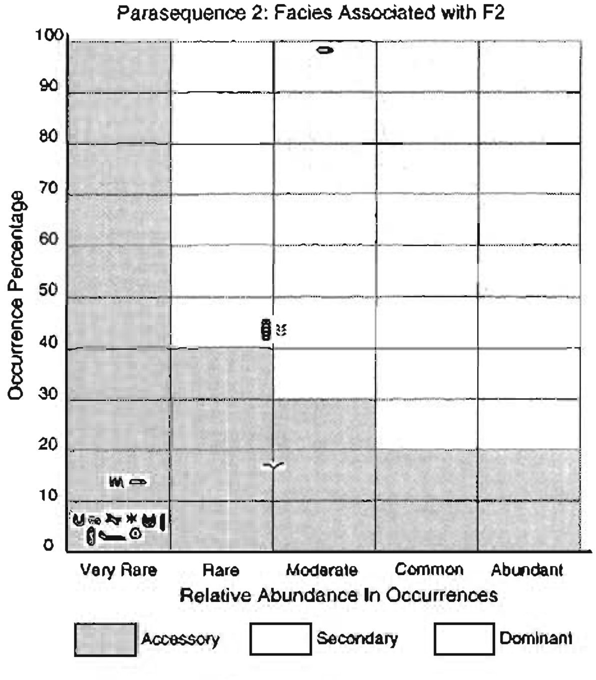

Fig. 17.—Cross-plot, showing ichnogenera occurrence percentage versus abundance percentage for interstratified mudstone and sandstone of Facies E overlying F2. Refer to Figure 4 for the legend of trace fossil symbols.

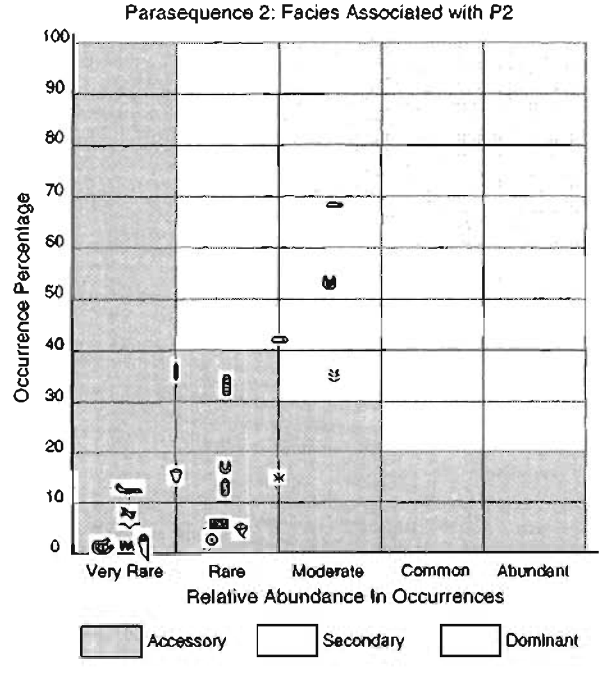

Fig. 18.—Cross-plot, showing ichnogenera occurrence percentage versus abundance percentage for facies overlying P2. Refer to Figure 4 for the legend of trace fossil symbols.

Helminthopsis, Anconichnus, Rosselia and *Conichnus* occur in only single intervals out of 24. The facies is more common toward the northwest end of the field, particularly in the vicinity of Township 39, Range 26W4.

Geometry of Parasequence 2

The coarse clastic unit of Parasequence 2 displays a northwest to southeast trend (Fig. 19), although not nearly so narrow a one as Parasequence 1. The interval broadens markedly toward the southeastern end of the field. Like Parasequence 1, the body preserves a depositional edge lying to the northeast (basinward), where it passes into the finer-grained deposits of Facies F. In contrast to the underlying parasequence, however, Parasequence 2 does not extend as far basinward, except in the southeastern part of the field. In the southwest (landward) direction, the zero edge is consistently erosional, associated with truncation by Parasequence 3. Parasequence 2 extends landward (southwest) of Parasequence 1, also onlapping the relief on BD-2 (Figs. 7 and 16). The coarse-grained deposits of Parasequence 2 vary markedly in thickness along the entire trend, ranging from approximately 20 cm to 3.9 m. These variable thicknesses are the result of differential erosion associated with the accumulation of Parasequence 3, which likely cannibalized much of its coarse clastic material from Parasequence 2. Hence, like the underlying parasequence, Parasequence 2 is also preserved largely as an erosional remnant.

Parasequence 3

Facies Overlying Flooding Surface 3 (F3)

The transgressive landward limit of the fine-grained facies associated with flooding surface F3 generally lies slightly seaward of those of F1 and F2, except in the southeastern part of the Joffre field, where it shifts markedly landward (Fig. 6). The facies associated with F3 overlie Parasequence 2 in 40 cored intervals and correspond to Facies E or more rarely, Facies F.

The interval is characterized by interbedded mudstone and sandstone (Figs. 4 and 8), typically with dispersed pebbles and granules of chert, glaucony, carbonaceous detritus and coalified wood fragments. Sandstone beds, ranging from 2-10 cm in thickness, comprise between 10% and 60% of the facies, although most units contain 10-30% sandstone. In landward positions, sandstone contents reach 30-60% and the facies corresponds to Facies F. Individual sandstone beds tend to be well sorted, and range in grain size from lower fine to lower medium. Sandstone beds are

