A SHARP-BASED SANDSTONE OF THE VIKING FORMATION, JOFFRE FIELD, ALBERTA, CANADA: CRITERIA FOR RECOGNITION OF TRANSGRESSIVELY INCISED SHOREFACE COMPLEXES

JAMES A. MACEACHERN[1], BRIAN A. ZAITLIN[2], AND S. GEORGE PEMBERTON[3]
[1] *Earth Sciences, Simon Fraser University, Burnaby, British Columbia V5A 1S6, Canada*
e-mail: jmaceach@sfu.ca
[2] *PanCanadian Petroleum Ltd., Box 2850, Calgary, Alberta T2P 2S5, Canada*
[3] *Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta T6G 2E3, Canada*

ABSTRACT: **The Viking Formation of the Joffre field comprises parts of three discrete sequences. Sequence 2 overlies an erosional discontinuity, termed BD-1, which is incised into underlying marine parasequences of the informally named ''Regional Viking''. The surface represents a sequence boundary that was transgressively modified during subsequent relative sea-level rise, and is commonly demarcated by the *Glossifungites* ichnofacies. Up to three parasequences are truncated by BD-1.**

Sequence 2 comprises an incised sandstone body passing basinwards into a granule- to pebble-bearing sandy mudstone. A complete facies succession consists of a thin granule to pebble lag mantling BD-1, grading upwards into thoroughly bioturbated gritty sandy mudstone, through intensely burrowed muddy sandstone, and into interbedded hummocky cross-stratified sandstone and burrowed sandstone. The facies contain diverse and uniformly distributed, open-marine trace-fossil suites displaying an upward progression from archetypal *Cruziana* through proximal *Cruziana* and into mixed *Skolithos–Cruziana* assemblages. The succession is interpreted to reflect a weakly storm-influenced upper offshore to proximal lower-shoreface deposit.

Incised shorefaces are allocyclically generated, and may be produced by forced regressive (falling stage), lowstand, or transgressive scenarios. Sequence 2 of the Joffre area is interpreted as a transgressively incised shoreface. It is distinguished from the other two sharp-based shoreface types largely on the basis of the extent of the erosional component of its basal discontinuity. In distal positions, BD-1 remains erosional even where it is overlain by facies deposited *below* fair-weather wave base. This is inconsistent with forced regressive and lowstand conditions because in weakly storm-influenced shorefaces, the regressive surface of erosion and the sequence boundary, respectively, pass into correlative conformities seaward of fair-weather wave base. Facies deposited below fair-weather wave base would therefore overlie the non-erosional correlative conformity surface. In a transgressive scenario, however, ravinement during erosional shoreface retreat generates an erosional discontinuity that may lie seaward of fair-weather wave base during subsequent progradation, because the surface was cut prior to progradation and while sea level was considerably lower. As a result, facies deposited below fair-weather wave base can overlie the erosional discontinuity.

INTRODUCTION

Sharp-based marine sandstone bodies have received considerable attention in recent years, particularly with the advent of genetic/sequence stratigraphy (e.g., Downing and Walker 1988; Plint 1988; Posamentier et al. 1992; Raychaudhuri et al. 1992; Davies and Walker 1993; Walker and Bergman 1993; Bergman 1994; Hunt and Tucker 1992, 1995; Ainsworth and Pattison 1994; Kolla et al. 1995; Van Wagoner 1995; Walker and Wiseman 1995). The recent emphasis of sequence stratigraphy has led to revised interpretations (or reinterpretations) of enigmatic marine or marginal marine coarse clastic deposits encased in offshore or shelf mudstone. Many of these were once routinely regarded as offshore bar or shelf sand ridge complexes (e.g., Tillman and Martinsen 1984, 1987), but have more recently been interpreted as incised-shoreface deposits (e.g., Walker and Bergman 1993; Bergman 1994) or as incised-delta deposits (e.g., Mellere and Steel 1995) stranded in offshore or shelf positions during subsequent transgression. Much debate surrounds the specific sequence stratigraphic scenario of shoreface incision, however. Various researchers have recognized that sharp-based shoreface sandstone bodies may be deposited under late highstand conditions (e.g., Van Wagoner 1995), forced-regression or falling-stage settings (e.g., Hunt and Tucker 1992; Walker and Bergman 1993; Bergman 1994), lowstand conditions (e.g., Plint 1988; Posamentier et al. 1992; Walker and Wiseman 1995), and transgressive conditions (e.g., Downing and Walker 1988; Raychaudhuri et al. 1992; MacEachern et al. 1995; MacEachern et al. 1998). Unfortunately, more attention has been accorded the mere presence of a sharp basal contact than to any other single characteristic of the succession. In our estimation, facies criteria necessary to differentiate between these systems are largely lacking, and recognition of their relation to relative sea-level position has been based primarily upon regional stratigraphic relationships. Core data from part of the Viking Formation in the Joffre field, however, highlights a facies relationship that aids in the differentiation of transgressively incised shorefaces from those produced by falls in relative sea level.

STUDY AREA AND DATA BASE

The Viking Formation Joffre field, discovered in 1953, is part of a NW–SE trend of fields that extends for some 250 km in central Alberta, Canada (Fig. 1). The Joffre field is located in Townships 37–39, Ranges 24W4–27W4, and extends for some 35 km along strike. A sharp-based sandstone body from the Viking Formation was analyzed from 72 cored intervals. The cored intervals were described in detail with regard to ichnology and sedimentology, and interpreted within a high-resolution sequence stratigraphic framework in order to determine the depositional environments with respect to relative sea level. The core data were integrated with the analyses of 700 geophysical well logs to facilitate the mapping of the Viking sequences and to carry correlations across the study area.

REGIONAL STRATIGRAPHIC RELATIONSHIPS

The Upper Albian (Lower Cretaceous) Viking Formation consists of west-derived siliciclastic deposits that prograded northwards and eastwards into the developing Alberta foreland basin in response to the progressive uplift of the Cordillera. The Viking Formation passes upwards from marine shale of the Joli Fou Formation and is overlain by the transgressive marine shale of the Westgate Formation (Fig. 2). The stratigraphic relationships of the interval are schematically illustrated in Figure 2 and are based on the work of Glaister (1959), McGookey et al. (1972), Weimer (1984), Cobban and Kennedy (1989), Stelck and Leckie (1990), Bloch et al. (1993), Caldwell et al. (1993), and Obradovich (1993).

The Viking Formation is highly complex and contains numerous internal discontinuities. Attempts to subdivide the interval into regionally correlative units have been undertaken by numerous workers, culminating in the recent work of R.G. Walker and his students (e.g., Burton and Walker in press). These attempts have sought to establish a formal allostratigraphic framework according to the rules of the North American Commission on Stratigraphic Nomenclature (1983).

JOURNAL OF SEDIMENTARY RESEARCH, VOL. 69, NO. 4, JULY, 1999, P. 876–892
1073-130X/99/069-876/$03.00

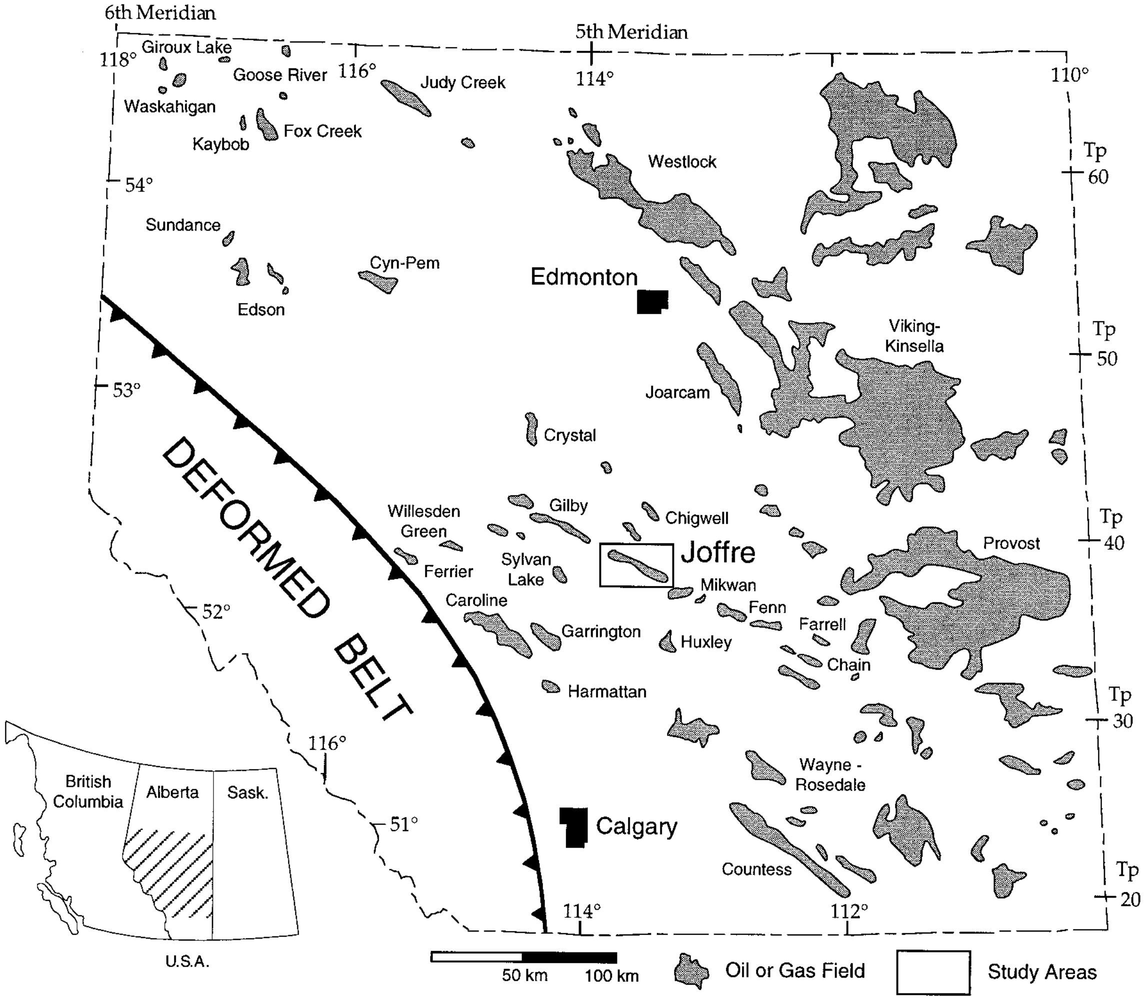

FIG. 1.—Major Viking Formation hydrocarbon field locations in Alberta, Canada (modified after MacEachern et al. 1998).

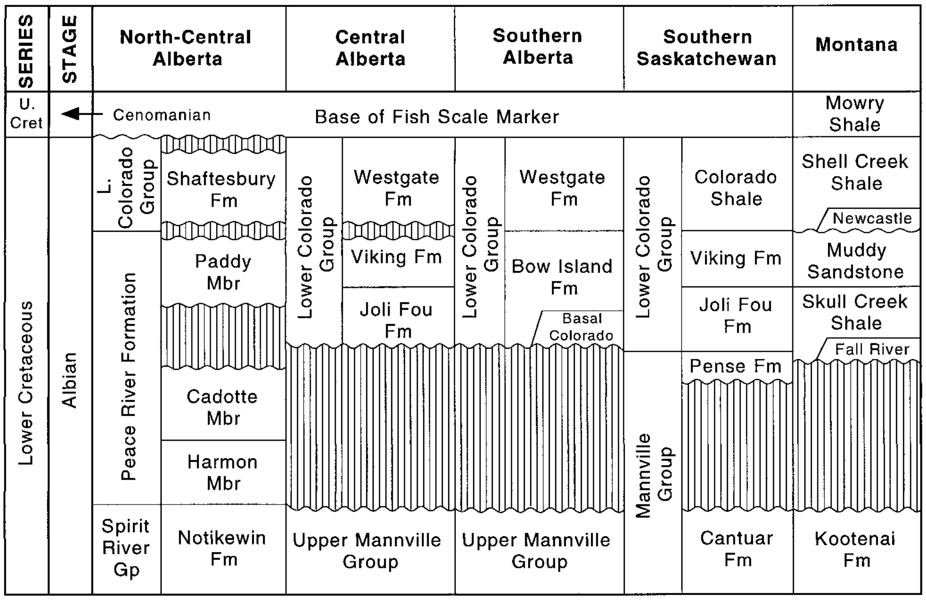

FIG. 2.—Stratigraphic correlation chart for the Viking Formation (modified after MacEachern et al. in press).

