River-dominated intervals show the least uniform trends of BI, because of the highly variable conditions related to river jet and plume near the bed, buffering environmental stresses. Therefore, wave-dominated deposits that are not affected by storms yield climax communities may show BI values of 4-5, reflecting the transition to longer-lived fair-weather conditions. Fair-weather waves facilitate persistent agitation of 0-2, owing to high accumulation rates, although this also depends on event frequencies. Upper surfaces of individual storm/river-flood beds may show BI values of 4-5, reflecting the transition to longer-lived fair-weather conditions. Fair-weather waves facilitate persistent agitation near the bed, buffering environmental stresses. Therefore, wave-dominated deposits that are not affected by storms yield climax communities with robust and diverse ichnofacies signatures reflecting “uniform and high” BI trend with values that average 4.

River-dominated intervals show the least uniform trends of BI, because of the highly variable conditions related to river jet and plume behavior. BI values vary from 0 to 4, with generally low ichnogeneic diversities. These alternations likely record seasonal to centennial fluctuations in sedimentation rate (river discharge) and water turbidity, which influences substrate conditions near distributary mouths.

Tide-dominated intervals tend to show the most ‘stressed’ conditions, reflecting “non-uniform and low” trend of BI, with values of 0-2. These fluctuations in sedimentation rate (river discharge) and water turbidity, which influences substrate conditions near distributary mouths. Event beds, such as storm and river-flood deposits, tend to show low BI (Bioturbation Index) values showing a marked increase in BI as delta lobes are quickly abandoned and transgressed. In contrast, across the maximum flooding surface, changes in ichnological signatures are subtle and rather uniform.

We suggest that different parts of a single delta may experience marked differences in river, wave, and tide influence over time, reflecting the enormous complexity of operative processes at various temporal and spatial scales. Detailed intra-parasequence, bed-scale analyses of trace fossils help to reveal this complex evolutionary history of a single delta.

INTRODUCTION

The widely used tripartite classification of deltas has stemmed from analysis of the planform morphology of modern deltas (Galloway 1975). This classification assumes that there is a direct relationship between the overall sand body and planform geometry and the internal framework-facies of deltas, both reflecting the same relative dominance of either river, tide, or wave energy. Consequently, deltas are routinely identified as fluvial-, tide- and wave-dominated end members. If the sediment source is not directly from a river, then the shoreline deposits are identified as one of the categories of non-deltaic shoreline types. Recently, the assumption of tripartite delta classification has been questioned, based on the fact that the plan-view morphologies of modern deltas reflect dominant surficial process but may not necessarily reflect the short-lived constructional processes, such as river floods, that dominate the internal facies architecture (Gani and Bhattacharya in review). Moreover, Bhattacharya and Giosan (2003) have pointed out that not only may a single delta show river-, wave-, and tide-dominated facies at various locations within the delta, but that a complete spectrum exists from strandplain systems with minor deltaic promontories to river-dominated deltas with minor wave reworking. We would make the additional point that the modern examples of deltas are a static snapshot of geologic time, and that it is possible for a single delta to evolve from one type to another during a single progradational history. For example, during the last 4 ka, the Mekong Delta has evolved from a ‘tide-dominated’ delta to a ‘tide-wave-dominated’ delta (Ta et al. 2002). Therefore, it may be misleading to designate an ancient deposit to any particular type of delta (or even non-delta), based on the proportion of dominant facies types in a few vertical logs, without first identifying the temporal and spatial scale of that depositional element within the broader context of the regional stratigraphy. We speculate that the mixed-energy deltas should be the norm rather than the exception. This internal complexity of various deltaic processes can be revealed by analyzing the bed-scale variations of ichnological signatures in a novel way, as presented in this paper.