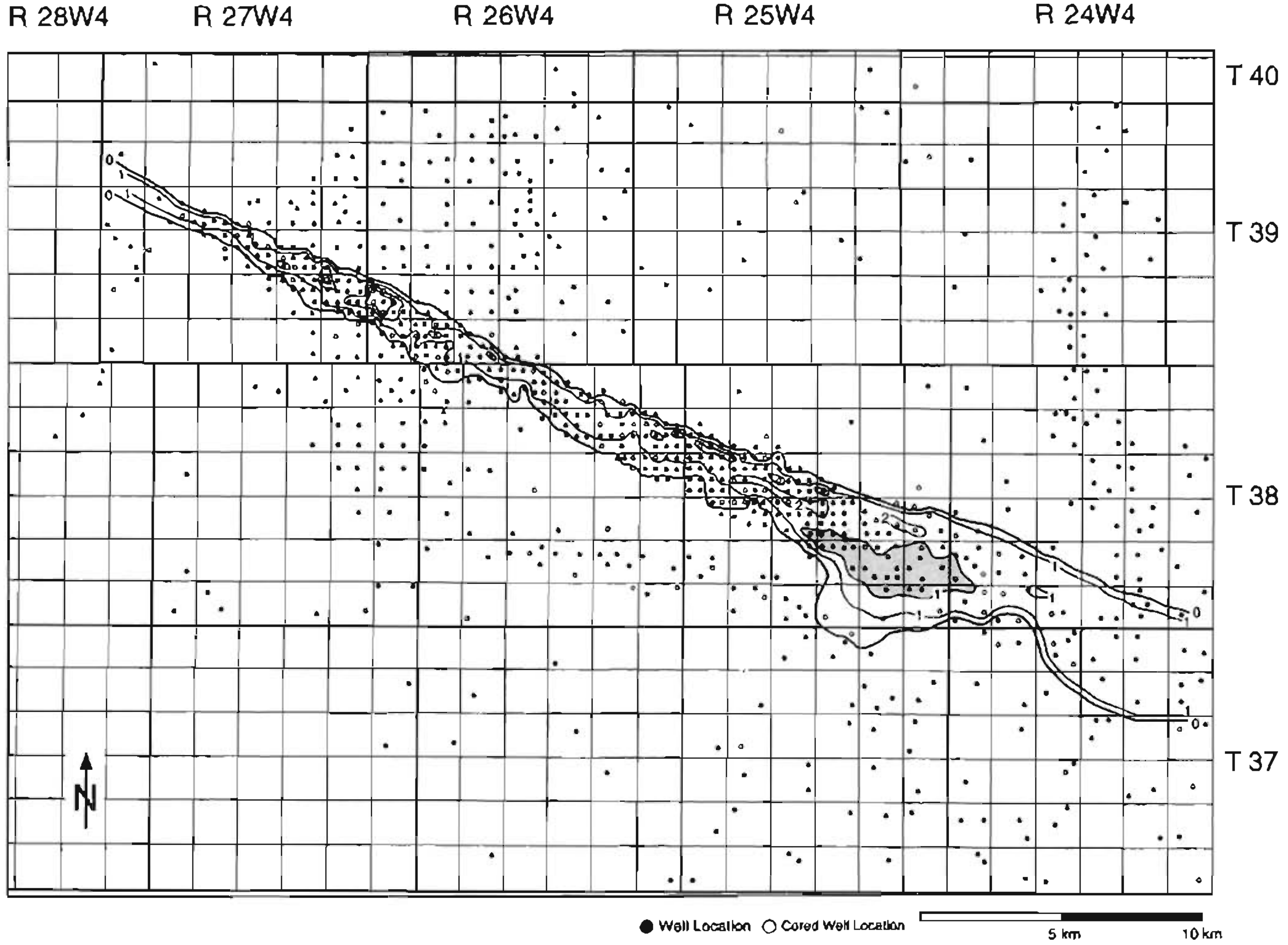

Fig. 19.—Isopach map of the coarse clastics of Parasequence 2. Contour interval is 1 m.

sharp based and show oscillation ripples, combined flow ripples, current ripples, and wavy parallel laminations. Convolute lamination, probably of dewatering derivation, occurs in two intervals. Mudstone beds range from 1-10 cm in thickness, are typically silt and sand poor, and locally are siderite cemented or display displacive siderite nodule development.

Burrowing intensity within these facies ranges from rare to common, though it is sporadically distributed. Trace fossil diversity (Fig. 20) is considerably greater than in similar facies associated with F1 and F2. The facies contains a total of 19 ichnogenera, but like that of facies associated with F2, this exaggerates the diversity of the suite. *Rosselia, Bergaueria, Rhizocorallium, Zoophycos*, and *Conichnus* occur in only single intervals, and only seven ichnogenera occur in 30% or more of the intervals. *Teichichnus, Planolites* and fugichnia constitute the only trace fossils that are ubiquitous.

On the other hand, most intervals display between two and 10 ichnogenera, though typically from four to seven. This, as well as the presence of *Helminthopsis, Chondrites* and *Diplocraterion* in more than 30% of the intervals suggests that these facies accumulated under a greater marine influence than those related to the underlying parasequences. The widespread presence of fugichnia within the succession attests to the episodic nature of sandstone deposition within the setting.

Facies Association Overlying Progradational/ Depositional Surface 3 (P3)

The facies association overlying P3 has the widest preserved distribution of lower Sequence 3, and occurs in 85 cored intervals. The succession overlying P3 also displays a higher degree of burrowing intensity and occurrence than those of the underlying parasequences (Fig. 21). The facies succession is broadly similar to that overlying P2, particularly in that the interval displays significant variations from proximal to distal positions. Unlike the facies associations overlying P1 and P2, this association typically lacks Facies A. The interval is wholly dominated by Facies B/C/D in proximal and intermediate positions, locally interfingering with and passing distally into Facies F toward the northeast. In proximal positions, the succession is characterized by Facies B/C/D locally intercalated with sand-dominated Facies F. In intermediate positions, the succession is characterized by relatively thick bedsets of Facies B/C/D with only very rare intervals of Facies F. In distal positions, the association is typified by sand-rich to sand-poor Facies F with minor intercalations of Facies B/C/D, reflecting the feather edges of coarse-grained deposition.

Facies B, C and D—Facies B/C/D units within Parasequence 3 are virtually identical to that of the underlying parasequences. The facies are encountered in 15 cored intervals within proximal positions. In these settings, the beds are thin, ranging from 0.2-1.7 m and averaging 0.5 m, and are interstratified with Facies F units of similar thickness. Within intermediate positions, these facies are encountered in 21 intervals and comprise bedsets 0.2-3.6 m in thickness, averaging 1.0 m. Facies F intervals are also intercalated, but considerably thinner than the trough cross-stratified facies. Trough cross-beds are of much larger scale than in proximal intervals. In addition, the bedsets are thinner toward the southeast end of the field, and thicken toward the northwest (averaging 1.5 m). The facies occurs in only a single core from a distal position, and is 0.3 m thick.

Bioturbation is generally of rare intensity, highly variable in distribution, and includes 13 ichnogenera. A significant number of intervals (5 of 15 intervals in proximal positions,

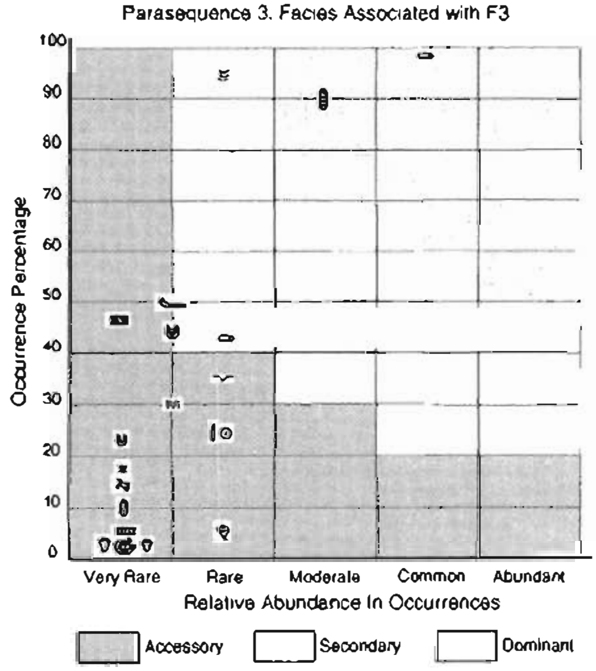

Fig. 20.—Cross-plot, showing ichnogenera occurrence percentage versus abundance percentage for interstratified mudstone and sandstone of Facies E overlying F3. Refer to Figure 4 for the legend of trace fossil symbols.