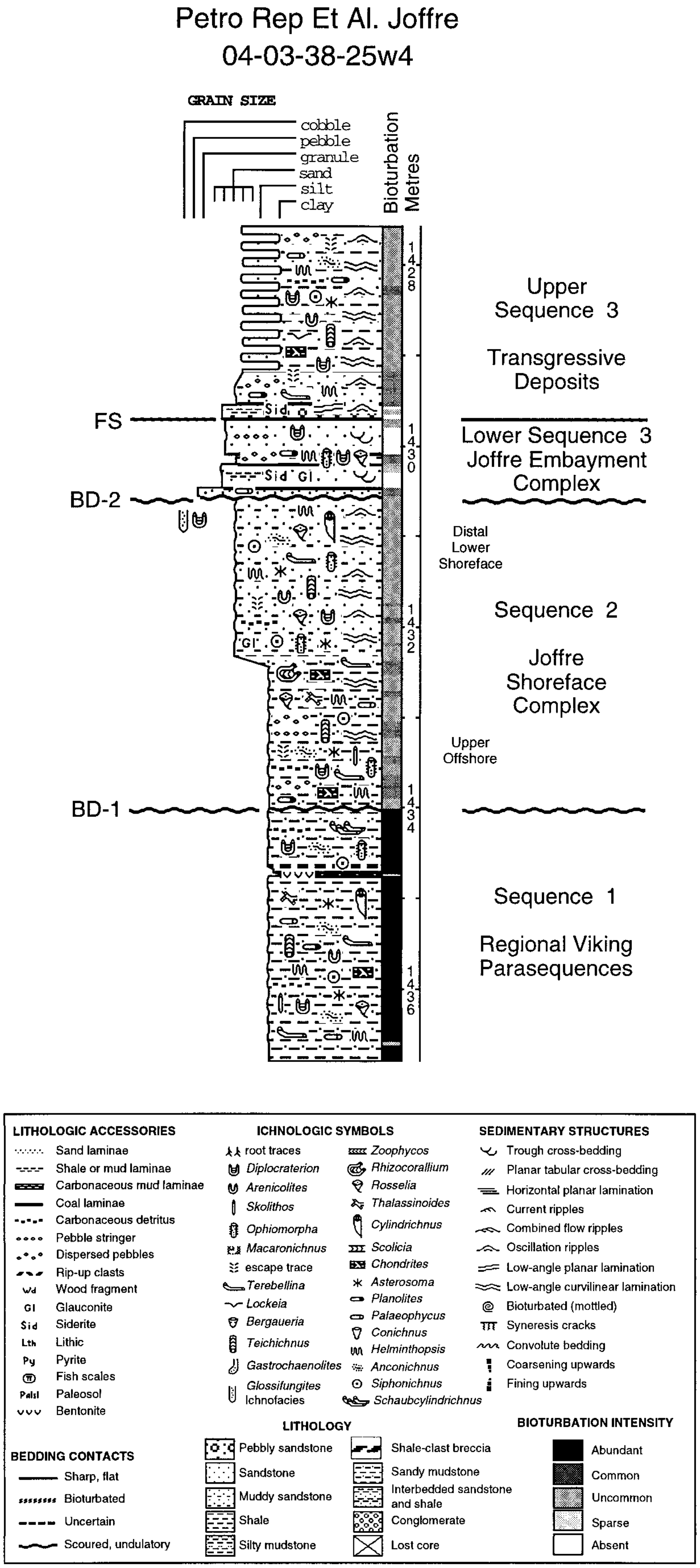

FIG. 3.—Representative litholog of the Viking Fm at Joffre. The Viking succession in the Petro Rep et al. Joffre 04-03-38-25W4 well illustrates three discrete sequences, separated by transgressively modified sequence boundaries (modified after MacEachern et al. 1998).

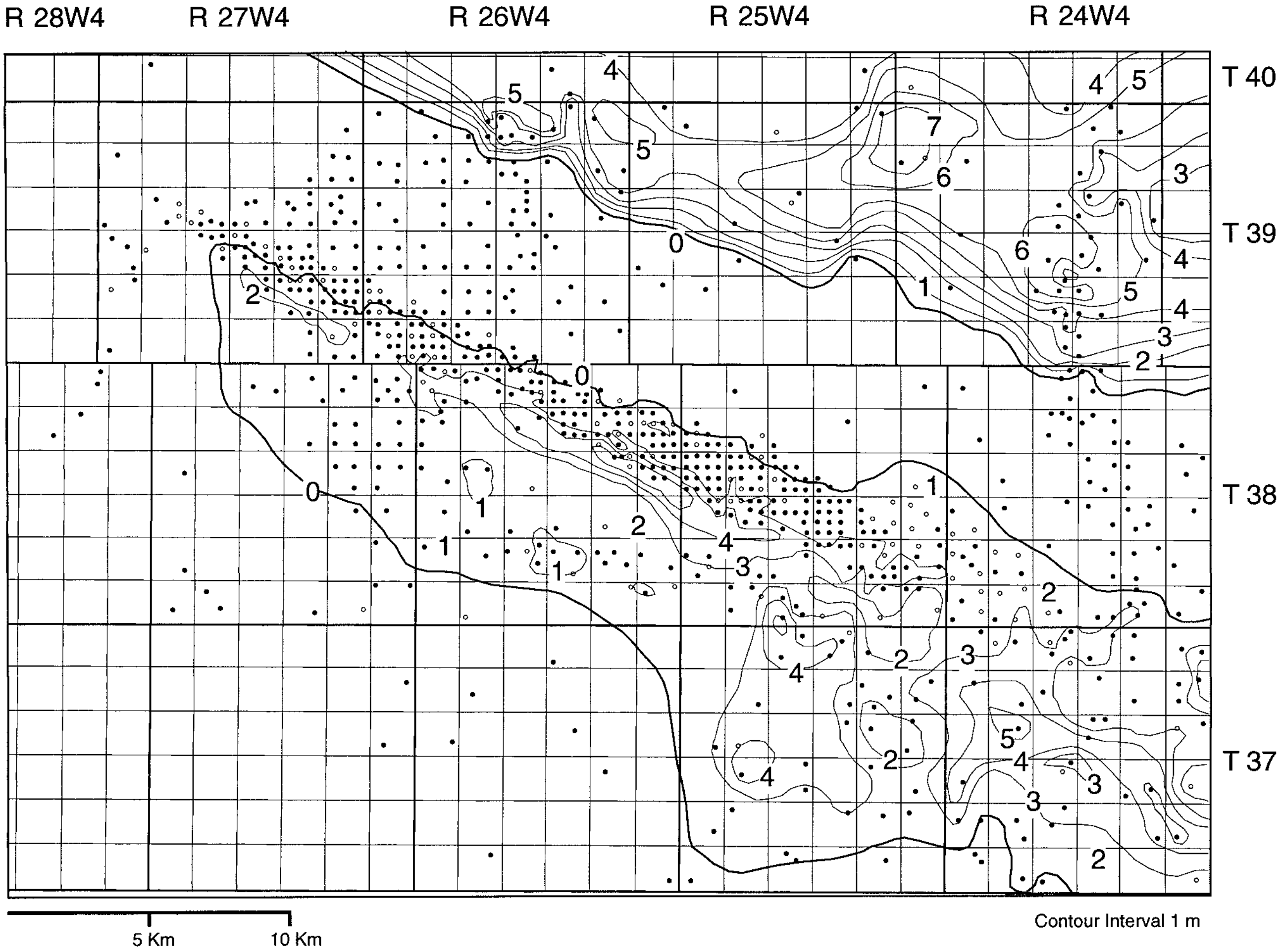

FIG. 4.—Isopach map of Sequence 2 in the Joffre field area. Note that Sequence 2 has been erosionally removed through the central part of the study area by the overlying Sequence 3 interval.

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 (Fig. 3). These major stratigraphic breaks were originally delineated by Downing and Walker (1988), and constituted the fundamental bounding discontinuities of their allostratigraphic units. BD-1 was originally termed ''E1'' by Downing (1986) and Downing and Walker (1988), and renamed BD-1 by Burton and Walker (in press). Boreen and Walker (1991) correlated the lower of the two surfaces (E1) to their VE3a surface.

Sequence 1, informally referred to as the ''Regional Viking'', consists of six regionally extensive, stacked, NW–SE-trending, open marine offshore to lower-shoreface parasequences arranged in a progradational parasequence set, interpreted to reflect a highstand systems tract. Parasequences range from 0.8 to 10.4 m in thickness, though most are 1.0–3.0 m thick. These parasequences are incised into by BD-1, an amalgamated sequence boundary and transgressive surface of erosion, and are overlain by deposits of Sequence 2, the subject of this paper. Sequence 2 is interpreted to reflect the progradation of a shoreface complex during a pause in transgression or a decrease in the accommodation/sediment ratio following the generation of BD-1. Sequence 2 deposits are incised into and locally removed by BD-2, a second amalgamated sequence boundary and transgressive surface of erosion (MacEachern et al. 1998). The BD-2 surface is overlain by Sequence 3, which constitutes the reservoir interval of the Viking Joffre field. Sequence 3 consists of three NW–SE-trending aprons of conglomerate, pebbly sandstone, and sandstone interbedded toward the northeast with brackish-water mudstone. The succession is interpreted to reflect three marginal-marine parasequences, comprising bay-head delta and distributary-channel deposits that prograded into a broad brackish-water embayment during incremental transgression (MacEachern et al. 1995; MacEachern et al. 1998). The reservoir interval is truncated by an overlying ravinement surface (FS), currently referred to as BD-2RT by Burton and Walker (in press), that marks the return of open marine deposition in the study area.

Sequence 2

Sequence 2 is preserved as an erosional remnant in the Joffre area (Fig. 4). The central part of the study area displays the complete erosional removal of Sequence 2 by the basal discontinuity of Sequence 3 (BD-2). In this area, Sequence 3 is incised into the marine parasequences of Sequence 1. The southern margin of the deposit is also an erosional edge, related to a combination of truncation by BD-2 and the later regional ravinement surface, FS (Fig. 3). The northwestern end of the deposit is only a local zone of erosional removal by BD-2 and FS. Study of the Gilby area to the northwest of Joffre demonstrates that Sequence 2 is locally preserved along the NW–SE trend delineated at Joffre (Raddysh 1988). The deposit continues to the southeast into the Mikwan and Fenn fields (Peterson 1995), and can be traced to the south to the Huxley field (Burton and Walker in press).

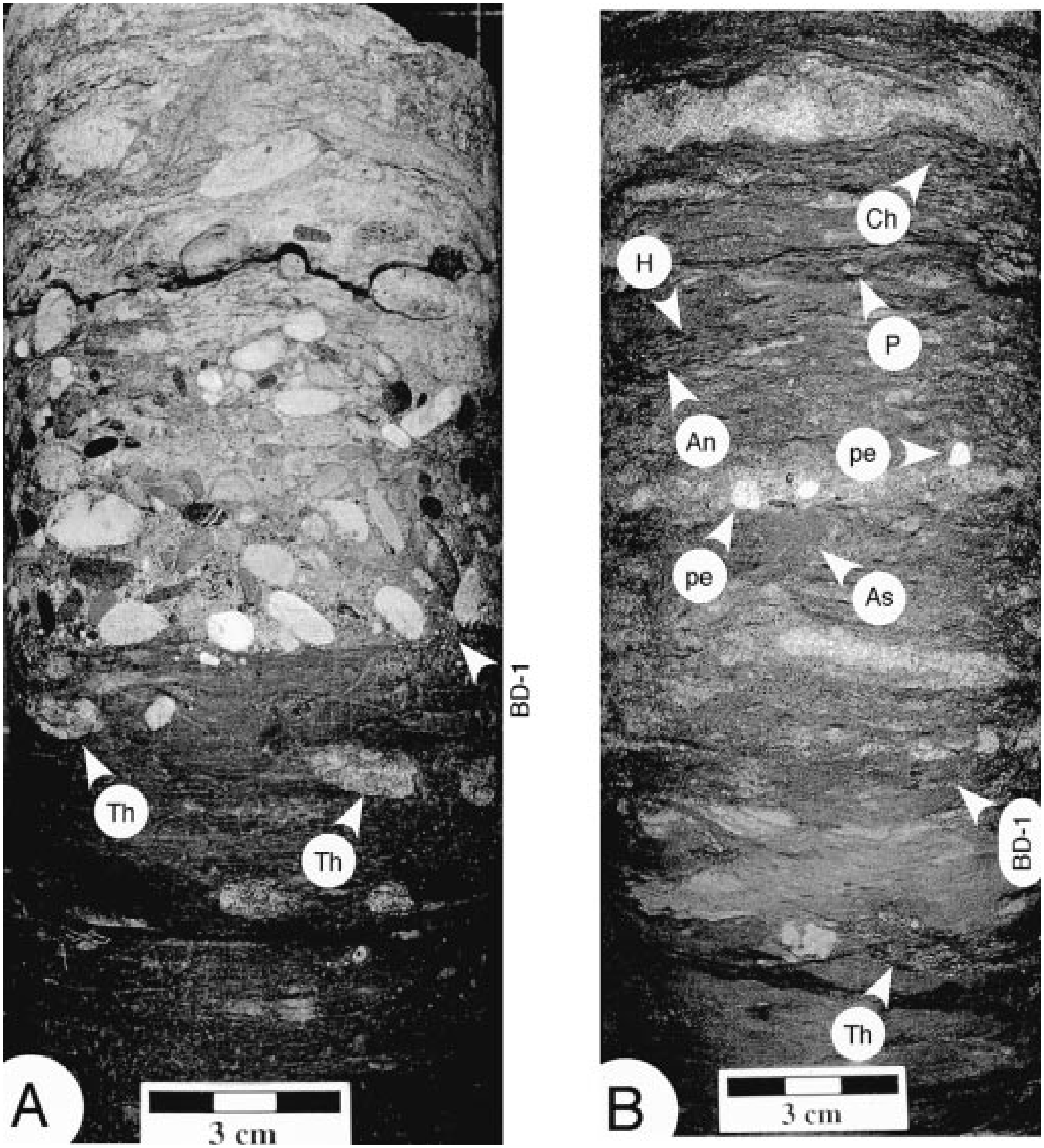

FIG. 5.—Photos of BD-1. **A)** BD-1 in a proximal position, marked by a *Glossifungites* assemblage of *Thalassinoides* (Th). The discontinuity is overlain by a pebble lag and muddy sandstones of Sequence 2. Well 09-16-39-27W4; 1562.5 m. **B)** BD-1 in a distal position marked by a *Glossifungites* assemblage of *Thalassinoides* (Th). The discontinuity is overlain by bioturbated sandy mudstone with dispersed pebbles (pe), *Helminthopsis* (H), *Anconichnus* (An), *Chondrites* (Ch), *Asterosoma* (As) and *Planolites* (P). Well 08-14-38-25W4, 1434.0 m.