Ichnology has emerged as a powerful tool in paleogeographic and paleoecologic analysis and interpretation that integrates trace fossil analysis with that of facies analysis and sequence stratigraphy. Ichnological models of non-deltaic shoreline successions are comparatively well established (e.g., Howard 1972; Pemberton and Frey 1984; MacEachern and Pemberton 1992; MacEachern et al. 1999; among many others) compared to their deltaic counterparts. Early studies of deltaic trace fossils (Turner et al. 1981; Ekdale and Lewis 1991) concentrated on identification and paleoenvironmental significance of individual ichnogenea. Recent studies (Gingras et al. 1998; Coates and MacEachern 1999, this volume) have made a comparative analysis of ichnology in deltaic (wave- and river-dominated) and non-deltaic shoreline deposits from subsurface cores. Another recent study (Gouramanis et al. 2003) of fluvo-deltaic ichnology mainly focuses on the description and identification of trace fossils from patchy outcrop data. Trace fossil analyses of tide-
influenced deltaic deposits are largely lacking. MacEachern et al. (in press) recently gave a thorough review on the ichnology of deltas. As deltas are very complex and dynamic shoreline depositional systems reflect a wide range of river and basinal processes (tide, wave, storm, and oceanic currents), a deltaic ichnological model should ideally be based on bed-scale variations of trace fossil signatures throughout the successions. High-resolution integration of sedimentology and ichnology can be very useful to identify the relative influence of waves, storms, tides, and rivers influx in the construction of a delta. This paper presents one of the first ichnological studies of delta deposits that systematically integrates bed-scale variations in sedimentology and ichnology through an entire deltaic parasequence. Our objective is to show the relative effects of fundamental shoreline processes (wave, storm, tide, and river) in resultant paleoichnology of a given deposit. In this paper, we use both core and outcrop data of Turonian deltaic strata from the Wall Creek Member, Wyoming, and the Ferron Sandstone Member, Utah (Fig. 1). An extensive database incorporating both outcrop and core taken behind the cliffs, are available for both the Wall Creek Member and the Ferron Sandstone Member. The paleogeographic and sequence stratigraphic interpretations of these strata, roughly equivalent in age, are well established (e.g. Chidsey 2001; Howell and Bhattacharya 2004; Gani and Bhattacharya in review). The Ferron was deposited in a high accommodation setting, whereas the Wall Creek was deposited in a low accommodation setting.

**GEOLOGY OF STUDY AREA**

The Cretaceous Western Interior Seaway (WIS) stretched roughly north-south in central North America, and developed on an eastward migrating and asymmetric retro-arc foreland basin (Lawton 1994; Fig. 1A), which contains one of the most studied sedimentary successions in the world. The present study deals with upper Turonian (Cobban, 1990; Gardner 1995a, 1995b) strata of Utah and Wyoming (Figs.1, and 2) deposited at the western margin of the Seaway. In Utah, these successions belong to an ‘intermediate-term stratigraphic cycle’ of the fluvio-deltaic ‘Ferronensis Sequence’ (from 90.25 Ma to 89 Ma), which, in turn, consists of seven ‘short-term stratigraphic cycles’ (Fig. 2B) each averaging a 0.2 ma duration (Gardner 1995b). In Wyoming, the Wall Creek Member (the uppermost member of Frontier Formation) is roughly time-equivalent to ‘Ferronensis Sequence’ or Upper Ferron Sandstone Member, and also consists of seven transgressive-regressive cycles of deltaic strata (Howell and Bhattacharya 2004; Fig. 2A), each averaging 0.2 ma in duration. As much of the Cretaceous is thought to represent ice-free green-house conditions, the origin of these stratigraphic cycles has variously been assigned to Milankovitch climatic cycles (Scott et al. 1998), or foreland basin tectonics related to thrust loading and fore-bulge migration (Gardner 1995b; Bhattacharya and Willis 2001). More recently, however, Miller et al. (2004) claimed that continental ice sheets paced sea-level changes during the Late Cretaceous. Accordingly, the stratigraphic cycles of the Cretaceous seaway may represent a complex origin of in-phase and/or out-of-phase interaction of glacio-eustatic and tectonic cycles. A pronounced and widespread Cenomanian-Turonian transgression led to the opening of the epeiric seaway towards the south, which established a northerly surficial flow of warm Tethyan water, countered by a southerly bottom flow of cooler Boreal waters along western margin of the seaway (Leckie et al. 1998). The upper Turonian clastic wedges of Wyoming and Utah show great sedimentologic and stratigraphic variability. The Wall Creek Member comprises seven major sandstone bodies (Howell and Bhattacharya 2004; Fig. 2A) that prograded southeast. Each of these sand bodies shows one or more upward-coarsening facies successions, called parasequences, bounded by a marine flooding surface commonly marked by a chert-pebble and shark-tooth lag. These parasequences show a mixture of top-truncated deltaic and shoreface deposits with varying amounts of wave, storm, tide, and river influence. Subaerial deposits are notably absent in these deposits because of the top truncation associated with marine transgression. The present study deals with the Wall Creek Member at the “Raptor Ridge”, located northeast of Natrona County, central Wyoming (Fig. 1B), and emphasizes Sandstone-3 to Sandstone-6. Following a detailed paleogeographic study, Sandstone-6 was interpreted as a mixed-influence delta, named ‘Raptor Delta’ (Gani and Bhattacharya, in review; Fig. 3A). River- and tide-dominated facies of this delta are present only at Raptor Ridge, where the sand body is also the thickest. The entire northeast flank of the delta shows wave-dominated facies, and could comprise the updrift side of the delta, according to the ‘asymmetric wave-influenced delta’ model of Bhattacharya and Giosan (2003).