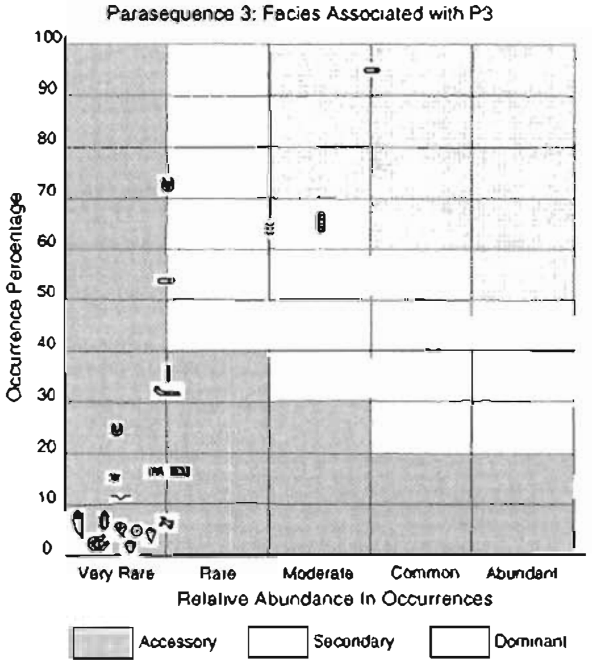

Fig. 21.—Cross-plot, showing ichnogenera occurrence percentage versus abundance percentage for facies overlying P3. Refer to Figure 4 for the legend of trace fossil symbols.

and 15 of 21 in intermediate positions) are entirely unburrowed. The trace fossil assemblage is characterized by *Diplocraterion* (m-c), *Planolites* (m-c), *Skolithos* (m), *Conichnus* (vr), *Palaeophycus* (vr-r), *Ophiomorpha* (vr), *Teichichnus* (vr), *Terebellina* (vr), *Arenicolites* (vr), *Rosselia* (vr), *Bergaueria* (vr), *Asterosoma* (vr), *Lockeia* (vr) and fugichnia (m-r). Proximal intervals typically contain 2-4 ichnogenera, and intermediate intervals contain 2-6 ichnogenera, though typically only three. Diversity of ichnogenera is actually quite low. In particular, most of the "very rare" trace fossils occur in only one or two intervals, greatly reducing the actual diversity of the assemblage. *Diplocraterion*, *Skolithos*, and *Planolites* can be considered the only recurring elements of the suite.

Facies F—Facies F occurs in proximal, intermediate and distal positions within Parasequence 3. The facies is virtually identical to equivalent facies in the underlying parasequences. In proximal positions, the facies was encountered in 17 intervals, ranging from 0.1-1.6 m in thickness, averaging 0.5 m. A total of 19 cored intervals contain Facies F in intermediate positions, ranging from 0.1-1.2 m, averaging 0.5 m. In distal positions, Facies F was encountered in 14 cores, and ranges from 0.2-2.1 m, averaging 0.9 m in thickness. Coarse-grained beds constitute between 10-60% of the units, though generally comprising 30-40% in most cases.

Burrowing intensity is typically rare to moderate in intensity, and becomes more pronounced in a basinward direction. Trace fossils are sporadically distributed throughout the intervals. The trace fossil assemblage in proximal, intermediate and distal settings is characterized by *Planolites* (m-a), *Teichichnus* (m-c), *Diplocraterion* (m-c; r in distal settings), *Palaeophycus* (m-c; r in distal settings), *Terebellina* (r-m), *Arenicolites* (vr-r), *Helminthopsis* (vr-r), *Chondrites* (vr-r), *Lockeia* (vr-r), *Skolithos* (vr-r), *Asterosoma* (vr), *Thalassinoides* (vr) and fugichnia (m-r). In intermediate and distal positions, the suite also includes *Siphonichnus* (vr), *Zoophycos* (vr), *Rhizocorallium* (vr), *Rosselia* (vr), *Ophiomorpha* (vr) and *Cylindrichnus* (vr). Most intervals in proximal positions contain between 3-9 ichnogenera, and typically 4-6. Intermediate intervals display 4-8 ichnogenera, though commonly six, while distal intervals range from 5-13 ichnogenera, and typically contain seven. The assemblage represents the most marine suite of all the successions within the lower portion of Sequence 3 (Fig. 4). Compared with the underlying highstand marine parasequences of the regional Viking Formation (Fig. 5), as well as the transgressive marine offshore deposits of Sequence 2 and the upper part of Sequence 3 (Fig. 22), however, the suite is impoverished and reflects environmental stress. Although containing an overall diversity of 17 ichnogenera, only *Planolites*, *Teichichnus*, *Diplocraterion*, *Palaeophycus*, *Terebellina*, and fugichnia can be considered recurring elements of the assemblage.

Geometry of Parasequence 3

The coarse clastic unit of Parasequence 3 displays a broad irregular apron in the study area (Fig. 23), although its depositional thicks lie along a northwest to southeast trend similar to the underlying parasequences. Likewise, the coarse clastic unit displays a depositional edge to the northeast (basinward), where it passes into Facies E interbedded mudstone and sandstone. Parasequence 3 extends further basinward than Parasequence 2, to approximately the limit of Parasequence 1. In the southwest (landward) direction, the zero edge is consistently erosional, associated with truncation by the overlying discontinuity FS, the regionally extensive wave ravinement surface that demarcates the return of open marine conditions to the study area. Parasequence 3 extends landward (southwest) of both underlying parasequences, and onlaps the remaining relief on BD-2 (Figs. 7 and 16). The coarse-grained deposits of Parasequence 3 are quite variable in thickness, ranging from approximately 10 cm to 4.1 m. The variable thicknesses are partly a function of: 1) differential erosion into Parasequence 2; 2) drape into lows developed on Parasequence 2; 3) variable erosional relief on BD-2; and 4) the magnitude of