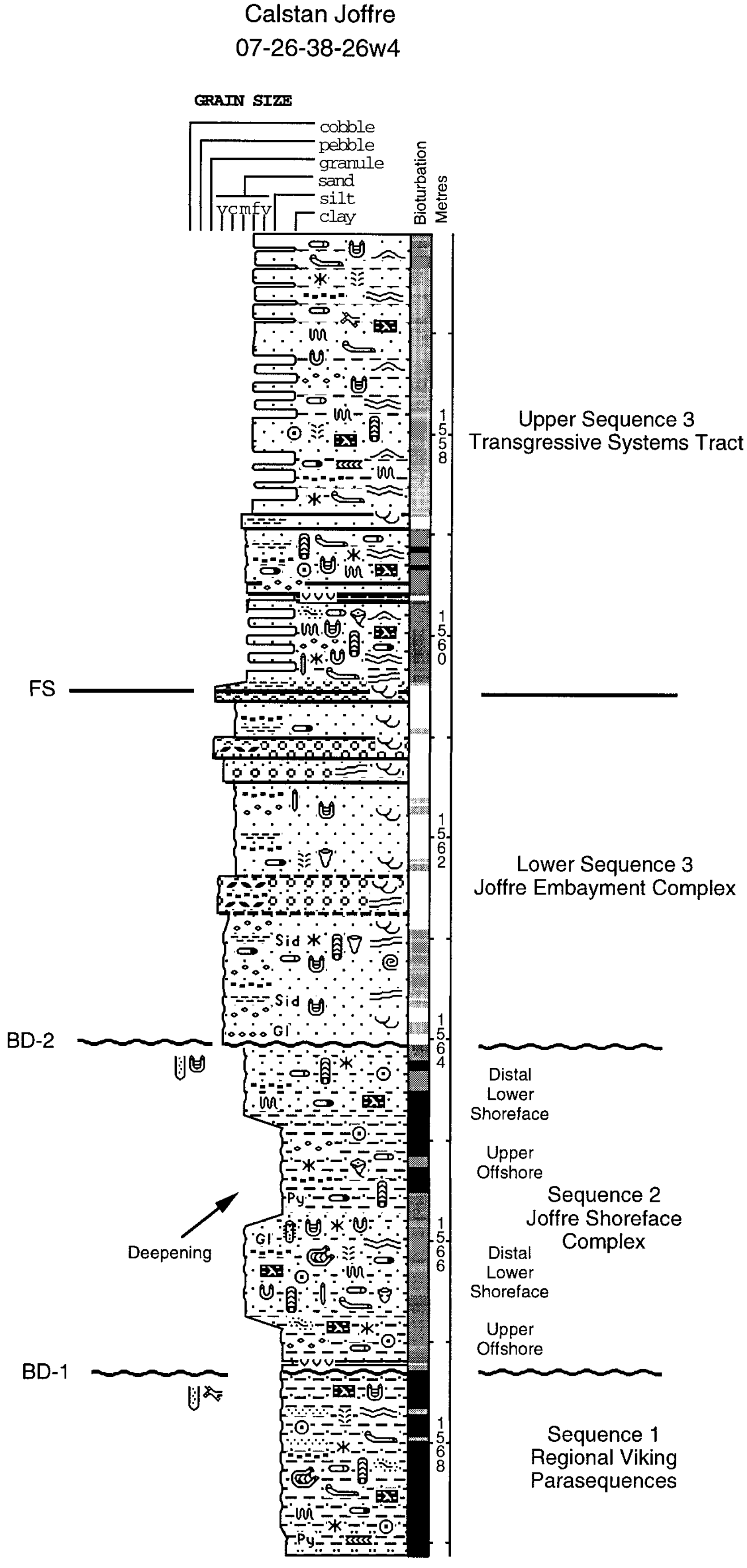

FIG. 6.—Litholog of Sequence 2 at Calstan Joffre 07-26-38-26W4. The interval shows an overall sanding-upward, progradational succession with an intercalated zone of relative deepening. See Figure 3 for legend of symbols.

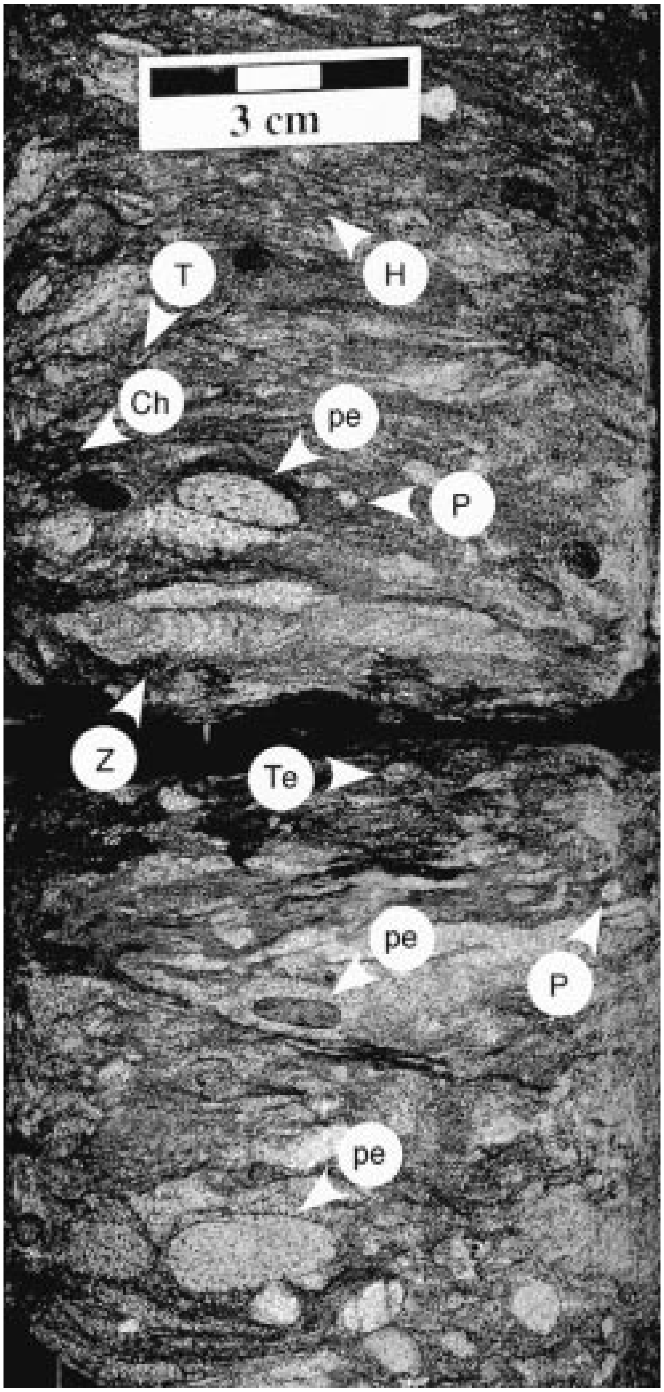

FIG. 7.—Photo of the intensely burrowed sandy mudstone facies with dispersed pebbles (pe), *Zoophycos* (Z), *Helminthopsis* (H), *Chondrites* (Ch), *Planolites* (P), *Teichichnus* (Te), and *Terebellina* (T), reflecting an open-marine archetypal *Cruziana* assemblage. Well 16-06-38-24W4; 1356.3 m.

With the exception of its erosional removal through the central part of the study area, Sequence 2 thickens toward the northeast.

Basal Discontinuity 1 (BD-1)

Basal Discontinuity 1 (BD-1; Fig. 5) is interpreted to be an amalgamated sequence boundary and flooding surface (MacEachern et al. 1998). The lowstand component to the origin of the surface is partly based on the considerable relief the surface displays regionally as it incises into the underlying marine parasequences of the informally named ''Regional Viking''. Three of these regionally extensive parasequences are truncated by BD-1, particularly notable along the southwest edge of the Joffre field. The discontinuity surface slopes steeply along the southwestern (landward) edge and flattens out to the northeast, forming an asymmetric scarp-like geometry. In addition to the regional extent of the surface and the pronounced truncation of underlying markers, BD-1 also reflects incision into underlying offshore and shelf mudstones. It is unlikely that these basinal facies could have been eroded solely by ravinement following progradational regression, because they would lie *below* a cover of offshore regressional facies. Furthermore, during subsequent transgression, any ravinement surface generated would necessarily lie above these facies, because fair-weather wave base would rise in relation to the magnitude of relative sea-level rise. Therefore, relative sea level must have fallen, shifting the shoreline past Joffre *prior to transgression*, in order to bring these basinal facies into a position where they could be transgressively ravined.

In proximal (southwestern) positions, the surface is locally overlain by a chert pebble lag or by muddy sandstone containing dispersed chert pebbles and granules (Fig. 5A). In distal (northeast) positions, BD-1 remains erosional, although it commonly lacks a discrete pebble lag (Fig. 5B). Overlying mudstone facies display a marked increase in the grain size of dispersed sand and locally contain dispersed chert granules and pebbles as well. In both proximal and distal positions, the surface is marked by the *Glossifungites* ichnofacies. The dominant ichnogenus is firmground *Thalassinoides*, with rarer *Diplocraterion habichi* and *Skolithos.*

The *Glossifungites* ichnofacies is a substrate-controlled 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 original resident softground trace-fossil communities and are generally passively infilled with sediment overlying the discontinuity.

Although 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. (1992b), Pemberton et al. (1992), and Pemberton and MacEachern (1995), misunderstanding as to its application to sequence stratigraphy persists in the literature. *Specifically, the Glossifungites assemblage is not restricted to sequence boundaries.*

The salient elements of the *Glossifungites* ichnofacies are as follows: (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 the eroding event and subsequent deposition. The exhumed substrate must be exposed at the sediment–water interface to permit colonization, and therefore the erosional event responsible for its exhumation cannot be directly responsible for deposition immediately overlying it. Discontinuity surfaces of autocyclic and allocyclic origin may be colonized by tracemakers of the *Glossifungites* assemblage, although those of the latter are more common. Consequently, surfaces of lowstand origin, transgressive origin, and composite origin can be demarcated by a *Glossifungites* suite (MacEachern et al. 1992a; MacEachern et al. 1992b; Pemberton and MacEachern 1995; MacEachern et al. 1998).

Facies Succession of Sequence 2

Sequence 2 consists of three facies, constituting an overall upward coarsening succession (Figs. 3, 6). Complete facies successions lie in basinward positions and consist of a thin granule to pebble lag mantling the discon-

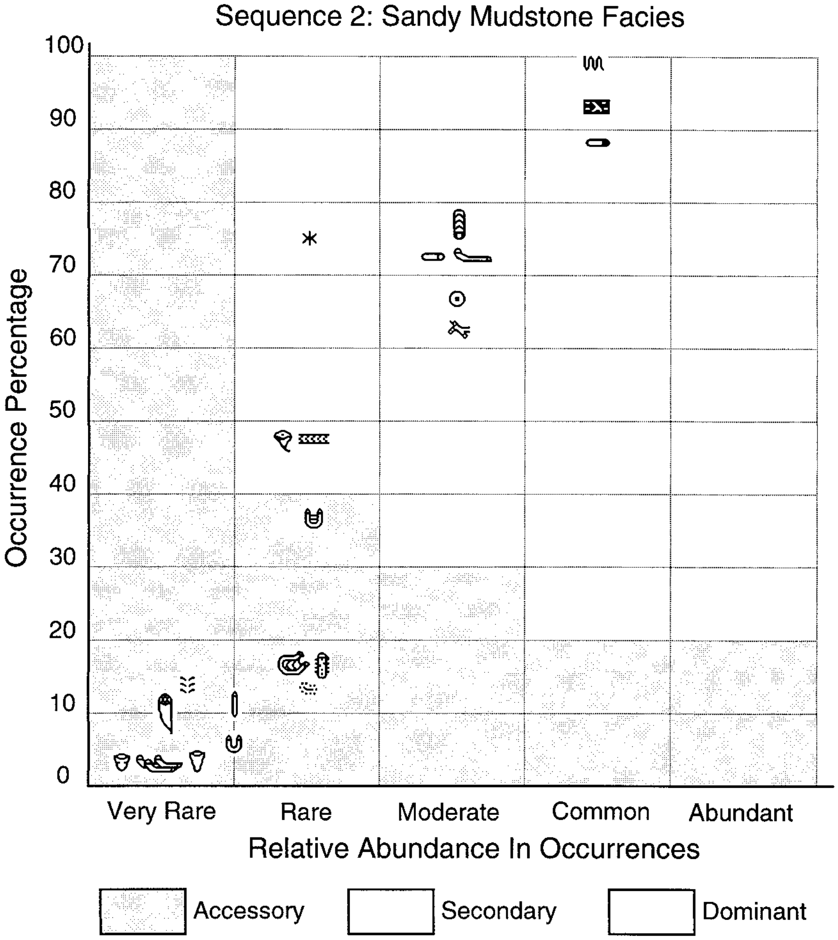

FIG. 8.—Ichnological cross-plot, showing ichnogenera occurrence percentage vs. abundance percentage for sandy mudstone facies of Sequence 2. The assemblage is based on the analysis of 29 intervals. See Figure 3 for legend of symbols.

tinuity, grading upward into gritty sandy mudstone, through muddy sandstone, and into interstratified low-angle, undulatory parallel-laminated sandstone and burrowed sandstone. In proximal positions, the succession is attenuated and muddy sandstone or laminated-to-burrowed sandstone may directly overlie the discontinuity. Toward the north (e.g., 07-26-38-26W4) where preservation of the sequence is generally more complete, the succession passes through a zone where it becomes muddier upward, before resuming its coarsening-upward character (Fig. 6). In many localities, one or two white bentonite horizons are intercalated. Locally one of the beds reaches 12 cm in thickness, and occupies a position below the muddy pause in the coarsening cycle. Preservation of the bentonite layers appears to be limited to the gritty sandy mudstone facies and therefore they are ineffective as a stratigraphic datums.