Regionally, the Ferron Sandstone forms a large lobate body that prograded northwest, north, and northeast, forming a large western embayment of the seaway, called the Sanpete Valley Embayment (Chidsey 2001; Fig. 1C). The Upper Ferron Sandstone Member consists of seven transgressive-regressive cycles (Fig. 2B) that, like the Wall Creek, also show a mixture of deltaic and shoreface strata with varying degrees of river, wave, and tide influences (e.g. Gardner 1995b; Chidsey 2001; Garrison in press). For example, Bhattacharya and Davies (2001) studied the first (basal) cycle of Upper Ferron Sandstone at the outcrop along Muddy Creek, and interpreted it as a river-dominated delta lobe that prograded northwestern. The present study examines the core of MC-2 at Muddy Creek Canyon (Chidsey 2001) (Fig. 2C). The entire core of MC-2 belongs to the ‘second transgressive-regressive cycle’ of the Upper Ferron Sandstone Member (Fig. 3A), which has been interpreted to contain four parasequences (Chidsey 2001). The logged interval of this article is the second parasequence from base (parasequence ‘Kf-2-Mi-b’), that was interpreted to be deposited in a deltaic environment (Chidsey 2001; Fig. 3B).

**DATA AND METHODOLOGY**

An integrated research project, focusing on deltaic, bed-scale facies architecture and reservoir characterization of the Wall Creek Member at Raptor Ridge, Wyoming (Fig. 1B) generated a superb data base of sedimentiological, ichnological, and petrophysical characteristics (e.g. Gani et al. 2004; Lee et al. 2004; Tang et al. 2004; Gani and Bhattacharya in review). Along with the outcrop study of several gully faces (both depositional pseudo dip and strike oriented), ten cores were taken behind the outcrop within an area of 300 m by 100 m. In this study, we used two of these ten wells (RR-2 and RR-7). Well RR-7 is located 220 m depositionally down-dip of Well RR-2. Well data were correlated and cross-checked with outcrop data at the Raptor Ridge site. The lower six sand bodies (Fig. 2A) of the Wall Creek Member were observed at Raptor Ridge. Sandstone-3 to Sandstone-6 were encountered at RR-2, whereas only Sandstone-6 was encountered in RR-7. We used another cored interval, from 93 m (303 feet) to 76 m (250 feet), of the MC-2 well at Muddy Creek, Utah (Fig. 1C). This interval represents part of the second transgressive-regressive cycle of the Upper Ferron Sandstone Member (Fig. 2B). Integrated sedimentological and ichnological analysis along with the interpretation of each of these three cores are presented (Figs. 5, 6, 9, and 11). The Selkachian approach (e.g., Pemberton et al. 1992; Pemberton et al., 2001) is taken in grouping the identified suites of ichnotaxa into the temporally and geographically recurring ichnocoenoses. Quantification of degrees of bioturbation in the sediments is emphasized in this study. The quantification scheme of bioturbation has been develop by Howard and Reineck (1972), and modified later by Taylor and Goldring (1993). The Bioturbation Index (BI) scheme of Taylor and Goldring (1993) is used in this
Fig. 1.– A) Cretaceous paleogeography of the Western Interior Seaway (WIS) during the middle Turonian. During this time the Wall Creek (in Wyoming) and Ferron (in Utah) were deposited into a retroarc foreland basin, sourced from topographic highs in the west developed during the Sevier Orogeny (modified from Bhattacharya & Willis 2001; and others). B) The Wall Creek crops out on the southeastern flanks of the Big Horn Mountains. This study focuses in the Wall Creek Member at Raptor Ridge. C) Ferron outcrops are located within the San Rafael Swell, northeast Utah. This study focuses on Muddy Creek Canyon (modified from Bhattacharya and Davies 2001).
articled to semi-quantitatively measure the degree of bioturbation in the sediments. However, rather than plotting it as a histogram (as suggested by Taylor et al. 2003) a continuous line curve of BI (comparable to a wireline log) is produced for each of the studied cores. This “BI log” (Fig. 4) facilitates illustration of subtle bed-scale variations, and, when presented alongside with other data, helps to integrate the evolutionary history of the deposits by trend analysis of log patterns throughout a vertical facies succession. The terminology and interpretation used in this trend analysis of the BI log is explained in Fig. 4, and is followed throughout this study. We also analyzed the preserved interrelationships of the ichnotaxa and their relationships with the sedimentary facies in which they occur. This type of continuous documentation of ichnological signature through the entire studied interval is best suited in subsurface core, because of the preservational bias of the outcrop data. These high-resolution data allowed us to make an ichnological comparison of the wave-, storm-, river-, and tide-dominated shoreline facies deposited in the Turonian Sea, so that the effects of these processes on the distribution of the trace fossils are better understood. Moreover, the changes of ichnological signature across bounding discontinuities are investigated and integrated with the developing sequence stratigraphic framework of the intervals.