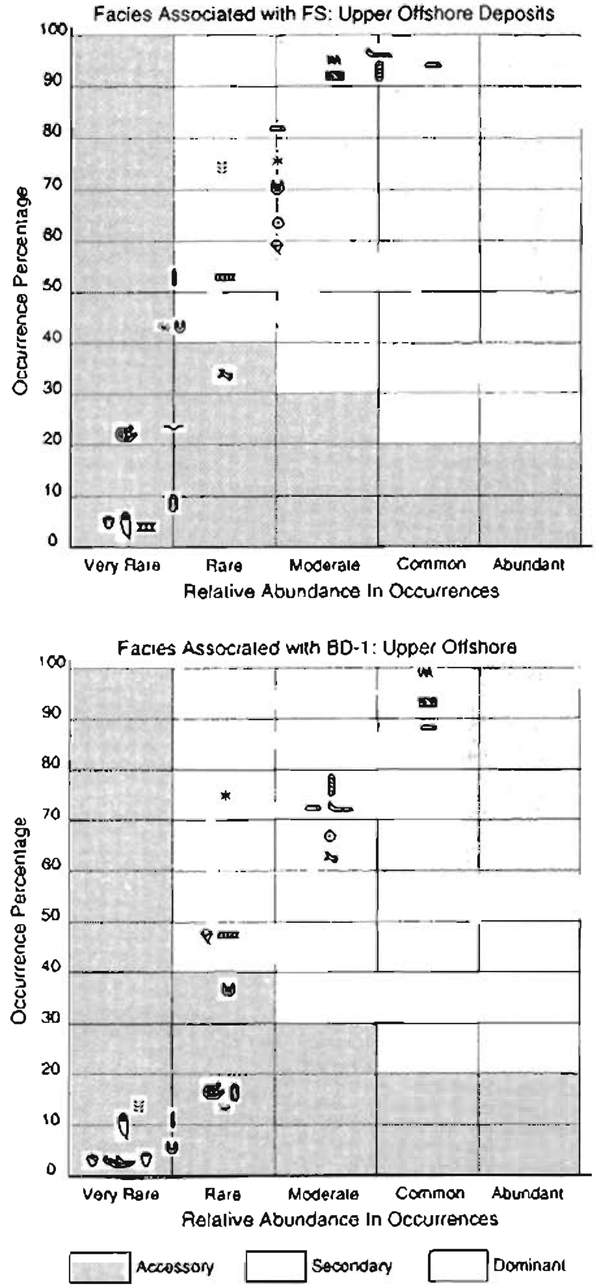

Fig. 22.—Cross-plots, showing ichnogenera occurrence percentage versus abundance percentage for transgressive offshore mudstone facies overlying BD-1 and FS. Refer to Figure 4 for the legend of trace fossil symbols.

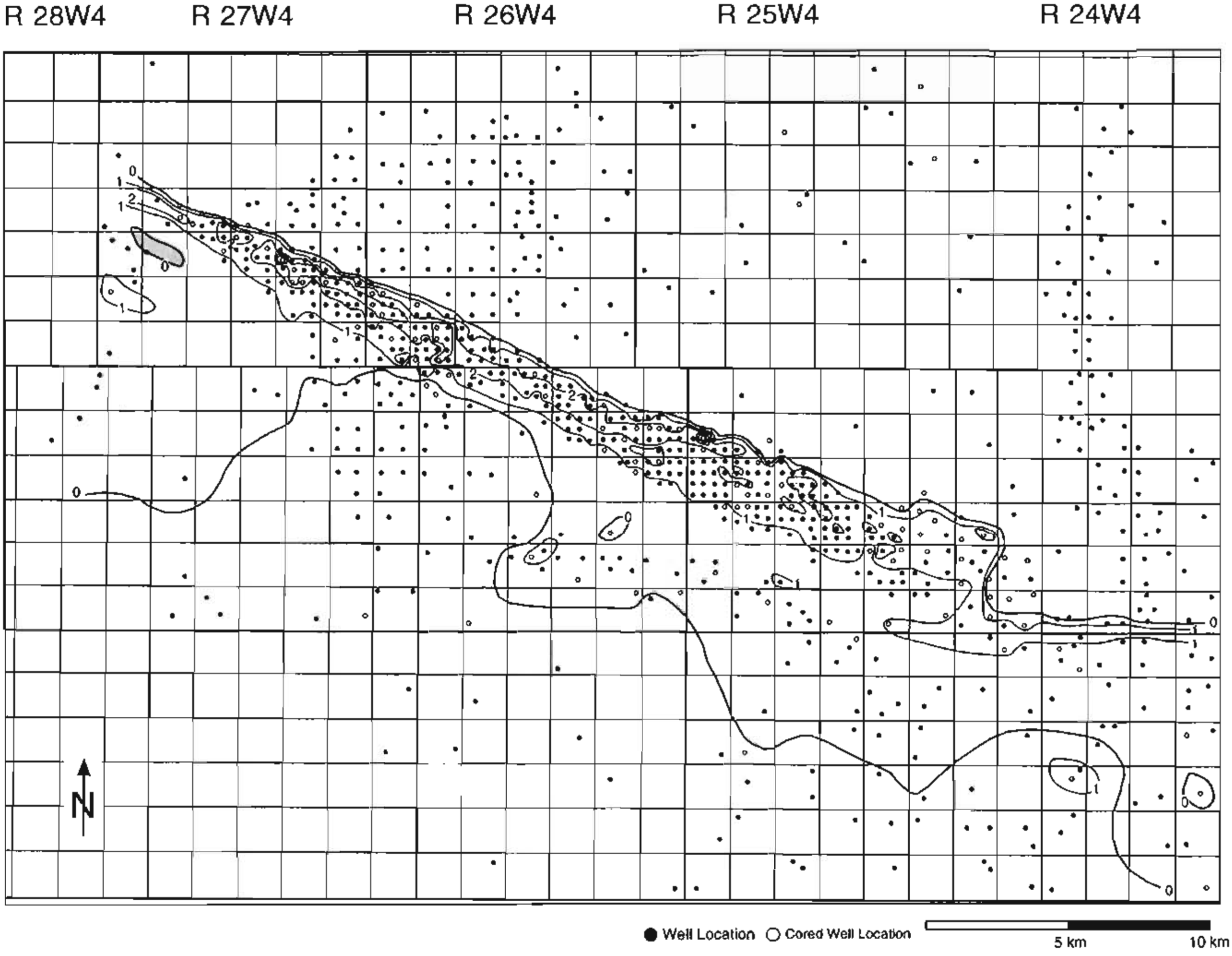

Fig. 23.—Isopach map of the coarse clastics of Parasequence 3. Contour interval is 1 m.

truncation by the overlying wave ravinement surfaces. Like the underlying parasequences, Parasequence 3 is preserved as an erosional remnant.

INTERPRETATION OF LOWER SEQUENCE 3

The interpretation of the facies within Sequence 3 has been addressed by MacEachern et al. (1998). They attributed the entire facies succession to deposition within a marginal marine bay-head delta/embayment complex, and provided compelling arguments dismissing both shoreface and incised valley interpretations as viable alternative depositional settings.

The basal discontinuity (BD-2) reflects a sequence boundary that was erosionally modified by, and amalgamated with, a wave-cut, bay ravinement surface. The glauconitic sandstone of Facies A is interpreted as a transgressive marine sand sheet, possibly consisting of original lowstand deposits reworked during transgressive modification of the sequence boundary during relative sea level rise that formed BD-2. Facies A contains the most diverse ichnological suite of the succession, presumably reflecting an initial period of largely marine conditions during ravinement.