The chert granule to pebble lag deposits capping the discontinuity are typically thin (1.0–10.0 cm), contain sideritized mudstone intraclasts, and are structureless. The gritty sandy mudstone (Fig. 7) near the base of the succession contain locally abundant, dispersed chert pebbles and granules, as well as dispersed upper fine to lower very coarse chert and quartz sand grains. Discontinuous, 0.5–2.0 cm thick lenses of sharp-based, undulatory, parallel-laminated to oscillation-rippled, fine-grained sandstone are intercalated. Carbonaceous detritus is dispersed throughout the facies. Dispersed grains of glaucony are locally present. The facies is moderately to thoroughly burrowed with a diverse, uniformly distributed trace-fossil assemblage consisting of *Helminthopsis, Chondrites, Zoophycos, Anconichnus, Terebellina, Planolites, Asterosoma, Thalassinoides,* and *Teichichnus*, with rare *Rosselia, Cylindrichnus, Schaubcylindrichnus, Palaeophycus, Skolithos, Siphonichnus, Rhizocorallium,* and *Diplocraterion* (Fig. 8). The trace-fossil suite corresponds to the fully marine, archetypal *Cruziana* ichnofacies.

This facies grades upward into a bioturbated, upper fine- to upper medium-grained muddy sandstone facies (Fig. 9). Dispersed chert granules and rarer pebbles are dispersed throughout the facies, and may be present as thin pebble stringers as well. Carbonaceous detritus and glaucony are present in some intervals. Sharp-based, low-angle, undulatory, parallel-laminated, fine-grained sandstone beds, 1.0–5.0 cm thick, are locally intercalated, but are uncommon and typically biogenically disrupted. This lamination is interpreted to reflect hummocky cross-stratification (HCS). The bulk of the facies is intensely bioturbated with a diverse and uniformly distributed trace-fossil assemblage. Ichnogenera include *Asterosoma, Teichichnus, Rosselia, Palaeophycus, Schaubcylindrichnus, Skolithos, Siphonichnus, Rhizocorallium, Ophiomorpha, Arenicolites, Terebellina, Planolites, Diplocraterion, Helminthopsis, Chondrites, Cylindrichnus, Thalassinoides,* and *Zoophycos* (Fig. 10). The assemblage represents an open marine, proximal *Cruziana* suite.

Towards the southwestern part of the study area, the bioturbated muddy sandstone facies grades upward into a laminated-to-burrowed, upper fine- to upper medium-grained sandstone facies (Fig. 11). Chert pebbles and granules are rare, but are locally dispersed throughout the facies. The facies comprises a composite bedset consisting of sharp-based, low-angle, undulatory, parallel-laminated sandstone beds that grade into moderately burrowed muddy sandstone beds. Laminated beds are typically 2.0–11.0 cm in thickness, separated by burrowed beds 1.5–5.0 cm thick. The lamination

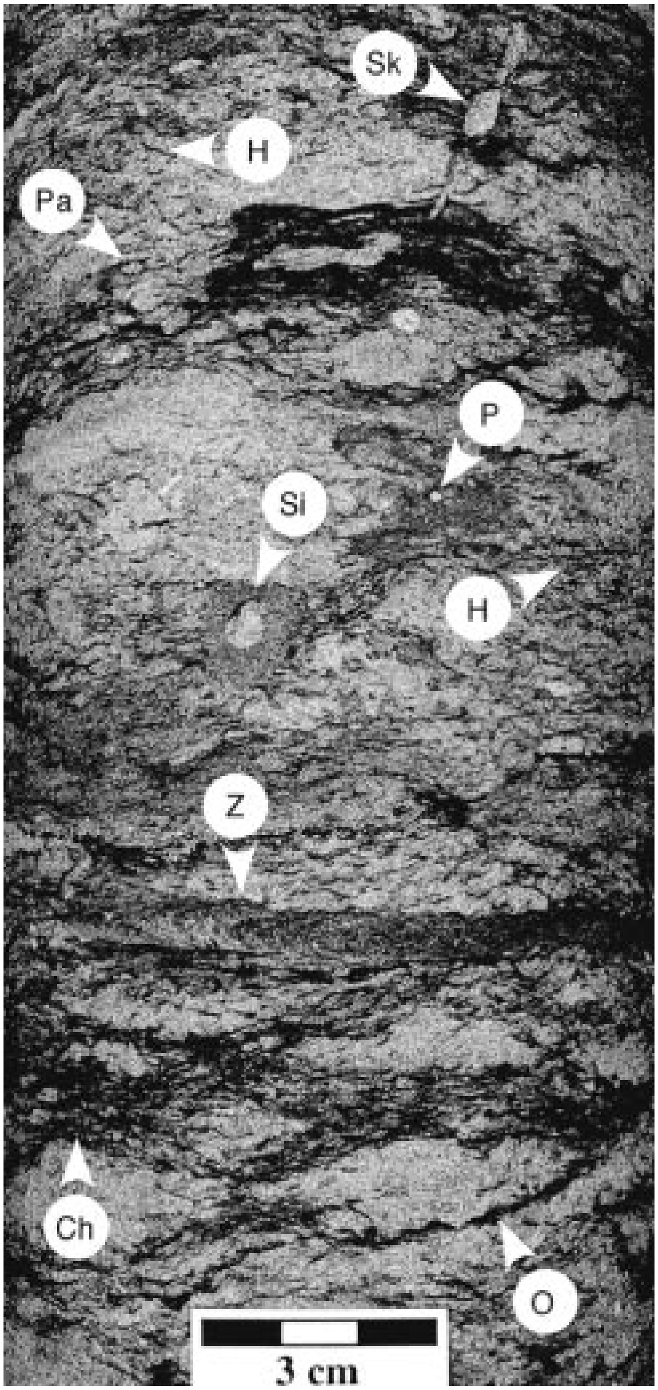

FIG. 9.—Photo of the muddy sandstone facies, thoroughly bioturbated with *Zoophycos* (Z), *Helminthopsis* (H), *Chondrites* (Ch), *Planolites* (P), *Siphonichnus* (Si), *Ophiomorpha* (O), *Palaeophycus* (Pa), and *Skolithos* (Sk), reflecting an open-marine proximal *Cruziana* assemblage. Well 16-02-38-26W4; 1513.4 m.

is interpreted to reflect HCS. The thin-bedded character of the beds is consistent with either distally generated tempestites or deposition in response to weak storms. The HCS sandstone beds contain fugichnia, *Diplocraterion*, *Skolithos*, and *Ophiomorpha.* The intervening burrowed sandstone beds display a trace-fossil suite comprising *Asterosoma, Teichichnus, Rosselia*, *Palaeophycus*, *Schaubcylindrichnus*, *Skolithos*, *Siphonichnus*, *Ophiomorpha*, *Arenicolites*, *Terebellina*, *Planolites*, *Diplocraterion*, *Helminthopsis*, *Chondrites*, and *Cylindrichnus*, with rare to very rare *Rhizocorallium*, *Zoophycos*, and *Thalassinoides* (Fig. 12). The facies shows partial segregation of trace-fossil communities into vertical escape and dwelling structures associated with the HCS beds, and mixed inclined/horizontal deposit feeding/carnivore structures and vertical dwelling structures associated with the alternating muddy sandstone beds. This constitutes a mixed *Skolithos–Cruziana* assemblage (Pemberton and Frey 1984; Pemberton and MacEachern 1997).

Miller (1995) has argued that ''*Terebellina*'' should now be considered *Schaubcylindrichnus freyi.* We suggest that the structure is unique and should be assigned to its own genus. Although the name ''*Terebellina*'' is currently invalid, we employ it here, pending re-evaluation of the genus.

Depositional Interpretation of Sequence 2

The facies succession of Sequence 2 is interpreted to reflect the progradation of a weakly storm-influenced shoreface. This is based on the coarsening-upward character of the succession, the presence of thin, largely nonamalgamated HCS storm beds, and the diverse, uniformly distributed *Cruziana* assemblages (Fig. 13; MacEachern and Pemberton 1992). These shoreface sandstone deposits pass upwards from, and basinwards into, upper-offshore mudstone. This paper employs the terminology of ''upper offshore'' as originally presented by Howard (1971, 1972), Howard and Reineck (1981), Howard and Frey (1984), and Frey (1990), which has subsequently been modified by MacEachern and Pemberton (1992) and Pemberton and MacEachern (1997). In our usage, the upper offshore is regarded to lie below fair-weather wave base but adjacent to (and grading from) the lower shoreface of a prograding shoreline. This proximity to the lower shoreface results in significant amounts of intercalated sand and silt with clay during ambient (non-storm) conditions, generating a sandy mudstone facies. We prefer this terminology to the less appropriate physiographic term ''shelf'', particularly within the Western Interior Seaway, where no shelf break existed.

The granule to pebble layer mantling the transgressively modified sequence boundary (BD-1) corresponds to a ravinement-reworked lag. The *Glossifungites* ichnofacies associated with the discontinuity indicates colonization of the firm substrate during or immediately following transgressive ravinement of the earlier sequence boundary.

The gritty sandy mudstone above the transgressive lag is interpreted to reflect upper-offshore deposition, primarily on the basis of the diverse, fully marine, archetypal *Cruziana* ichnofacies. This is supported by predominantly muddy deposition, reflecting accumulation below fair-weather wave base. Trace fossils are uniformly distributed and bioturbation is of high intensity, attesting to slow, continuous deposition. The intercalated, thin, low-angle undulatory parallel-laminated (HCS) sandstone beds are interpreted to have accumulated below fair-weather wave base and correspond to infrequent, low-energy storm events.

The bioturbated muddy sandstone is interpreted to reflect lower-shoreface deposition. The gradational transition to a sandy substrate marks the encroachment of fair-weather wave base where persistent wave agitation was able to winnow, or to keep suspended above the bed, much of the mud. The paucity of storm beds in this facies demonstrates a weak storm influence on the setting. This is further supported by the diverse, abundant, and uniformly distributed proximal *Cruziana* assemblage, reflecting slow, continuous deposition of sand under conditions of moderate energy (MacEachern and Pemberton 1992; Pemberton and MacEachern 1997). The overlying laminated-to-burrowed sandstone facies corresponds to proximal lower-shoreface conditions. The relative thickening and increased number of HCS storm beds attest to progressive shallowing along the shoreface depositional profile. Fair-weather trace-fossil assemblages preserved between these storm beds reflect the introduction of greater numbers of dwelling structures by suspension-feeding organisms than those of the underlying muddy sandstone deposits, supporting a slightly more proximal depositional position for the laminated-to-burrowed facies (Figs. 12, 13). The escape

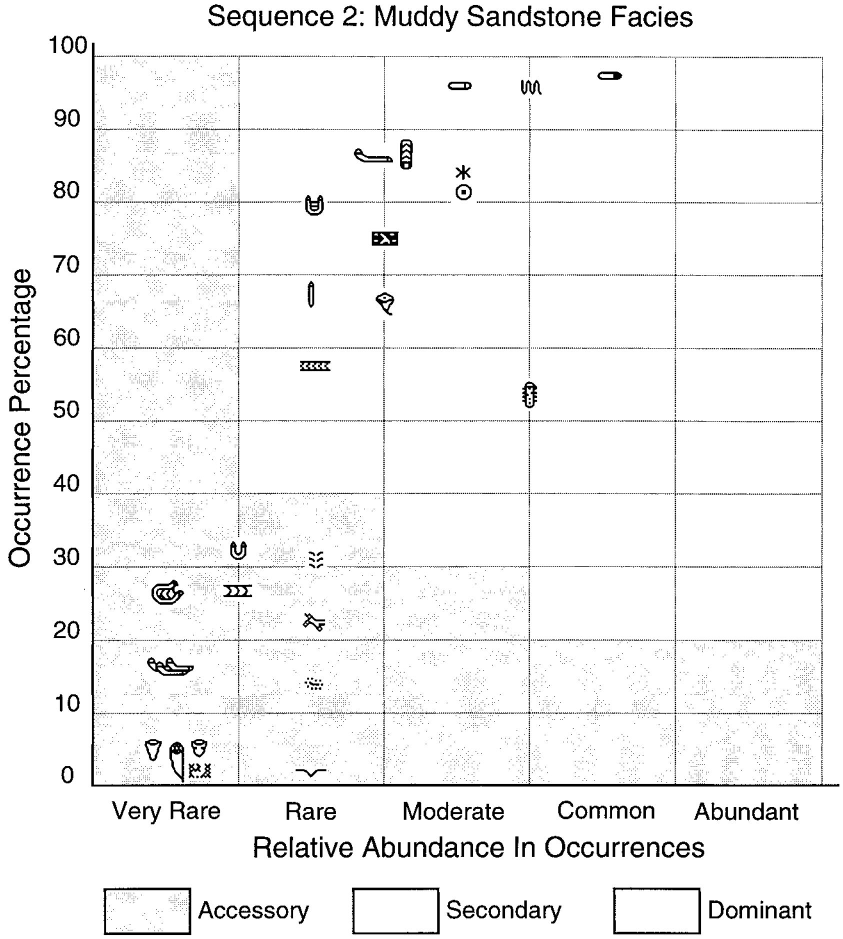

FIG. 10.—Ichnological cross-plot, showing ichnogenera occurrence percentage vs. abundance percentage for muddy sandstone facies of Sequence 2. The assemblage is based on the analysis of 94 intervals. See Figure 3 for legend of symbols.

structures and deeply penetrating dwelling structures within the laminated beds are attributable to event-related behaviours and opportunistic organisms, and are typical of colonization of storm beds (Pemberton and Frey 1984; Pemberton and MacEachern 1997).