The generalized paleogeography of the Upper Turonian shoreline systems at the western margin of the Interior Seaway in Wyoming and Utah has been presented as a series of juxtaposed delta lobes fed from rivers generated at the emerging edges of thrust sheets to the east (e.g., Gardner 1995; Chidsey 2001). In a situation like this, any of these shoreline deposits can be considered as part of a large ‘deltaic complex’, and can show variable proportions of river-, wave-, storm-, and tide-dominated/influenced facies, depending upon the part of the delta to which they belong to (e.g. updrift vs. downdrift; open marine vs. bay vs. embayment). The clastic successions presented in this study are part of one of these deltaic complexes (Fig. 3). However, when characterizing various sub-environments of these deposits, we have used deltaic terminology (e.g., prodelta, delta front) where evidence directly points to a delta, and general shoreline terminology (offshore, shoreface) where this is not. This paper is not aimed at differentiating ‘deltaic’ and ‘non-deltaic’ strata with the help of ichnology, but rather at showing the control of fundamental shoreline processes (wave, storm, tide, and river) in the resultant paleoichnology of a given deposit.
The overlying Sandstone-4 overlies a TSE, with a thin (8 cm) and non-uniform trend of BI values (Figs. 4 and 6). This interval gradually culminates in an MxFS. It is notable that there is no trend break in BI values across the MxFS. Sandstone-4b is only 2 mm thick and shows an upward transition from a distal expression of the Cruziana Ichnofacies to the archetypal Cruziana Ichnofacies. Low-angle parallel laminations and wave ripple laminations indicate wave-generated facies. Overall, BI values show a uniform and upward increasing trend, although there is a sudden increase in BI at 14.6 m. However, there is no change in BI values across the MxFS capping the top of Sandstone-4b.

The Sandstone-5 is broadly similar to Sandstone-4a, although the sedimentary structures are more obscured in Sandstone-5 (Fig. 7). The interval 13.1-8.3 m shows a high BI (averaging 5), with a uniform, and upward-increasing trend of the BI log. BI values decline sharply across a transgressive surface (TS) at 8.3 m. The TS is overlain by transgressive deposits hosting suites characterized by a high diversity distal expression of the Skolithos Ichnofacies, passing upward into a low diversity distal expression of the Cruziana Ichnofacies. This transgressive deposit, characterized by a uniform and upward-decreasing trend of BI (Figs. 4 and 6), culminates with an interpreted MxFS at 6.8 m. Like the previous example, there is no trend break in the BI log across the MxFS.