The coarse clastics of Facies B/C/D are interpreted to reflect migrating dunes within channels. The restricted trace fossil suite demonstrates that channel deposition occurred in marginal marine conditions. The multiple scours, fining upward character, and uniform orientation of the trough cross-stratification, coupled with the presence of intercalated mudstone laminae, mudstone interbeds, and non-resistant mudstone rip-up clasts, are consistent with deposition in response to channelized flow. The mudstone interbeds and laminae attest to repeated fluctuations in flow strength. These deposits are interpreted to reflect marine-influenced distributary channels of bay-head delta systems, associated with the intertidal portions of the embayment. The distribution of Facies B, C, and D, which fringes the southwest edge of the embayment along the entire strike of the deposit, implies multiple point sources for clastic input. Shore-normal feeder systems do not appear to have been preserved in the area, and were likely removed during later wave ravinement associated with the flooding surface FS at the top of Parasequence 3 (Fig. 4).

Facies E is interpreted to reflect marginal marine, sandy (proximal) and muddy (distal) bay deposits, affected by wave processes, subordinate storm events and rare current processes. Upward increase in sandstone content within individual parasequences reflects shallowing of the bay during fill, and locally, may indicate close proximity to a bay-head delta, particularly where it grades upward or landward into Facies F intervals. The trace fossil assemblage is consistent with a salinity-stressed setting (Pemberton et al., 1992; MacEachern and Pemberton, 1994), characterized by pronounced fluctuations in salinity. The ichnological suite is intermediate in diversity and abundance between the more brackish-water, central basin deposits of the Viking Formation estuarine incised valley complexes (MacEachern and Pemberton, 1994), and the unstressed, fully marine highstand parasequences of the Regional Viking, the transgressively incised offshore/shoreface deposits of Sequence 2, and the overlying transgressive offshore deposits of upper Sequence 3. The palynological and foraminiferal paleoecology of these deposits strongly support this interpretation of an intermediate salinity condition (MacEachern et al., this volume).

The interstratified conglomerate, pebbly sandstone, sandstone, and mudstone of Facies F are interpreted to reflect progradation of the bay-head delta front into the embayment, and display primary structures that reflect a combination of oscillatory, storm event, combined flow and current depositional processes. In particular, the storm-induced stratification consists of thin (<15 cm thick) low angle, undulatory parallel lamination, reflecting either a distal depositional position, or a highly sheltered one. Given the interbedding of conglomeratic sandstone beds, presence of dispersed pebbles, and intercalation of current-generated structures, a sheltered (embayed) interpretation is favoured over a distal (basinal) one. The low diversity trace fossil suite, coupled with the close association of this facies with Facies E supports this environmentally stressed, inshore embayment interpretation. Facies F constitutes the depositional platform across which Facies B/C/D progrades. In many localities, the contact relationships between these facies are erosional, however, this is to be expected, given the channel interpretation afforded Facies B/C/D. The sharp erosional contact between these facies does not imply, therefore, a stratigraphic discontinuity of allocyclic origin. The interstratified character of these facies on a small scale strongly supports a genetic relationship, where autocyclic processes are responsible for their vertical and lateral juxtaposition.

Discussion of an Incised Valley Interpretation

Despite the marginal marine character of the succession, an estuarine incised valley complex is untenable, given the characteristics of the deposit. In the first place, the deposit is oriented parallel to the inferred shoreline trends during Viking time. Although some valleys may become re-oriented to parallel old shoreline trends during lowstand conditions (cf., Suter et al., 1987; Thomas and Anderson 1994; Sullivan et al., 1995), this has not been the case for any of the *known* incised valley complexes of Viking age in Alberta. All currently recognized Viking Formation valley complexes have orientations perpendicular to inferred paleoshoreline trends (Reinson et al., 1978; Boreen and Walker, 1991; Pattison, 1991; MacEachern and Pemberton, 1994; Pattison and Walker, 1998).

In the second place, fluvial deposits or fluvially-supplied deposits are entirely lacking in the vicinity of the stratigraphically lowest position of BD-2. Isopach thicks for the lower part of Sequence 3 correspond to predominantly muddy intervals within the succession, believed to consist of the brackish-water mudstone and thin sandstone of Facies E. If BD-2 had been cut by fluvial incision, it would require the valley to have operated as a zone of total coarse-sediment bypass, not only during lowstand conditions, but during early transgression and concomitant increasing accommodation space as well. Further, the succession cannot be accounted for using a terraced valley model of the type proposed by Blum (1992), because cross sections clearly demonstrate that the coarse-grained facies along the margins of the deposit interdigitate with brackish-water, fine-grained deposits to the northeast (Figs. 7 and 16), indicating a genetic relationship.

The remaining problem with an incised valley interpretation is that the three internal parasequences onlapping BD-2 possess orientations inconsistent with a shore-parallel incised valley. In valleys, parasequences are oriented with their strikes perpendicular to the valley trend, onlap the depositional surfaces in an up-valley direction, and downlap/offlap in a down-valley direction. In contrast, Parasequences 1, 2 and 3 strike *parallel* to the length of the deposit (NW-SE; Figs. 15, 19 and 23), while onlapping to the southwest and offlapping to the northeast (Figs. 7 and 16). This orientation is more characteristic of shoreline or intertidal parasequences.

Discussion of a Transgressive Shoreface Interpretation

Despite the shore parallel orientation, the succession is not consistent with the previously proposed transgressively incised shoreface interpretation of Downing and Walker (1988), or the high frequency forced regression shoreface model of Burton and Walker (this volume). In shoreface depositional models, trough cross-stratified coarse clastics are generally regarded to correspond to upper shoreface (nearshore) conditions subjected to high energy, wave-forced currents and longshore drift processes (cf., Clifton et al., 1971; Davidson-Arnott and Greenwood, 1976; Hunter et al., 1979). This seems particularly true for currents capable of transporting the gravels of Facies C and D. These gravels, however, are regularly and widely interstratified with marginal marine mudstone, and interbedded mudstone and sandstone at a variety of scales, ranging from millimetres to decimeters and demonstrate repeated fluctuations between traction transport and suspension deposition. In addition, the presence of mudstone rip-up clasts implies incision into, or erosion across the fine-grained deposits, atypical of upper shoreface settings. Such non-resistant rip-up clasts are unlikely to have survived transport or reworking for any significant period in the nearshore (surf zone) environment. The suggestion that these facies corresponds to lower or middle shoreface deposits is equivocal. We know of no modern setting or ancient shoreface succession that is dominated by current ripple lamination and trough cross-stratification.