Cores in several localities demonstrate that northeastward progradation of the Sequence 2 shoreface was not continuous, but rather experienced a slight landward shift of the shoreline, likely associated with a rise in relative sea level (Fig. 6). In these areas, upper-offshore sandy mudstone passes into lower-shoreface muddy sandstone reflecting initial progradation, but subsequently, this facies grades upward back into the sandy mudstone facies. This demonstrates that upper-offshore conditions were reestablished, probably because of a pause in shoreface progradation and a slight transgression. After this relative deepening event, progradation resumed, marked by a gradational upward transition to lower-shoreface muddy sandstone deposits.

Sequence 2 and the Stratigraphic Interpretation of Sharp-Based Shorefaces

The stratigraphic interpretation of sharp-based shoreface or deltaic sandstone bodies can be problematic. Such deposits have been variably assigned to progradation of late highstand successions (e.g., Van Wagoner 1995), forced regression (falling stage) systems (e.g., Hunt and Tucker 1992; Walker and Bergman 1993; Bergman 1994; Davies and Walker 1993), lowstand systems (e.g., Posamentier et al. 1992; Posamentier and Chamberlain 1993; Mellere and Steel 1995; Walker and Wiseman 1995), and transgressively incised complexes (e.g., Downing and Walker 1988; Raychaudhuri et al. 1992; MacEachern 1994; MacEachern et al. 1998). Despite this, many workers continue to regard sharp-based shoreface sandstone bodies to be exclusively of falling stage or lowstand origin.

From a facies perspective, however, these sharp-based shoreface successions are virtually identical. Their principal difference lies in the nature of the basal contact with the underlying facies. One can make a distinction between forced regressive, lowstand, and transgressive complexes, all that overlie allocyclic discontinuities, and highstand complexes that overlie autocyclic erosional surfaces. In the case of the autocyclic basal surface, recognition may follow a number of avenues, but one of the most obvious is the lack of incision and concomitant truncation of regional markers in the underlying succession. As well, the shoreface deposits show a marked genetic affinity of facies across a boundary that most commonly reflects the erosional base of an individual storm bed. In contrast, those complexes that overlie allocyclic discontinuities are incised into underlying successions, truncate regional markers, and can be regarded as incised shoreface successions. Sequence 2 corresponds to an incised-shoreface complex.

Incised-shoreface units may correspond to forced regressive, lowstand, or transgressively incised systems (Fig. 14). The forced-regressive shoreface overlies a regressive surface of erosion cut by wave action during the falling stage of relative sea level. Likewise, the lowstand shoreline overlies the marine part of the sequence boundary, also cut by wave erosion. The transgressively incised shoreface, however, overlies a wave ravinement surface, cut during rise of relative sea level. The succession reflects a period of shoreline progradation during overall transgression, when sediment supply outpaced relative rise of sea level. Differentiation between these incised complexes is difficult but can be achieved through careful documentation of the erosional extent of the basal discontinuity.

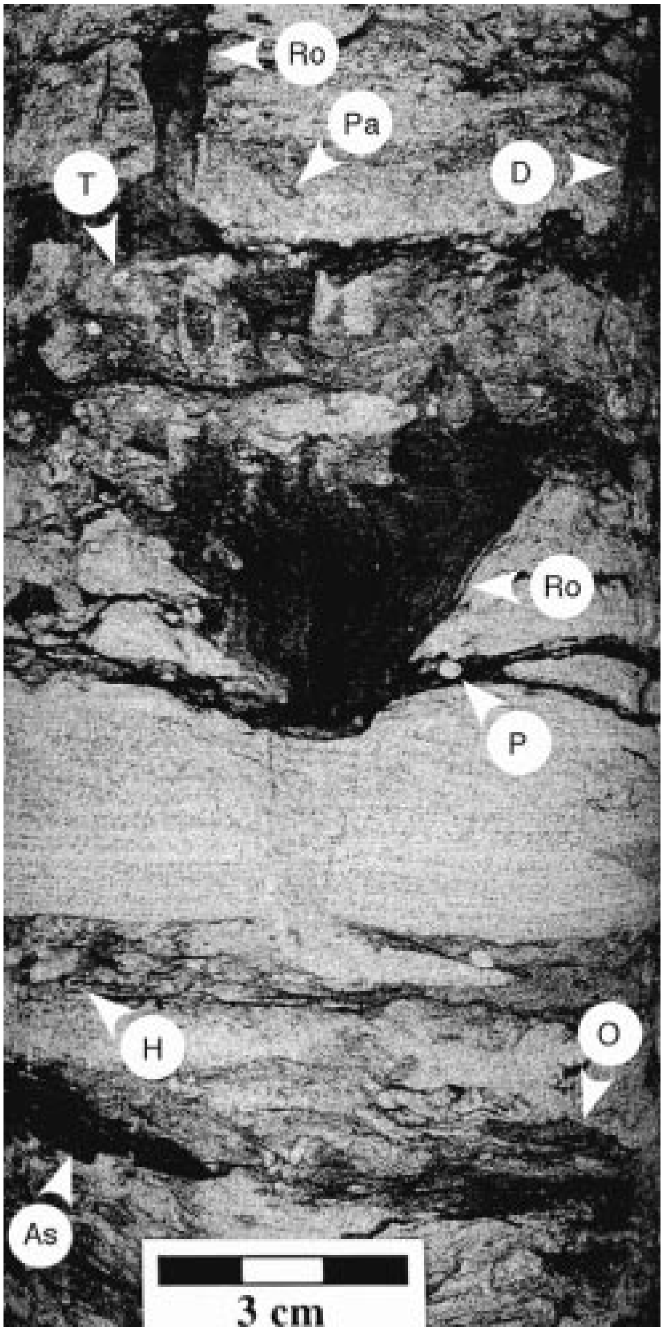

FIG. 11.—Photo of the laminated-to-burrowed sandstone facies, sporadically burrowed with *Rosselia* (Ro), *Planolites* (P), *Terebellina* (T), *Palaeophycus* (Pa), *Ophiomorpha* (O), *Asterosoma* (As), and minor *Helminthopsis* (H), reflecting an open-marine, mixed *Skolithos–Cruziana* assemblage. Well 04-03-38-25W4, 1431.8 m.

Forced Regressive and Lowstand Shorefaces

There has been considerable discussion and debate regarding the validity of differentiating lowstand from forced-regression deposits (e.g., Hunt and Tucker 1992, 1995; Kolla et al. 1995). The work of Helland-Hansen and Gjelberg (1994) and Mellere and Steel (1995), however, illustrate the utility of discriminating falling-stage systems tracts associated with forced regression from the final lowstand shoreline corresponding to maximum fall of sea level, but prior to transgression. A forced-regressive or falling-stage origin has been proposed for sharp-based sandstone bodies of the Viking Formation in the Garrington field (Davies and Walker 1993) and Kaybob field (MacEachern 1994; Pemberton and MacEachern 1995). Posamentier et al. (1992) and Posamentier and Chamberlain (1993) interpreted sharp-based sandstone deposits at Joarcam to reflect a lowstand-shoreface deposit. Lowstand-shoreface deposits have also been interpreted in the Lindbrook and Beaverhill Lake fields (Walker and Wiseman 1995), although their figure 6 suggests that the ''Lindbrook a'' deposit might better be regarded as a falling-stage shoreface, given that the ''Lindbrook b'' shoreface lies farther basinward and likewise overlies a regressive surface of erosion.

Forced-regressive shoreface and/or deltaic deposits overlie regressive surfaces of erosion (RSE). These surfaces are cut in submarine conditions and pass basinward into conformable surfaces analogous to correlative conformities (Fig. 14). The RSE are cut by wave erosion as relative sea level falls, bringing more basinal facies into the zone of wave attack. Continued sea-level fall results in the subaerial exposure of the falling-stage shorefaces, and their subsequent cannibalization by later regressive surfaces of erosion and ultimately the sequence boundary. The preservation potential of these deposits is considerably less than that of the lowstand shoreface, and the correlative conformities of the RSE are, in particular, unlikely to be preserved in the rock record. Kolla et al. (1995) regard the RSE that bound falling-stage deposits merely as higher-order sequence boundaries reflecting incremental rather than continuous fall of relative sea level.

Lowstand shorefaces directly overlie sequence boundaries, and basinwards, the correlative conformities (Plint et al. 1988; Posamentier et al. 1992). Landward of the shoreface, the sequence boundaries are cut by subaerial erosion. At the base of the shoreface, however, sequence boundaries are cut within a marine setting and therefore favor colonization by substrate-controlled assemblages such as the *Glossifungites* ichnofacies. Posamentier et al. (1992) imply with their figure 14 that the submarine component of the erosional discontinuity is properly part of the correlative conformity, holding with the mainstream sequence stratigraphic view that the unconformable part of the sequence boundary must be a subaerial surface. This seems unreasonable, because in many instances truncation of underlying markers occurs in this position, and demonstrates an unconformable rather than conformable relationship (e.g., Plint et al. 1986; Plint 1988; Walker and Wiseman 1995). The correlative conformity is more appropriately restricted to the depositional (non-erosional) surface lying basinward of the unconformity.

In storm-dominated systems, the extent of the allocyclically generated submarine component of the RSE or sequence boundary may be masked by synsedimentary storm erosion surfaces and appear to extend to storm-weather wave base. This would result in development of a series of vertically stacked and offlapping smaller-scale autocyclic surfaces rather than a single allocyclic surface, but recognition of this condition may be problematic unless outcrop exposure is exceptional. In the subsurface, identification of this would be extremely difficult. These autocyclic surfaces are rapidly buried under tempestites, however, and therefore not colonized by *Glossifungites* assemblages.

In weakly storm-influenced settings, however, the erosional component of the sequence boundary is unlikely to persist basinward of fair-weather wave base, and therefore defines a sharp base to the lower shoreface. Basinwards of this position, finer-grained offshore deposits occur above the correlative conformity and during progradation grade upwards into lower-shoreface muddy sandstones (Fig. 14). As a result, the *Glossifungites* ichnofacies will not occur in positions below fair-weather wave base. In these basinal positions, coarse-grained lag deposits are likely to be absent as well. The correlative conformity may, however, represent a sharp facies contact, marked by an abrupt change in proximality of facies, grain size, and trace-fossil assemblage (Fig. 15).

Both forced-regressive and lowstand shoreface and delta deposits tend to be fairly thin. This is believed to be largely a function of diminished accommodation space (Plint 1988; Posamentier et al. 1992; Van Wagoner

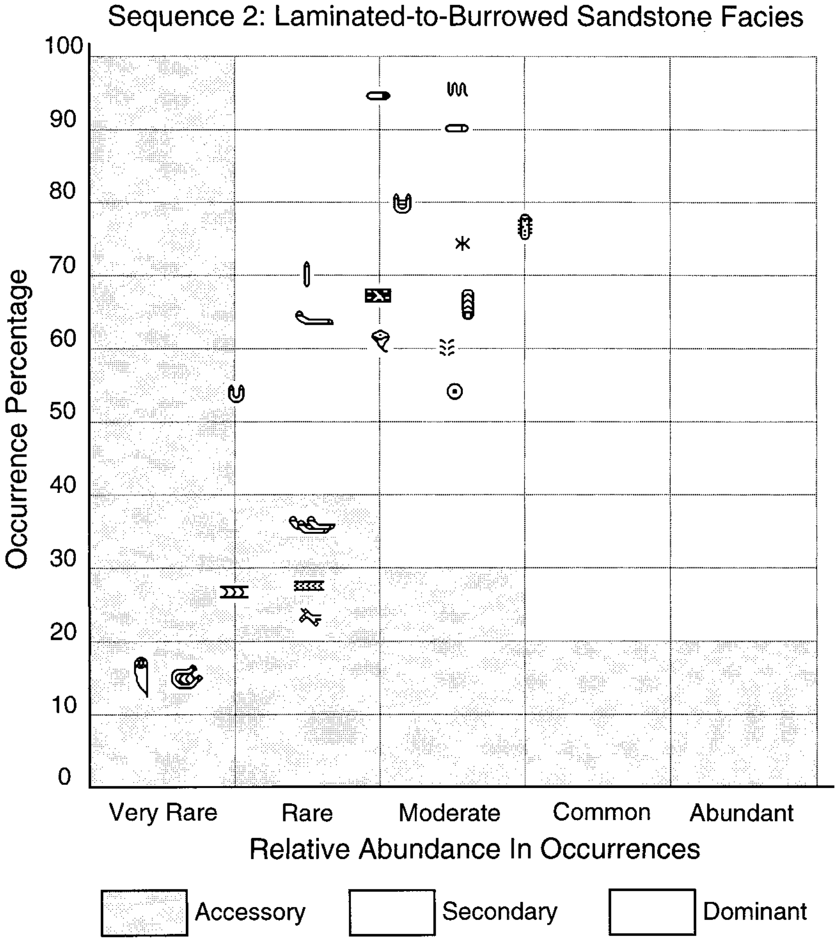

FIG. 12.—Ichnological cross-plot, showing ichnogenera occurrence percentage vs. abundance percentage for laminated-to-burrowed sandstone facies of Sequence 2. The assemblage is based on the analysis of nine intervals. See Figure 3 for legend of symbols.