The Sandstone-6 differs from all of the older sandstones in several respects. The most important is the dominance of tide-generated sedimentary structures. In outcrop, older parasequences show a relatively low inclination (roughly < 1°) of clinoforms, whereas, the clinoforms of Sandstone-6 reach 4° inclinations. The lower part (6.8-4 m) of Sandstone-6 shows remnant parallel laminations and suites attributable to the Cruziana Ichnofacies with high BI values (3-4). Higher BI values are consistent with wave-affected facies. This interval shows a rather uniform trend of the BI log. The uppermost 2.6 m characteristically contains herringbone cross-bedding, originating from alternating flood and ebb tidal condition, with a non-uniform and low trend of the BI log (BI 0-1). Overall, the sandstone shows an upward-decreasing trend of BI values.

**DESCRIPTION AND INTERPRETATION OF CORES**

**WALL CREEK MEMBER**

*Well RR-2—* Sedimentological and ichnological data and their interpretations of the RR-2 cores are presented in Fig. 6 (for legend see Fig. 5). Core photos are presented in Fig. 7. Rather than repeating the data presented in Fig. 6, only important observations are described here. The entire core represents, from oldest to youngest, Sandstone-3 to Sandstone-6, each bounded by a transgressive surface of erosion (TSE), or maximum flooding surface (MxFS). In Sandstone-3, the lowermost interval (35.35-33.2 m) shows remnant parallel lamination, largely destroyed by bioturbation ranging from BI 1-4. The BI log of this interval shows an overall high (BI 3-4) but non-uniform trend (Figs. 4 and 6). Parallel laminations are better preserved in the overlying 33.2-31.5 m interval, reflected by suites of the archetypal Skolithos Ichnofacies. Episodic sedimentation is indicated by the development of fugichnia, and locally unburrowed sandstones, erosionally truncating an underlying highly burrowed interval (Fig. 8A). The BI trend of this interval is “low and non-uniform” (BI 1-2). The parallel laminations of these two intervals are thought to represent tempestites deposited in a shoreface environment. The remainder of this parasequence is devoid of visible traces (BI 0; cryptobioturbation is not included in this calculation). Indistinct development of parallel lamination (Fig. 8B) and a thin horizon of mud chips probably indicate high-energy sedimentation. The lack of bioturbation could be either due to removal of traces by erosion, or habitat unfavorable to infauna.

The overlying Sandstone-4 overlies a TSE, with a thin (8 cm) and predominantly muddy interval, containing suites reflecting a low diversity expression of the Cruziana Ichnofacies (Fig. 8C) and a BI of 2. The lower muddy interval of Sandstone-4a contains uncommon, 2-4 cm thick, sandstone beds, interpreted as remnants of distal tempestites (Fig. 8D). Bioturbation uniformly increases and then decreases upward (from BI 5 to 6, then back to 5) through the upper part of sandstone-4a, with a concomitant obliteration of primary sedimentary structures. A turnaround of relative sea level is interpreted at 18.3 m, marked by the development of a TSE, highlighted by an abrupt decrease of BI values and the reappearance of storm erosion. The interval 18.3-15 m lying above this TSE comprises transgressive deposits, showing a “high and uniform” trend of BI with values of 4 (Figs. 4 and 6). This interval gradually culminates in an MxFS. It is notable that there is no trend break in BI values across the MxFS. Sandstone-4b is only 2 mm thick and shows an upward transition from a distal expression of the Cruziana Ichnofacies to the archetypal Cruziana Ichnofacies. Low-angle parallel laminations and wave ripple laminations indicate wave-generated facies. Overall, BI values show a uniform and upward increasing trend, although there is a sudden increase in BI at 14.6 m. However, there is no change in BI values across the MxFS capping the top of Sandstone-4b.