Further, if Facies B/C/D reflect nearshore deposition, then one would expect these facies would fine and pass gradationally seaward into contemporaneous middle- and lower-shoreface burrowed to hummocky/swaley stratified sandstone. In contrast, these facies cut into or directly overlie the interstratified conglomerate, sandstone and mudstone of Facies F (Fig. 14), that displays a mixture of oscillatory structures, thin (and, we believe, sheltered rather than distal) storm-generated laminations, combined flow structures and current structures. The coarse clastics also pass basinward into, and become interstratified with the thinly interbedded oscillation rippled fine-grained sandstone and dark mudstone of Facies E (Fig. 8), which likewise reflect low energy (and, we believe, highly sheltered) settings (Figs. 7 and 16). Facies E and Facies F are unlikely to have been deposited in offshore or shelf conditions because:

1) the abrupt transition from coarse clastics to fine-grained deposits (e.g., Fig. 16) over distances of approximately

400 m constitutes depositional gradients that are too steep for a transition from the upper shoreface to the offshore;

2) Facies E contains a low diversity, stressed trace fossil suite consistent with reduced salinity settings. This suite is impoverished compared with the fully marine offshore deposits of the underlying transgressive shoreface succession and highstand regional Viking parasequences as well as the offshore deposits overlying FS (compare Figs. 5 and 22 with any of Figs. 9, 11, 17, 18, 20 or 21). Although various parameters may contribute to environmental stress, the nature of the assemblage generated is more easily accommodated by sporadic but overall reduced salinity conditions, rather than as a result of changes in oxygenation, food resources or substrate consistency; and

3) foraminiferal assemblages within the mudstone generally display a low diversity of forms, and a paucity of environmentally sensitive genera, consistent with the stressed conditions associated with reduced salinity settings (MacEachern et al., this volume).

Summary of Proposed Interpretation

An alternative model for lower Sequence 3 is presented in Figure 24, and better accounts for the problematic relationships already discussed. The BD-2 surface reflects transgressive ravinement that erosively modified the sequence boundary at the base of Sequence 3. This early stage of transgressive ravinement reworked available lowstand sediments landward to produce the basal, glauconitic, pebbly sandstone of Facies A, which onlap part of the relief on BD-2. This transgression introduced a broad, shallow brackish-water embayment in the Joffre area. Incremental cycles of progradation were punctuated by relative rises in sea level, and resulted in marginal marine flooding surfaces that separate three, coarse-grained, shallowing upward cycles comprising the stacked parasequences.

All three parasequences are broadly similar. They predominantly consist of sharp, erosionally based, trough cross-stratified sandstone, pebbly sandstone and conglomerate toward the southwestern margin of the deposit, which progressively overlie interstratified conglomerate, sandstone and mudstone in intermediate positions, and ultimately depositionally thin and/or become interstratified with interbedded mudstone and sandstone toward the northeast. Each parasequence is partially truncated by overlying deposits and each progressively onlaps relief developed on BD-2 in a landward (southwest) direction.

Each parasequence comprises the deposits of shore-normal and shore-parallel marginal marine channels and creeks, that fed coarse clastics to bay-head deltas fronting the elongate, shore-parallel brackish-water embayment (Fig. 24). The coarse clastics of Facies B/C/D accumulated along the southwestern (landward) margin of the embayment in the form of marginal marine distributaries that cut into and coalesced with Facies F bay-head delta front deposits, forming a broad, shore-parallel (NW-SE oriented), coarse-grained bay-head delta "apron". As the embayment filled, high sediment supply to the bay-head delta aprons permitted these systems to prograde northeastward into the bay, interfingering with the finer-grained brackish-water bay deposits of Facies E.

The marginal marine flooding surfaces (F1, F2 and F3) separating the parasequences are interpreted to reflect fluctuations in the rate of transgression, rather than as variations in sediment supply due to autocyclic channel switching/avulsion. Fluctuations in transgressive rate are favoured because of the along-strike persistence of all three flooding surfaces. Pulses of relative sea level rise allowed the brackish bay mudstone and interbedded sandstone and mudstone of Facies E to onlap the more proximal bay-head delta/channel complexes along the entire length of the embayment. The northeastward progradation of the coarse-grained deposits along the length of the embayment resulted in parasequences with shore-parallel strikes, offlapping/downlapping to the northeast and onlapping to the southwest. The fact that Parasequence 1 and Parasequence 3 have similar progradational limits while the intervening parasequence displays a landward progradational limit makes it impossible to define the succession as either a progradational or retrogradational parasequence set. Major transgression resulted in wave ravinement surface FS, and returned the area to open marine offshore conditions. This, coupled with the increased abundance and diversity of ichnogenera within Parasequence 3 supports increasing marine conditions, and indicates that the lower Sequence 3 succession is best placed within a transgressive systems tract.

The proposed model suggests the existence of a barrier complex lying northeastward of the zero edge of the Joffre embayment complex; a barrier whose deposits are conspicuously absent from the depositional record. Certainly there is indirect evidence of this barrier's existence. Facies E displays ichnological and sedimentological characteristics that indicate it was environmentally restricted and sheltered from open marine conditions, presumably by a barrier system. The preservation potential of a barrier complex is low, and resumed transgression which cut the ravinement surface FS across the top of the embayment deposit may have removed much, if not all, of the evidence of this depositional setting (cf., Rampino and Sanders, 1980; Nummedal and Swift, 1987; Walker, 1992). All that might remain of the barrier complex itself is the granule or pebble lag and thin sandstone deposit mantling FS. Alternatively, some of the upper portion of Parasequence 3, itself, may consist of reworked deposits derived from the backstepped barrier during initial transgression across the area. The paucity of core data available from immediately northeast of the Joffre Field further inhibits the identification of any barrier system remnants.

The major transgression, marked by FS, returned the study area to fully marine conditions and displaced the shoreline well to the south and southwest. The deposits overlying FS constitute the upper portion of Sequence 3.

Discussion of the Forced Regression Shoreface Model of Burton and Walker (this volume)

In light of some of the complexities within the succession at Joffre, Burton and Walker (this volume) have reassessed the original interpretation of Downing and Walker (1988). In their revised interpretation, two sharp-based conglomeratic shoreface successions are recognized, that reflect high frequency relative falls in sea level during an overall transgression. This model is broadly similar to that proposed by Davies and Walker (1993) for the Caroline/Garrington area. This revised model alleviates some of the difficulties in juxtaposing relatively thick mudstone-dominated units against conglomeratic deposits because the new model proposes that these facies are not contemporaneous and therefore do not reflect laterally adjacent environments. We have several concerns with the new interpretation, however.