1995). Walker and Wiseman (1995) have suggested that the damping of wave energy across broad shallow platforms lying outboard of the shoreface contributes to this, because it inhibits incision into the underlying firmly compacted mud. As a result, facies tracts within these shoreface types may be attenuated or even absent. Both successions tend to be relatively coarse grained and are commonly capped by transgressive deposits (Posamentier et al. 1992; Walker and Wiseman 1995). Sandbody widths and width/thickness ratios have also received some consideration as a means of discriminating between these systems, but because of the effects of such controls as variations in sediment supply, rate of change of accommodation space, basin gradient, and duration of shoreline progradation, caution must clearly be exercised.

The regional stratigraphic context of the sharp-based shoreface and/or delta deposits has principally been used as a basis for sequence stratigraphic interpretation, in our estimation. Ainsworth and Pattison (1994) have discussed the problem of attached versus detached lowstand complexes, highlighting some of the difficulties in differentiating between the two scenarios. Falling-stage interpretations are most commonly based on the presence of additional incised shoreface and/or delta deposits lying basinward of them *within the same sequence.* Lowstand deposits, on the other hand, tend to be recognized mainly on the basis of the absence of such shorefaces. Given that such deposits may be detached and lying considerably basinward, the sequence stratigraphic interpretation of such deposits may, in some cases, be highly suspect. Walker and Wiseman (1995) have conceded this uncertainty with respect to the Lindbrook shorefaces.

Both complexes are typically sharp-based in proximal positions and gradationally based in basinal positions. Consequently, only the lower-shoreface, middle-shoreface, and upper-shoreface deposits overlie the *erosional expression* of the sequence boundary or the RSE, and may be demarcated by the *Glossifungites* ichnofacies. Landward, a ravinement surface may become amalgamated with the sequence boundary and RSE during the ensuing transgression (Fig. 14; e.g., Plint et al. 1986; Plint 1988; Pemberton and MacEachern 1995). We suggest that the correlative conformity of the RSE has an exceedingly low preservation potential in falling-stage deposits, in contrast to that of lowstand-shoreface deposits. The forced-regressive deposits are subjected to subsequent erosion and subaerial exposure during continued fall of relative sea level, as well as the potential of transgressive ravinement during ensuing rise of relative sea level (Fig. 14). The lowstand deposits, on the other hand, are produced at the lowest position of relative sea-level fall, and are unlikely to be subsequently ravined, because water depths are increased and fair-weather wave base shifted landward during later transgression. The presence of a correlative conformity might be taken as a significant support for a lowstand interpretation of a deposit.

Transgressively Incised Shorefaces

Several Viking Formation oil and gas fields in central Alberta produce hydrocarbons from NW–SE-trending, sharp-based shoreface sandstones interpreted to rest upon transgressive surfaces of erosion incised into underlying facies; these include Chigwell (Raychaudhuri et al. 1992), Joffre (Downing and Walker 1988; MacEachern et al. 1995, MacEachern et al. 1998), Gilby (Raddysh 1988), and Giroux Lake (MacEachern 1994). These successions can be regarded as high-energy parasequences bounded by ravinement surfaces.

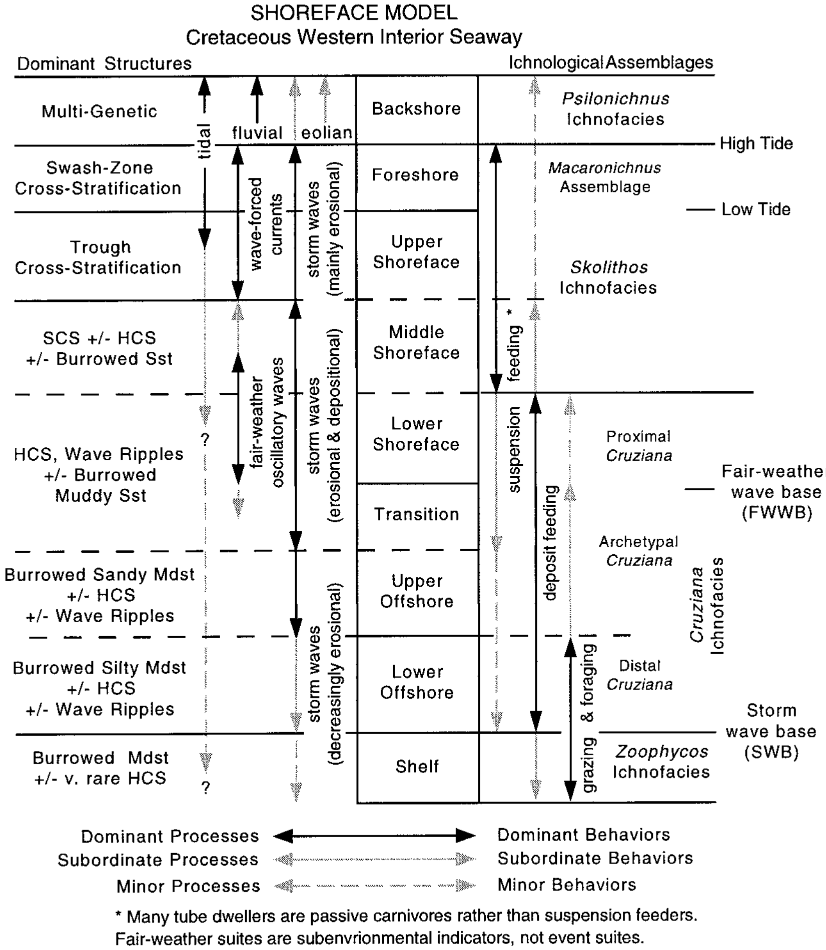

FIG. 13.—An ichnological–sedimentological model for sandstone-dominated shoreface deposits of the Cretaceous Western Interior Seaway (modified after MacEachern and Pemberton 1992).

Analysis of transgressive surfaces of erosion has had a relatively long history since Stamp (1921) originally defined the term ''ravinement''. A number of landmark papers have discussed the characteristics and implications of ravinement surfaces, particularly with respect to their processes of formation, their depths of incision, the interplay of rate of sea-level rise with preexisting topography and shoreface depth on the preservation potential of coastal-plain deposits, surface diachroneity, and associated facies (e.g., Fischer 1961; Swift 1968; Belknap and Kraft 1981, 1985; Pilkey et al. 1981; Nummedal and Swift 1987). MacEachern et al. (1992a) discussed the ichnological suites associated with ravinement surfaces and their associated facies.

Although transgressively incised shorefaces tend to display thicker successions than do falling-stage systems, reflecting the increased accommodation space available, the ''transgressive'' interpretation has rested mainly with the perceived position of the deposits in the regional stratigraphic framework rather than with any intrinsic characteristics of the succession itself. For example, Posamentier et al. (1992) and Posamentier and Chamberlain (1993) interpreted the Joarcam deposit as a lowstand shoreface. Walker and Wiseman (1995), however, reinterpreted it as a *transgressive shoreface*, primarily on the basis of the observation of underlying and basinward shoreface deposits at Lindbrook, which they regarded as lowstand in origin. Furthermore, despite the Lindbrook deposits being given a lowstand interpretation, Walker and Wiseman (1995) indicated that should an additional shoreface deposit within their sequence 1 be discovered farther to the northeast, the ''incision at Lindbrook a would then represent a transgressive incision formed during southwestward movement of the shoreline'' (p. 136).

We suggest that this uncertainty can be alleviated somewhat through careful study of the erosional extent of the basal discontinuity. In the transgressive scenario, lower- and upper-offshore deposits, reflecting deposition below fair-weather wave base, can overlie the erosional component of the basal discontinuity. Transgressive ravinement forms an erosional discontinuity that ultimately can lie seaward of fair-weather wave base during subsequent progradation. This is because the erosional surface is cut prior to shoreface progradation while sea level is considerably lower (Fig. 14). Walker and Wiseman (1995) noted that an erosional surface always underlies the offshore transition mudstone in such settings, though the implication of that observation was not made clear. Furthermore, because *Glossifungites* assemblages commonly demarcate transgressive surfaces of erosion (MacEachern et al. 1992a; MacEachern et al. 1992b), they can be formed in positions where the overlying facies reflect deposition well below fair-weather wave base (Fig. 5B), in marked contrast to either forced-regression or lowstand systems. A coarse-grained lag is also likely to be associated with the transgressive discontinuity in these basinal positions, unlike the lowstand scenario. These ravinement surfaces ultimately pass seaward into non-erosional marine flooding surfaces (Fig. 14).

Sequence 2 of the Viking Formation at Joffre possesses features that are most consistent with a transgressively incised 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 (offshore sandy mudstones; Fig. 5B), is inconsistent with a forced-regression or lowstand model, and possibly the best indication of a transgressive origin. The presence of a *Glossifungites* assemblage associated with the basinal expression of this erosion surface attests to its transgressive origin. In the forced-

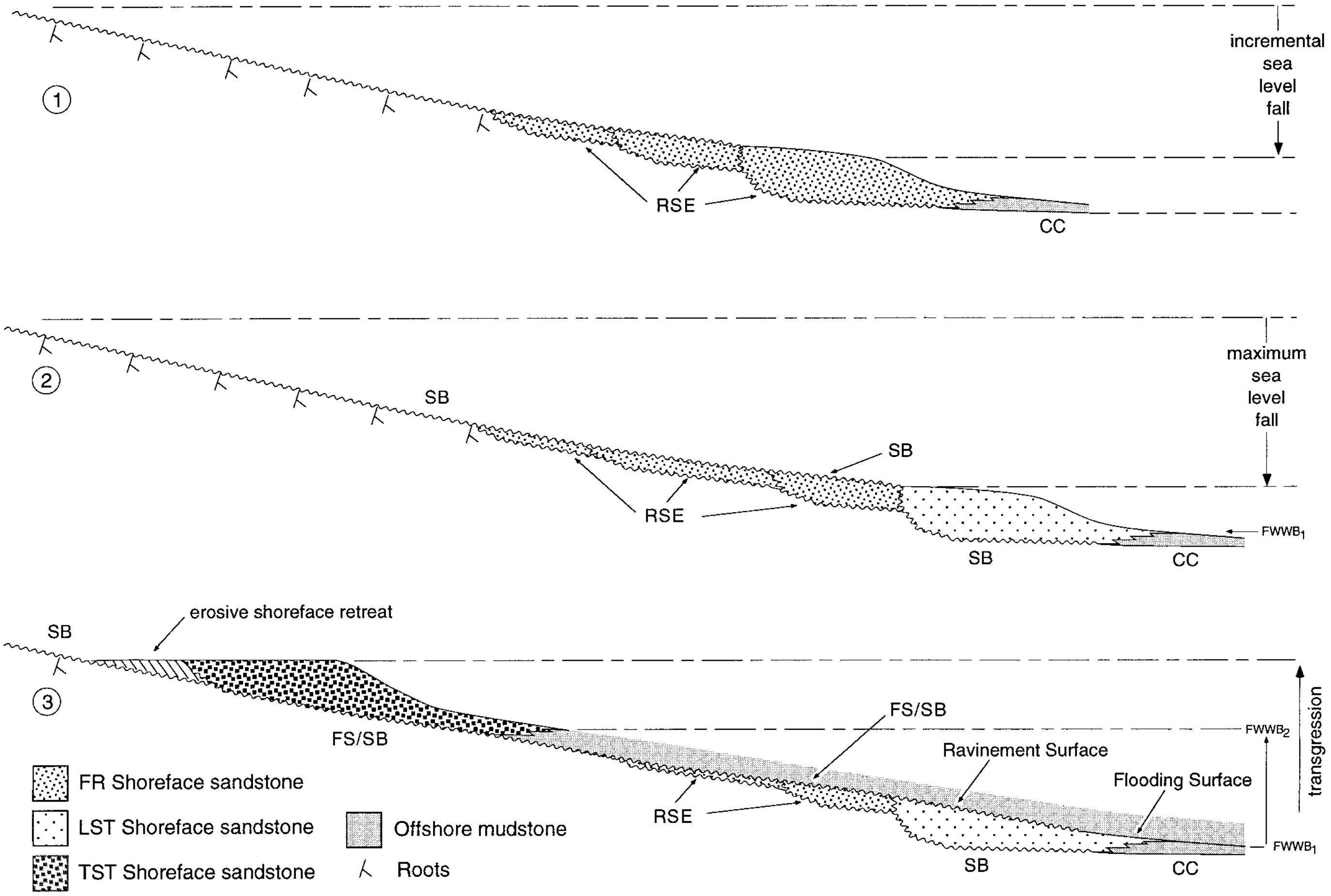

FIG. 14.—Differentiation of forced-regressive, lowstand, and transgressively incised shoreface complexes. Sharp-based, discontinuity-bounded (incised) shoreface successions can be ascribed to one of three main sequence stratigraphic settings. Model 1 reflects forced regression (falling stage) reflecting initial incremental fall of relative sea level and the development of a shoreface resting on an RSE. Model 2 shows the development of the lowstand shoreface, which reflects the most seaward position of the shoreline associated with the lowest position of sea level. Note that the erosional component of the sequence boundary extends only as far seaward as fair-weather wave base (FWWB), where it passes into a correlative conformity. In model 3, rise of relative sea level generates a low-energy flooding surface in basinal positions that passes landward into a transgressive ravinement surface as it floods across the lowstand and forced-regressive shorefaces. During a pause in transgression, shoreface progradation occurs, producing a transgressively incised shoreface. Note that offshore mudstone can overlie the enclosed portion of the discontinuity.

regression or lowstand scenario, the RSE or sequence boundary, respectively, would pass into a (non-erosional) correlative conformity seaward of fair-weather wave base and lack a *Glossifungites* suite.