The core of RR-7 well (Fig. 9) only contains Sandstone-6. The basal 11.9-2.2 m interval of this parasequence comprises silty/sandy mudstone, mostly homogenized due to thorough bioturbation (BI 4). Suites are attributable to the distal expression of the Cruziana Ichnofacies (Fig. 10A); hence the interval is interpreted to reflect wave-affected offshore deposits. This interval includes a single, 25 cm-thick sandstone bed (Fig. 10B), showing remnant parallel lamination interpreted to reflect either storm or river-flood deposits. The BI log of this interval shows a high and uniform trend (BI 4). BI values decrease sharply at 9.2 m. The interval 9.2-8.8 m comprises heterolithic muddy sandstone, containing a low diversity expression of the archetypal Cruziana Ichnofacies. This interval is interpreted as prodelta deposits. A 1.6 m thick sandstone bed with low-angle accretion lamination and an erosional lag at its base directly overlies the prodelta deposits. In the outcrop, Sandstone-6 shows a number of channelized deposits encased within lower to middle delta front deposits. These channels are interpreted as subaqueous terminal distributary channels (Gani and Bhattacharya in review) filled with gravities (deposits of sediment gravity flows, sensu Gani 2004). The thick sandstone bed
of RR-7 represents one of these channelized gravites, and shows a low and uniform trend (Figs. 4 and 9) of the BI log (BI mostly 0, rarely 1). The next interval (7.5-5.5 m) shows a dominance of landward-directed, dune-scale cross-bedding, which locally includes thin mm-scale mud drapes and couplets along foresets (Fig. 10E). The interval reflects tidal deposits with a strong flood-tidal component (Gani and Bhattacharya, in review). The BI trend of this interval is low and non-uniform (BI 0-2). The next interval (5.5-5.3 m) shows parallel laminations, interpreted as delta-front gravites, with an upward-increasing trend of BI values (0-2). The remainder of Sandstone-6 reflects monotonous successions of cross-bedding, with a low and uniform trend of the BI log (BI mostly 0, rarely 1), probably generated in a tide-/river- dominated condition. A couple of calcite-cemented horizons, burial diagenetic in origin (Nyman 2003), are present. The overall BI values of Sandstone-6 show an upward-decreasing trend.

FERRON SANDSTONE MEMBER

Well MC-2– The core of MC-2 well shows several parasequences that belongs to the second transgressive-regressive cycle of Gardner (1995). The thickest parasequence (‘KF-2-Mi-b’ of Chidsey 2001, interpreted as deltaic deposit; Fig. 3B) was chosen for this study (Fig. 11). The basal interval (92.5-91.5 m) consists of sandy mudstones, with intercalated 1-2 cm thick horizons of current and wave rippled cross-lamination. Small-scale failure structures (Fig. 12A) are observed in this interval. In the nearby Muddy Creek outcrop, synsedimentary growth faults have been described (e.g. Bhattacharya and Davies 2001). The above failure structure is probably associated with growth faults commonly developed due to the overloading of delta-front sand over under-compacted prodelta mud. This interval shows a non-uniform and upward-increasing trend (Figs. 4 and 12) of BI values (0-4). In the next interval (91.5-89.7 m), sandstone beds commonly contain parallel lamination and locally distinct normal grading, thought to represent delta-front gravites. Several discrete horizons (1-3 cm) of unburrowed, black mudstones are also observed. The BI log of this interval shows a non-uniform trend, where BI values vary from 0 to 3. The facies from 92.5 m to 89.7 m are interpreted as river-dominated deposits.

The next interval (89.7-87 m) is intensely bioturbated (BI 5) with few remaining parallel laminations (Fig. 12C). The absence of river- and tide-generated structures, and overall high BI values probably suggest that this interval is wave-affected. The BI log characteristically shows a uniform and high trend. The interval 87-84.5 m consists of repetitive, upward-finining cycles (averaging 25 cm
Fig. 6. Sedimentological and ichnological graphic logs of RR-2 with interpretations. For legend, see Fig. 5. For location, see Fig. 1B.
Fig. 7.– Box photos of cores of RR-2. Boxes are in order from base (a) to top (c), and from right to left.