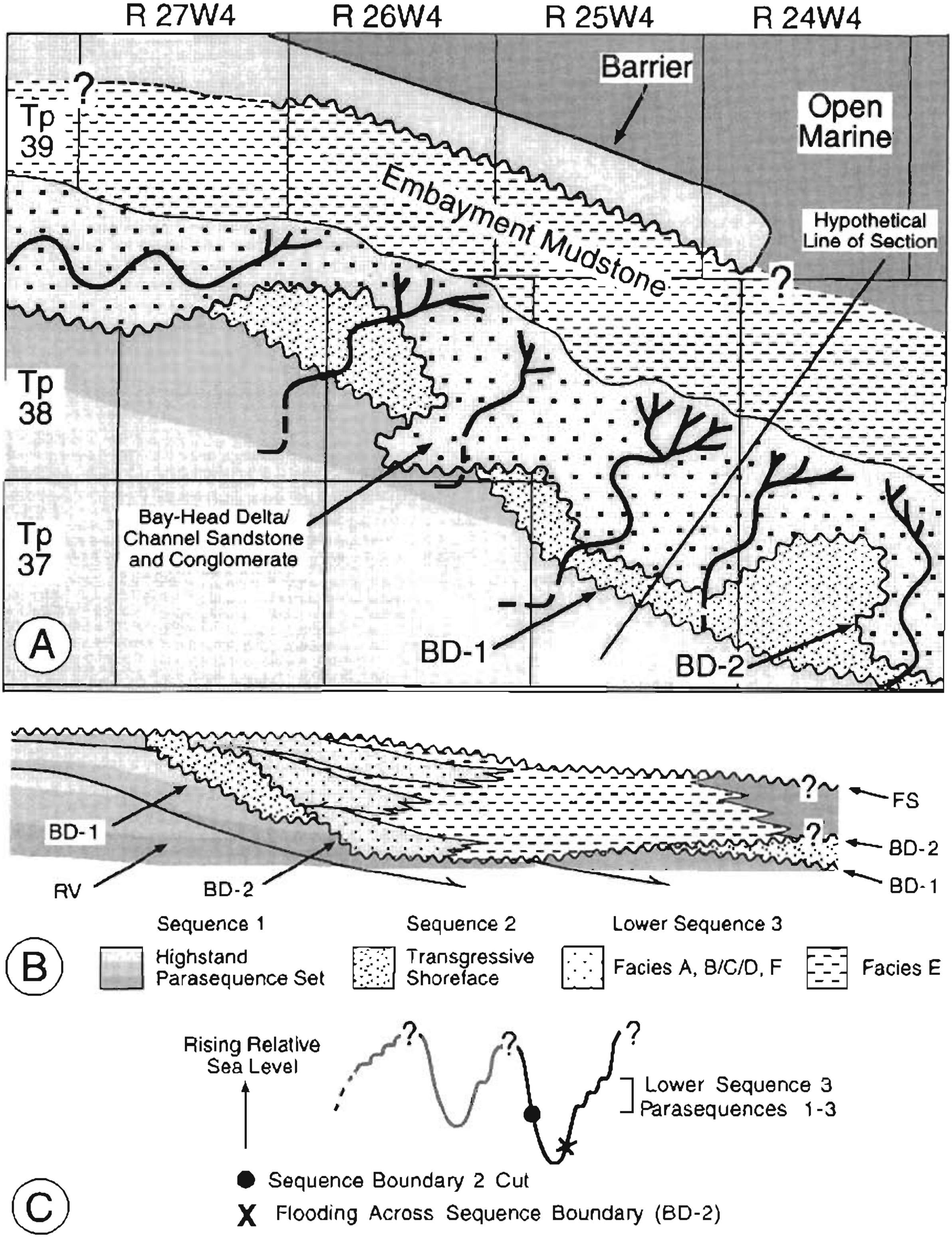

Fig. 24.—Depositional model for the lower portion of Sequence 3 (modified after MacEachern et al., 1998). A: Paleogeographic map of Parasequence 3 in lower Sequence 3. The hypothetical line of section is shown for the cross-section in B. The model shows the suggested position of a barrier complex (not preserved) B: A schematic cross-section showing incision of Sequence 1 and Sequence 2 by lower Sequence 3. C: Proposed relative sea level changes in response to Viking deposition in the study area. Relative sea level changes associated with lower Sequence 3 are shown in black.

1. The central position of their interpretation is that the conglomeratic sandstone represent lower shoreface deposition. We are aware of no shoreface complexes that consist exclusively of trough cross-stratified bedforms in the lower shoreface component of the system. Their contention that these are generated by longshore currents seems untenable, since longshore currents primarily operate in the nearshore zone (upper shoreface). Rip currents are oriented normal to the paleoshoreline, and as a mechanism, cannot explain the shore-parallel extension of cross-stratified sandstone. The suggestion that the facies might be formed by storm-forced currents leaves one wondering why the facies are exclusively current-generated and do not pass basinward into finer-grained hummocky stratified sandstone, particularly, since Facies E and F demonstrate that fine-grained sand does exist basinward of these coarser clastics. Further, the trough cross-stratified beds contain a variety of intervening mudstone at all scales, ranging from interlaminae to interbeds. Mudstone rip-up clasts are common and record erosional amalgamation of these current-generated bedforms and scouring of adjacent and intervening mudstone. We find these features unusual for lower shoreface deposits.

2. The criticism that the "juxtaposition of medium- to coarse-grained cross-bedded sandstone with mudstone horizons are unusual" (Burton and Walker, this volume) is not consistent with the available core and well log data. From the 91 cores that we have logged within lower Sequence 3, 86 of them (96%) consist of cross-bedded intervals containing mudstone interlaminae and/or beds 1-3 cm thick. Further, 47 cored intervals (52%) display the presence of mudstone beds 3 cm or thicker, and are most abundant in a basinward position. The common occurrence of mudstone rip-up clasts in sandstone lying landward of the step on BD-2 clearly demonstrates that such interbedding was more widespread but has been removed by erosional amalgamation of the sandbodies. We also disagree that there is any fundamental difference between Burton and Walker's "split" and the black mudstone of their Facies 4 (cf., their Fig. 11). Our analysis of the ichnological, palynological, and foraminiferal assemblages from the black mudstone shows that there is no significant difference between those they regard as the "split" and those lying basinward of it (MacEachern et al., 1998; this volume). The minor differences between the upper part of their "split" and black mudstone are attributable to variations along a proximal-distal trend.

3. Burton and Walker (this volume) contend that there are only two parasequences in the succession. This is based on their interpretation that the sandstone immediately below BD2 RT in the 10-13-38-25W4 well does not correlate with the upper sandstone in the 06-13-38-25W4 well (their Figs. 7 and 11). We have based the existence of the three parasequences on correlations using 18 cross-sections and comparison with more than 700 geophysical well logs across the length of the Joffre field. Further, the correlations employed in their Figures 7 and 11 are curious. The last three wells in Figure 7 and the last two cores in Figure 11 do not contain their underlying datum and therefore do not have a basis for their positioning. We also question the validity of employing an underlying datum, particularly one within the regional Viking that is separated from the interval in question by two sequence boundaries. The overlying datum we have employed is the widespread bentonite encased within offshore marine mudstone. It is highly unlikely that there was any paleotopographic relief on this datum. We believe that this inherently yields a better alignment of wells and favours superior correlations. Their correlation of Facies 2 and Facies 3 truncated by BD2-RT in Burton and Walker (this volume; their Fig. 11) is curious. The upward climb of these facies in a basinward direction, particularly where BD-2 becomes deeply incised, is unconventional and unnecessary, in our opinion. Our correlations in MacEachern et al. (1998; our Fig. 10) and in Figures 7 and 16 show three discrete prograding sandbodies that downlap in a basinward direction. The underlying datum employed by Burton and Walker (this volume) also appears to be the cause of the odd morphology on BD2 RT and BD3 depicted in their Figure 12. Their correlation illustrates ravinement/flooding surfaces that appear to rise and then fall (as it incises) in a progressively landward direction. In our estimation, this is an unlikely morphology for a transgressive surface.