Another support for a transgressive origin for Sequence 2 is related to the internal facies variations within the vertical succession. The upward transition from lower-shoreface to upper-offshore deposits indicates a pulse of transgression during the progradational history of the Sequence 2 shoreface (Fig. 6). Forced-regressive bodies consist of only a single parasequence, whereas Sequence 2 consists of two. A lowstand shoreface may, however, consist of more than one parasequence if it is associated with the earliest stages of rise of relative sea level. Nonetheless, we believe that this deepening cycle is easier to reconcile with a pause in progradation during an overall transgression than to a pulse of transgression associated with the falling stage of relative sea level.

CONCLUSIONS

1. The Viking Formation of the Joffre Field comprises parts of three discrete sequences. Sequence 2 overlies an erosional discontinuity, termed BD-1, which is incised into underlying marine parasequences of the informally named ''Regional Viking''. The surface represents a sequence boundary that was transgressively modified during subsequent relative sea-level rise, and is commonly demarcated by the *Glossifungites* ichnofacies. Up to three regionally extensive marine parasequences are truncated by BD-1.

2. Sequence 2 comprises an incised sandstone body passing basinwards into granule- to pebble-bearing sandy mudstone. A complete facies succession consists of a thin granule to pebble lag mantling BD-1, grading upward into gritty sandy mudstone, through muddy sandstone, and into interstratified HCS sandstone and burrowed sandstone. In proximal positions, muddy sandstone or laminated-to-burrowed sandstone deposits directly overlie BD-1. The facies contain diverse and uniformly distributed, open-marine trace-fossil suites displaying an upward progression from archetypal *Cruziana* through proximal *Cruziana* and into mixed *Skolithos*–*Cruziana* assemblages. The interval is interpreted to reflect a weakly storm-influenced upper-offshore to proximal lower-shoreface succession.

3. Sharp-based marine shoreface sandbodies variably reflect progradation of late highstand successions (typically strongly storm-dominated), falling stage (forced regressive systems), lowstand-incised complexes, and transgressively incised systems. The first corresponds to autocyclic progradation, whereas the latter three are allocyclic, incised into underlying facies, and bounded by sequence-stratigraphically important discontinuities. In the case of the incised-shoreface scenarios, the sandbody is genetically unrelated to the underlying facies.

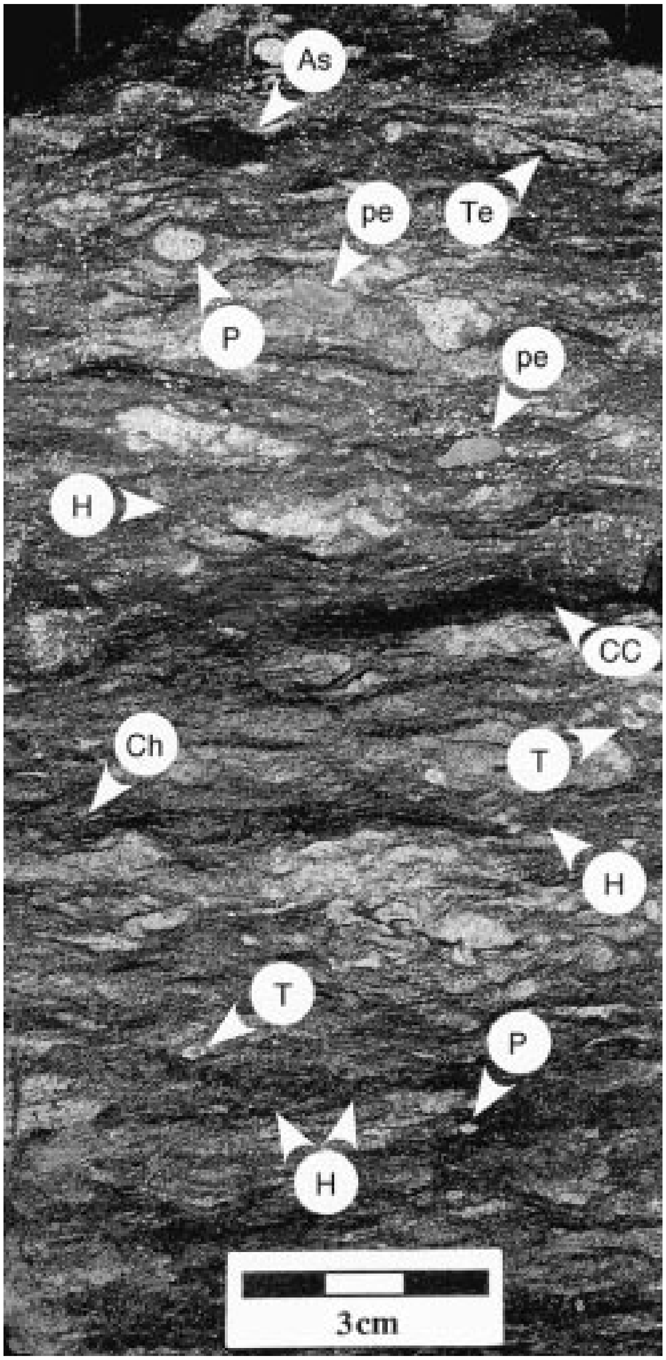

FIG. 15.—Photo of a correlative conformity (CC) from the Viking Formation of the Judy Creek field, separating finer-grained sandy mudstone below from pebble-bearing (pe), coarser-grained sandy mudstone above. Both facies contain an open-marine, archetypal *Cruziana* assemblage with *Helminthopsis* (H), *Chondrites* (Ch), *Terebellina* (T), *Planolites* (P), *Asterosoma* (As), and *Teichichnus* (Te), interpreted to reflect an upper-offshore environment. Well 10-35-64-13W5; 1483.0 m.

4. These incised complexes correspond to very different sequence-stratigraphic scenarios. Forced-regressive shorefaces overlie regressive surfaces of erosion (RSE), whereas lowstand shorefaces directly overlie sequence boundaries. Transgressively incised shorefaces directly overlie ravinement surfaces that either lie a very short stratigraphic distance from the sequence boundaries or represent transgressively modified sequence boundaries. Differentiating between these incised shorefaces in the rock record, however, can be problematic. In the Viking Formation, the three discontinuity types are locally mantled with chert granules and small pebbles. The erosional parts of the discontinuities can also contain elements of the *Glossifungites* ichnofacies. Furthermore, the facies reflecting the various subenvironments of the incised-shoreface types appear indistinguishable from one another.

5. Discrimination between the three possible sequence stratigraphic scenarios can be aided, in part, by the relationship of the facies with the underlying erosional discontinuity and its correlative (depositional) surface.

6. The forced-regression (falling stage) and lowstand scenarios are broadly similar; the RSE is analogous to the sequence boundary in that the submarine component underlying the shoreface is cut by wave erosion and extends only as far seaward as fair-weather wave base in weakly storm-influenced systems. As a result, the RSE and the submarine part of the sequence boundary may be colonized by tracemakers of the *Glossifungites* ichnofacies. Seaward of these positions, the RSE and sequence boundary become (non-erosional) correlative conformities. As a result, a *Glossifungites* assemblage would not be expected to develop in positions where overlying facies indicate deposition *below* fair-weather wave base. Coarse-grained lag deposits are expected to be absent in these positions as well. Lowstand incised shorefaces may be unique in preserving the correlative conformity seaward of the erosional component of the sequence boundary. Forced-regressive systems are likely to have their correlative conformity removed during continued fall of relative sea level and/or subsequent transgressive ravinement.

In storm-dominated systems, the submarine component of the sequence boundary may become masked or removed by syndepositional storm-erosion surfaces, and appear to extend to storm-weather wave base. Although in reality this would consist of a series of smaller-scale vertically stacked and offlapping autocyclic surfaces rather than a single allocyclic surface, determining this condition may be difficult, particularly in the subsurface. These autocyclic surfaces are rapidly buried under tempestites and therefore not colonized by *Glossifungites* assemblages.

7. In the scenario of a transgressively incised shoreface, however, ravinement permits the generation of an erosional discontinuity that will ultimately lie seaward of fair-weather wave base during subsequent progradation. This is because the discontinuity is cut prior to shoreface progradation while sea level is considerably lower. A *Glossifungites* assemblage is therefore likely to demarcate the ravinement surface or a transgressively modified sequence boundary, even in positions where overlying facies reflect deposition well *below* fair-weather wave base. On this basis, the coarsening-upward marine succession of Sequence 2 at Joffre is interpreted to reflect a transgressively incised shoreface complex.

ACKNOWLEDGMENTS

This paper derives from a postdoctoral project undertaken by the first author in collaboration with the other authors. The project was funded by a Natural Sciences and Engineering Research Council (NSERC) Collaborative Research and Development (CRD) Grant 180563 awarded to S.G. Pemberton, as well as by a NSERC Operating Grant 184293 awarded to J.A. MacEachern. The data were collected while the first author was engaged at PanCanadian Petroleum Ltd. The authors thank PanCanadian Petroleum Ltd. for their financial and logistical support throughout the course of this study. Thorough review by Ron Steel, Paul Myrow, and Diane Kamola greatly improved this paper, and we gratefully acknowledge their efforts.

REFERENCES

AINSWORTH, R.B., AND PATTISON, S.A.J., 1994, Where have all the lowstands gone? Evidence for attached lowstand systems tracts in the Western Interior of North America: Geology, v. 22, p. 415–418.

BELKNAP, D.F., AND KRAFT, J.C., 1981, Preservation potential of transgressive coastal lithosomes on the U.S. Atlantic shelf: Marine Geology, v. 42, p. 429–442.

BELKNAP, D.F., AND KRAFT, J.C., 1985, Influence of antecedent geology on stratigraphic preservation potential and evolution of Delaware's barrier systems: Marine Geology, v. 63, p. 235–262.

BERGMAN, K.M., 1994, Shannon Sandstone in Hartzog Draw–Heldt Draw fields reinterpreted as detached lowstand shoreface deposits: Journal of Sedimentary Research, v. B64, p. 184–201.

Bloch, J., Schröder-Adams, C., Leckie, D.A., McIntyre, D.J., Craig, J., and Staniland, M., 1993, Revised stratigraphy of the lower Colorado Group (Albian to Turonian), Western Canada: Bulletin of Canadian Petroleum Geology, v. 41, p. 325–348.

Boreen, T., and Walker, R.G., 1991, Definition of allomembers and their facies assemblages in the Viking Formation, Willesden Green area, Alberta: Bulletin of Canadian Petroleum Geology, v. 39, p. 123–144.

Burton, J.A., and Walker, R.G., in press, Linear, transgressive shoreface sandbodies controlled by fluctuations of relative sea level: Lower Cretaceous Viking Formation in the Joffre–Mickwan–Fenn area, Alberta, Canada, *in* Bergman, K.M., and Snedden, J.W., eds., Isolated Shallow Marine Sand Bodies: Sequence Stratigraphic and Sedimentologic Perspectives: SEPM, Concepts in Sedimentology and Paleontology No. 7.

Caldwell, W.G.E., Diner, R., Eicher, D.L., Fowler, S.P., North, B.R., Stelck, C.R., and von Holdt Wilhelm, L., 1993, Foraminiferal biostratigraphy of Cretaceous marine cyclothems, *in* Caldwell, W.G.E., and Kauffman, E.G., eds., Evolution of the Western Interior Basin: Geological Association of Canada, Special Paper 39, p. 477–520.

Cobban, W.A., and Kennedy, W.J., 1989, The ammonite *Metengonoceras* Hyatt, 1903, from the Mowry Shale (Cretaceous) of Montana and Wyoming: U.S. Geological Survey, Bulletin 1787-L, p. L1–L11.

Davies, S.D., and Walker, R.G., 1993, Reservoir geometry influenced by high frequency forced regressions within an overall transgression; Caroline and Garrington fields, Viking Formation (Lower Cretaceous) Alberta: Bulletin of Canadian Petroleum Geology, v. 41, p. 407–421.

Downing, K.P., 1986, The depositional history of the Lower Cretaceous Viking Formation at Joffre, Alberta, Canada [unpublished Master's thesis]: McMaster University, Hamilton, Ontario, 137 p.

Downing, K.P., and Walker, R.G., 1988, Viking Formation, Joffre Field, Alberta: shoreface origin of long, narrow sand body encased in marine mudstones: American Association of Petroleum Geologists, Bulletin, v. 72, p. 1212–1228.