Fig. 8. – (Page Opposite) Ichnology of wave-dominated RR-2 and outcrop equivalents. See Fig. 6 for the lithology of RR-2. A) Parallel laminated tempestite truncating burrowed fairweather interval [note *Chondrites* (Ch)]. Lower shoreface deposits, 34.29 m depth, Sandstone-3. B) Monotonous, parallel lamination of unburrowed upper shoreface deposits (28.1 m depth, Sandstone-3). C) TSE at the top of Sandstone-S3, 27.88 m depth. Note that the mudstone above this surface is less intensely bioturbated than the silty mudstone at the top part of the photo. D) Offshore deposits of Sandstone-4a, 26.92 m depth. Traces include *Chondrites* (Ch), *Zoophycos* (Zo), *Phycosiphon* (Phy), and *Terebellina* (Ter). Note thin remnant tempestites and marcasite nodule (mar) filling *Chondrites* tube. E) Lower shoreface deposits (BI 5) of Sandstone-4a, 24.4 m depth. Traces include *Phycosiphon* (Phy), *Thalassinoides* (Th), *Chondrites* (Ch), and *Helminthopsis* (He). *Phycosiphon* occupy ghosts of *Thalassinoides*. F) Lower shoreface deposits of Sandstone-4a, 22 m depth. Homogenization is due to repetitive burrowing (BI 6). Only *Chondrites* (Ch) are identifiable. G) Lower shoreface deposits of Sandstone-4a, 20.85 m depth. Traces include *Thalassinoides* (Th), *Chondrites* (Ch), and *Phoebichnus* (Pho). Large diameter (5 cm) *Thalassinoides* are passively filled with parallel lamination. H) Transgressive deposits (BI 4) at the upper part of Sandstone-4a, 16.68 m depth. Traces include *Phoebichnus* (Pho), *Chondrites* (Ch), *Ophiomorpha irregulare* (Op), *Phycosiphon* (Phy) and *Skolithos* (Sk). Note scattered shell fragments (sh) toward the top. I) Middle shoreface deposits (BI 5) of Sandstone-5, 9.43 m. Traces include *Ophiomorpha irregulare* (Op), *Chondrites* (Ch), and *Phycosiphon* (Phy). Burrow walls of *Ophiomorpha* are ramified only in the upper half. J-L) Outcrop of middle shoreface deposits. J) *Chondrites* on the upper surface of a sandstone bed, Sandstone-1. K) Large (length >50 cm) *Skolithos* in Sandstone-4. L) Large (6 cm in diameter) *Skolithos* in Sandstone-5.
thick), in which parallel laminated sandstones locally pass upward out of massive sandstone units, and grade into burrowed muddy sandstones (Fig. 12D). These beds, interpreted as delta-front gravites, probably originated during high discharge river-floods. This interval shows a non-uniform (alternating low and high) trend of BI values (1-4). The next interval (84.5-80 m) includes stacked, trough cross-stratified, ripple cross-laminated, and parallel laminated sandstones (Fig. 12E). A single muddy sandstone horizon with soft-sediment deformation structures and almost vertically aggraded climbing ripples, are thought to represent rapid, river-born sedimentation. The BI log of this interval shows a non-uniform trend, where BI values range from 0 to 3. The next interval (80-78 m) yields no sedimentary structures, and gives a uniform and upward-increasing trend of BI values (increases from 1 to 5). The uppermost interval comprises trough cross-bedded sandstone overlain by transgressive deposits. The BI log shows a low and more or less uniform trend (BI 0-1), with a sudden increase in BI across the transgressive surface.
ICHNOLOGICAL COMPARISONS OF WAVE-, STORM-, TIDE-, AND RIVER-DOMINATED SEDIMENTATION

In the deltaic successions described above, a distinct pattern of ichnological signatures has been observed for each of the controlling processes of waves, storms, tides, and river sediment influx. These patterns are described below, according to the interpreted subenvironments of deposition. In general, Sandstone-3 of RR-2 is storm-dominated, Sandstone-4 and Sandstone-5 of RR-2 are wave-dominated, Sandstone-6 of RR-2 and RR-7 is mixed-energy (river, tide and wave), and the parasequence of MC-2 is river- and wave-dominated successions (Figs. 6, 9, and 11).