4. Our paleontologic analysis of the intervening mudstone demonstrates salinity conditions intermediate between fully marine and estuarine (MacEachern et al., this volume). We feel that these are exactly the types of conditions that can be expected within a partially barred lagoonal embayment or a shallow bay. Although we find environmentally sensitive foraminifera present in some intervals, they occur in very low numbers and are consistent with stressed conditions compared to open marine facies. The paleoecology of the foraminiferal suite is most consistent with a salinity reduction, rather than substrate consistency or high sedimentation rates (MacEachern et al., this volume). We also noted that the palynological suites of the embayment facies are similar to the open marine, but attributed this to the ease to which palynomorphs are washed in from the offshore. Burton and Walker (this volume) mistakenly claim that we see individual parasequences become more marine upward, a feature inconsistent with the encroachment of the bay-head delta complexes. What we see, instead, is that each *successive* parasequence is more marine than the one underlying it, with the exception of the glauconitic transgressive sand sheet at the base. This progressive change heralds the onset of major transgression, marked by the development flooding surface FS (their BD2 RT).

5. Burton and Walker (this volume) reject the interpretation of an embayment complex because they see no preserved record of it. We argue that the preservation potential of the barrier complex, itself, is low (cf., Rampino and Sanders, 1980; Nummedal and Swift, 1987; Walker, 1992), particularly if the rate of sea level rise is slow. 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 mudstone and coarse clastics feeding into the embayment, however, have a higher preservation potential because they occupy a paleotopographic depositional low, and the ravinement surfaces rise topographically as the shoreline translates landward. We believe that the most likely indication of a barrier complex in the ancient record is the recognition of the lagoonal deposits themselves. The facies of lower Sequence 3 demonstrate an abundance of features that reflect brackish water sheltered conditions, consistent with a lagoonal origin.

Further, although we have postulated the existence of a barrier system as a means to generate a lagoonal/embayment complex, we do not believe that a barrier is essential. It is possible that the entire succession may reflect a shallow, open bay, markedly reduced in salinity due to freshwater dilution associated with coarse clastic input to the bay-head delta systems along the bay margin. A broadly similar model was employed by Mellere and Steel (1995) and Mellere (1996) to explain cross-stratified sandstone overlying shoreface parasequences from the Haystack Mountain Formation of Wyoming. An open bay system would facilitate some nearshore (longshore drift?) modification of the bay-head delta systems and straightening of the depositional edge within Lower Sequence 3 at Joffre.

SUMMARY

The Viking Formation of the Joffre area comprises parts of at least three discrete sequences. The Viking reservoir facies lie within the lower part of Sequence 3. During Sequence 3 time, there was a relative fall of sea level that permitted the excavation of a sequence boundary. This sequence boundary dissected the underlying marine shoreface deposits of Sequence 2 and locally incised through them and into the regional Viking parasequences of Sequence 1 (Figs. 7 and 16), reflecting a shift of the shoreline to the north and northeast of the study area. The sequence boundary was subsequently erosionally modified by wave ravinement during an ensuing transgression, forming a broad NW-SE trending asymmetric incision referred to as BD-2 (Fig. 24). Any overlying lowstand deposits were reworked to produce the transgressive lags and glauconitic transgressive sand sheets (Facies A) that mantle the surface. This transgression generated a broad, NW-SE trending embayment of the shoreline, possibly separated from the open marine seaway by a barrier complex lying in the northeastern portion of the study area. An alternative model is that the complex accumulated within a broad, shallow, open bay sheltered from the strong waves and storms developed in the interior seaway.

Pauses in the rate of flooding during transgression permitted periods of northeastward progradation of conglomeratic bay-head delta complexes into the brackish-water embayment. The bay-head deltas were supplied with sediment from small, shore-normal and shore-parallel marginal marine channels. The coarse-grained deposits coalesced to form broad, NW-SE trending aprons, consisting of distributary channel and bay-head delta front deposits along the southwestern margin of BD-2 (Facies B/C/D and Facies F, respectively), that interfinger with marginal marine, interstratified mudstone and sandstone (Facies E) in a basinward (northeastward) direction. Variations in sediment supply and autocyclic channel/delta abandonment may have caused much of the lithological heterogeneity within individual parasequences.

Allocyclically generated fluctuations in the rate of transgression resulted in the shifting of brackish-water bay deposits over the bay-head delta/channel complexes, and generated three discrete parasequences marked by marginal marine or bay flooding surfaces (F1, F2 and F3). Short-lived pulses of progradation (P1, P2 and P3) resulted in the deposition of bay-head delta front deposits over the bay mudstone, ultimately capped by distributary channel complexes. Each parasequence onlaps relief on BD-2 along its landward (southwestern) margin, and offlaps/downlaps to the northeast (Figs. 7 and 16). These parasequences constitute the Joffre embayment complex of lower Sequence 3. Although the parasequences do not stack into a retrogradational parasequence set, the upper most parasequence displays an increased marine influence, and the top of the succession is truncated by a regionally extensive transgressive ravinement surface (FS), suggesting that lower Sequence 3 belongs in a transgressive systems tract. The resumed transgression that cut the ravinement surface FS terminated brackish-water deposition and returned the study area to fully marine, offshore conditions.

Successions characterized by coarse clastics regularly interstratified with marine or marginal marine mudstone are commonly interpreted either as coarse-grained conglomeratic shoreface deposits (cf., Downing and Walker, 1988; Posamentier et al., 1992; Davies and Walker, 1993; Walker and Bergman, 1993; Posamentier and Chamberlain, 1993; Bergman, 1994; Bergman and Walker, 1995) or as estuarine incised valley complexes (cf., Reinson et al., 1988; Boreen and Walker, 1991; Pattison, 1991; Sullivan et al., 1995). The ichnological, sedimentological and sequence stratigraphic characteristics of the succession demonstrate that neither model is appropriate for lower Sequence 3 of the Viking Formation at Joffre, and point to an alternative model.

In modern settings, relative sea level rise has encouraged the development of highly embayed transgressive shorelines, commonly fronted by barrier systems. During subsequent wave ravinement, these barrier complexes are likely to be destroyed or preserved only as erosional remnants consisting of offshore to lower shoreface deposits that rest on marine flooding surfaces. The back-barrier mudstone and the coarse clastics feeding into the embayment, however, have a comparatively higher preservation potential during the transgression. This is because these deposits occupy a paleotopographic low, and the ravinement surface rises topographically during erosive shoreface retreat. Alternatively, a broad, shallow, open bay may be highly sheltered from open marine conditions even without a barrier complex, and could explain many of the characteristics of lower Sequence 3. In spite of the ubiquitous occurrence of brackish lagoonal and embayment environments in modern transgressive shoreline systems, current interpretations of ancient transgressive successions appear to ignore or fail to recognize the deposits of these environments.

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