Fischer, A.G., 1961, Stratigraphic record of transgressive seas in the light of sedimentation on the Atlantic coast of New Jersey: American Association of Petroleum Geologists, Bulletin, v. 45, p. 1656–1666.

Frey, R.W., 1990, Trace fossils and hummocky cross-stratification, Upper Cretaceous of Utah: Palaios, v. 5, p. 203–218.

Glaister, P., 1959, Lower Cretaceous of southern Alberta and adjoining areas: American Association of Petroleum Geologists, Bulletin, v. 43, p. 590–640.

Helland-Hansen, W., and Gjelberg, J.G., 1994, Conceptual basis and variability in sequence stratigraphy: A different perspective: Sedimentary Geology, v. 92, p. 31–52.

Howard, J.D., 1971, Comparison of the beach-to-offshore sequence in modern and ancient sediments, *in* Howard, J.D., Valentine, J.W., and Warme, J.E., eds., Recent Advances in Paleoecology and Ichnology: American Geological Institute, Short Course Lecture Notes, p. 148–183.

Howard, J.D., 1972, Trace fossils as criteria for recognizing shorelines in stratigraphic record, *in* Rigby, J.K., and Hamblin, W.K., eds., Recognition of Ancient Sedimentary Environments: Society of Economic Paleontologists and Mineralogists, Special Publication 16, p. 215–225.

Howard, J.D., and Frey, R.W., 1984, Characteristic trace fossils in nearshore to offshore sequences, Upper Cretaceous of east-central Utah: Canadian Journal of Earth Sciences, v. 21, p. 200–219.

Howard, J.D., and Reineck, H.E., 1981, Depositional facies of a high energy beach-to-offshore sequence: comparison with low-energy sequence: American Association of Petroleum Geologists, Bulletin, v. 65, p. 807–830.

Hunt, D., and Tucker, M.E., 1992, Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall: Sedimentary Geology, v. 81, p. 1–9.

Hunt, D., and Tucker, M.E., 1995, Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall—Reply: Sedimentary Geology, v. 95, p. 147–160.

Kolla, V., Posamentier, H.W., and Eichenseer, H., 1995, Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall—Discussion: Sedimentary Geology, v. 95, p. 139–145.

MacEachern, J.A., 1994, Integrated ichnological–sedimentological models: applications to the sequence stratigraphic and paleoenvironmental interpretation of the Viking and Peace River formations, west-central Alberta [unpublished Ph.D. thesis]: University of Alberta, Edmonton, Alberta, 618 p.

MacEachern, J.A., and Pemberton, S.G., 1992, Ichnological aspects of Cretaceous shoreface successions and shoreface variability in the Western Interior Seaway of North America, *in* Pemberton, S.G., ed., Applications of Ichnology to Petroleum Exploration, A Core Workshop: SEPM, Core Workshop 17, p. 57–84.

MacEachern, J.A., Bechtel, D.J., and Pemberton, S.G., 1992a, Ichnology and sedimentology of transgressive deposits, transgressively-related deposits and transgressive systems tracts in the Viking Formation of Alberta, *in* Pemberton, S.G., ed., Applications of Ichnology to Petroleum Exploration, A Core Workshop: SEPM, Core Workshop 17, p. 251–290.

MacEachern, J.A., Pemberton, S.G., and Zaitlin, B.A., 1995, A late lowstand to early transgressive coarse-grained tongue from the Viking Formation of the Joffre Field, Alberta: embayment complex or shoreface wedge?, *in* Swift, D.J.P., Snedden, J.W., and Plint, A.G., eds., Tongues, Ridges and Wedges: Highstand *versus* Lowstand Architecture in Marine Basins: SEPM Research Conference, Powder River and Bighorn Basins, Wyoming, June 24–29, unpaginated.

MacEachern, J.A., Raychaudhuri, I., and Pemberton, S.G., 1992b, Stratigraphic applications of the *Glossifungites* ichnofacies: Delineating discontinuities in the rock record, *in* Pemberton, S.G., ed., Applications of Ichnology to Petroleum Exploration, A Core Workshop: SEPM, Core Workshop 17, p. 169–198.

MacEachern, J.A., Stelck, C.R., and Pemberton, S.G., in press, Marine and marginal marine mudstone deposition: paleoenvironmental interpretations based on the integration of ichnology, palynology and foraminiferal paleoecology, *in* Bergman, K.M., and Snedden, J.W., eds., Isolated Shallow Marine Sand Bodies: Sequence Stratigraphic and Sedimentologic Perspectives: SEPM, Concepts in Sedimentology and Paleontology No. 7.

MacEachern, J.A., Zaitlin, B.A., and Pemberton, S.G., 1998, High-resolution sequence stratigraphy of early transgressive deposits, Viking Formation, Joffre Field, Alberta, Canada: American Association of Petroleum Geologists, Bulletin, v. 82, 729–756.

McGookey, D.P., Haun, J.D., Hale, L.A., Goodell, H.G., McCubbin, D.G., Weimer, R.J., and Wulf, G.R., 1972, Cretaceous System, *in* Mallory, W.W., ed., Geological Atlas of the Rocky Mountain Region, U.S.A.: Denver Colorado, Rocky Mountain Association of Geologists, p. 190–228.

Mellere, D., and Steel, R.J., 1995, Facies architecture and sequentiality of nearshore/shelf sandbodies (Haystack Mountains Formation—Wyoming, U.S.A.): Sedimentology, v. 42, p 551–574.

Miller, W., 1995, ''*Terebellina*'' (equals *Schaubcylindrichnus freyi* ichnosp. nov.) in Pleistocene outer-shelf mudrocks of northern California: Ichnos, v. 4, p. 141–150.

North American Commission on Stratigraphic Nomenclature, 1983, North American Stratigraphic Code: American Association of Petroleum Geologists, Bulletin, v. 67, p. 841–875.

Nummedal, D., and Swift, D.J.P., 1987, Transgressive stratigraphy at sequence-bounding unconformities: some principles derived from Holocene and Cretaceous examples, *in* Nummedal, D., Pilkey, O.H., and Howard, J.D., eds., Sea-Level Fluctuation and Coastal Evolution: SEPM, Special Publication 41, p. 241–260.

Obradovich, J.D., 1993, A Cretaceous time scale, *in* Caldwell, W.G.E., and Kauffman, E.G., eds., Evolution of the Western Interior Basin: Geological Association of Canada, Special Paper 39, p. 379–396.

Pemberton, S.G., and Frey, R.W., 1984, Ichnology of storm-influenced shallow marine sequence: Cardium Formation (Upper Cretaceous) at Seebe, Alberta, *in* Stott, D.F., and Glass, D.J., eds., The Mesozoic of Middle North America: Canadian Society of Petroleum Geologists, Memoir 9, p. 281–304.

Pemberton, S.G., and MacEachern, J.A., 1995, The sequence stratigraphic significance of trace fossils: examples from the Cretaceous foreland basin of Alberta, Canada, *in* Van Wagoner, J.C., and Bertram, G., eds., Sequence Stratigraphy of Foreland Basin Deposits—Outcrop and Subsurface Examples from the Cretaceous of North America: American Association of Petroleum Geologists, Memoir 64, p. 429–475.

Pemberton, S.G., and MacEachern, J.A., 1997, The ichnological signature of storm deposits: the use of trace fossils in event stratigraphy, *in* Brett, C.E., and Baird, G.C., eds., Paleontological Event Horizons: Ecological and Evolutionary Implications: New York, Columbia University Press, p. 73–109.

Pemberton, S.G., MacEachern, J.A., and Frey, R.W., 1992, Trace fossil facies models: environmental and allostratigraphic significance, *in* Walker, R.G., and James, N., eds., Facies models: Response to Sea Level Change: St. John's, Newfoundland, Geological Association of Canada, p. 47–72.

Peterson, J.C., 1995, Ichnology, sedimentology and stratigraphy of the Lower Cretaceous Viking Formation at Mikwann, Fenn and Chain, Alberta, Canada [unpublished M.Sc. thesis]: University of Alberta, Edmonton, Alberta, 131 p.

Pilkey, O.H., Blackwelder, B.W., Knebel, H.J., and Ayers, M.W., 1981, The Georgia Embayment continental shelf: stratigraphy of a submergence: Geological Society of America, Bulletin, v. 92, p. 52–63.

Plint, A.G., 1988, Sharp-based shoreface sequences and ''offshore bars'' in the Cardium Formation of Alberta: their relationship to relative changes in sea level, *in* Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., and Van Wagoner, J.C., eds., Sea-Level Changes: An Integrated Approach: SEPM, Special Publication 42, p. 357–370.

Plint, A.G., Walker, R.G., and Bergman, K.M., 1986, Cardium Formation 6. Stratigraphic framework of the Cardium in subsurface: Bulletin of Canadian Petroleum Geology, v. 34, p. 213–225.

Plint, A.G., Walker, R.G., and Duke, W.L., 1988, An outcrop to subsurface correlation of the Cardium Formation in Alberta, *in* James, D.P., and Leckie, D.A., eds., Sequences, Stratigraphy, Sedimentology: Surface and Subsurface: Canadian Society of Petroleum Geologists, Memoir 15, p. 167–184.

Posamentier, H.W., and Chamberlain, C.J., 1993, Sequence stratigraphic analysis of Viking Formation lowstand beach deposits at Joarcam field, Alberta, Canada, *in* Posamentier, H.W., Summerhayes, C.P., Haq, B.U., and Allen, G.P., eds., Stratigraphy and Facies Associations in a Sequence Stratigraphic Framework: International Association of Sedimentologists, Special Publication 18, p. 469–485.

Posamentier, H.W., Allen, G.P., James, D.P., and Tesson, M., 1992, Forced regressions in a sequence stratigraphic framework: concepts, examples, and exploration significance: American Association of Petroleum Geologists, Bulletin, v. 76, p. 1687–1709.

Raddysh, H.K., 1988, Sedimentology and ''geometry'' of the Lower Cretaceous Viking Formation, Gilby A and B Fields, Alberta, *in* James, D.P., and Leckie, D.A., eds., Sequences, Stratigraphy, Sedimentology: Surface and Subsurface: Canadian Society of Petroleum Geologists, Memoir 15, p. 417–430.

Raychaudhuri, I., Brekke, H.G., Pemberton, S.G., and MacEachern, J.A., 1992, Depositional facies and trace fossils of a low wave energy shoreface succession, Albian Viking Formation, Chigwell Field, Alberta, Canada, *in* Pemberton, S.G., ed., Applications of Ichnology to Petroleum Exploration, A Core Workshop: SEPM, Core Workshop 17, p. 319–337.

Saunders, T., and Pemberton, S.G., 1986, Trace fossils and sedimentology of the Appaloosa Sandstone: Bearpaw–Horseshoe Canyon Formation transition, Dorothy, Alberta: Canadian Society of Petroleum Geologists, Field Trip Guide Book, 117 p.

Savrda, C.E., 1991, Ichnology in sequence stratigraphic studies: An example from the Lower Paleocene of Alabama: Palaios, v. 6, p. 39–53.

STAMP, L.D., 1921, On cycles of sedimentation in the Eocene Strata of the Anglo-Franco-Belgium Basin: Geological Magazine, v. 58, p. 108–114.

STELCK, C.R., AND LECKIE, D.A., 1990, Biostratigraphy of the Albian Paddy Member (Lower Cretaceous Peace River Formation), Goodfare, Alberta: Canadian Journal of Earth Sciences, v. 27, p. 1159–1169.

SWIFT, D.J.P., 1968, Coastal erosion and transgressive stratigraphy: Journal of Geology, v. 76, p. 444–456.

TILLMAN, R.W., AND MARTINSEN, R.S., 1984, The Shannon shelf-ridge sandstone complex, Salt Creek anticline area, Powder River Basin Wyoming, *in* Tillman, R.W., and Siemers, C.T., eds., Siliciclastic Shelf Sediments: SEPM, Special Publication 34, p. 85–142.

TILLMAN, R.W., AND MARTINSEN, R.S., 1987, Sedimentologic model and production characteristics of Hartzog Draw field, Wyoming, a Shannon shelf ridge sandstone, *in* Tillman, R.W., and Weber, K.J., eds., Reservoir Sedimentology: SEPM, Special Publication 40, p. 15–112.

VAN WAGONER, J.C., 1995, Sequence stratigraphy and marine to nonmarine facies architecture of foreland basin strata, Book Cliffs, Utah, U.S.A., *in* Van Wagoner, J.C., and Bertram, G., eds., Sequence Stratigraphy of Foreland Basin Deposits—Outcrop and Subsurface Examples from the Cretaceous of North America: American Association of Petroleum Geologists, Memoir 64, p. 137–223.

WALKER, R.G., AND BERGMAN, K.M., 1993, Shannon Sandstone in Wyoming: a shelf-ridge complex reinterpreted as lowstand shoreface deposits: Journal of Sedimentary Petrology, v. 63, p. 839–851.

WALKER, R.G., AND WISEMAN, T.R., 1995, Lowstand shorefaces, transgressive incised shorefaces, and forced regressions: examples from the Viking Formation, Joarcam area, Alberta: Journal of Sedimentary Research, v. B65, p. 132–141.

WEIMER, R.J., 1984, Relation of unconformities, tectonics, and sea level changes, Cretaceous of the Western Interior, U.S.A., *in* Schlee, J.S., ed., Interregional Unconformities and Hydrocarbon Accumulation: American Association of Petroleum Geologists, Memoir 36, p. 7–35.

Received 23 February 1998; accepted 16 September 1998.