OFFSHORE/PRODELTA DEPOSITS

Wave-dominated offshore to prodeltaic successions (Sandstone-4 to Sandstone-6 at RR-2 and RR-7), consist mostly of sandy mudstones,
and contain suites that reflect a distal expression of the *Cruziana* ichnofacies passing upward into the archetypal *Cruziana* ichnofacies (Fig. 8D). The dominant ichnogenera include *Chondrites*, *Zoophycos*, *Helminthopsis*, and *Phycosiphon*. The latter two represent grazing foraging structures. *Chondrites* (Figs. 8D and 8J), the single most abundant ichnogenus in the prodeltaic and offshore deposits of the studied successions, may represent deep-tier chemosymbiont behavior (e.g., Seilacher 1990; Bromley 1996). The sporadic occurrence of 1-4 mm diameter marcasite (FeS$_2$) nodules in these sediments (Fig. 8D) suggests that such structures may have tapped a sulphide-rich substratal environment. Locally, some of these nodules are found within the tubes of *Chondrites*. *Ophiomorpha*, *Trichichnus*, and *Skolithos* are found very rarely in the remnant thin sandstone beds, which show oscillation ripples and HCS. This suite is diminutive in size, and is probably indicative of r-selected opportunistic colonization (e.g., Saunders et al. 1994). The subordinate ichnogenera include *Asterosoma*, *Teichichnus*, *Planolites*, *Terebellina* (sensu lato), *Thalassinoides*, *Palaeophycus tubularis*, *Palaeophycus heberti*, *Rosselia*, and *Cylindrichnus*, in order of decreasing abundance. Among these, *Terebellina* (sensu
of decreasing abundance (Fig. 12A). Of the above, the dwelling/deposit-feeding structures of passive carnivores; the remainder record structures attributable to deposit-feeders. The uniform trend of the BI log is very characteristic of these wave-dominated deposits (Figs. 4, 6, and 9). A low value of BI (averaging 2) is consistent with a prodelta environment, whereas higher values (averaging 4) probably points to an offshore environment mostly unaffected by river effluent (Figs. 6 and 9). High diversities of trace fossils generally indicate open marine conditions (Pemberton et al., 1992; MacEachern and Pemberton 1992; Gingras et al. 1998; MacEachern et al. in press). Uniform bioturbation reflects homogenous distribution of food, normal salinity, and available oxygen in the seawater, due to persistent wave agitation, and/or a wider colonization window (the time available for colonization by trace-makers) reflecting slow deposition rates.

River-dominated prodelta deposits consist of interbedded mudstones and sandstones, and are found in the lowermost part of MC-2 (Fig. 11). These deposits show the suites consistent with the diverse, archetypal Cruziana ichnofacies. Ichnogenera comprise Chondrites, Palaeophycus tubularis, Thalassinoides, Planolites, Teichichnus, Cylindrichnus, Zoophycos, Phycosiphon, Conichnus, Asterosoma, fugichnia, Ophiomorpha nodosa, and Palaeophycus heberti, in order of decreasing abundance (Fig. 12A). Of the above, the dwelling/ suspension-feeding (or omnivore?) structure of Ophiomorpha nodosa, the dwelling structures of Palaeophycus tubularis and Conichnus, and fugichnia are confined to the rippled sandstone beds, and may represent doomed pioneers (cf. Füllimi and Grimm 1990). Two different sizes of Chondrites are observed. Robust forms show tube diameters of 1 mm, whereas diminutive forms are 0.5 mm in diameter (Fig. 12A). BI trend is characteristically non-uniform, with values ranging from 0 to 4. This may reflect a small colonization window associated with high and episodic deposition rates, and is the most characteristic of river-dominated prodelta deposits. Thin (1-3 cm) and unburrowed layers of black, fissile mudstones, thought to be a characteristic of river-dominated prodelta environments (Leithold 1989; MacEachern et al. in press) occur sporadically.

**SHOREFACE/DELTA FRONT DEPOSITS**

The deposits of this setting show a marked variation in ichnological signatures, largely reflecting the dominant process of deposition and local paleogeographic settings.

**Wave- and storm-affected deposits** –Wave- and storm-dominated shoreface deposits are extensively developed in Sandstone-3, 4, and 5 of RR-2 (Figs. 6, and 7). Lower shoreface successions pass upward out of units interpreted as the offshore transition, which yield suites reflecting diverse and archetypal Cruziana ichnofacies. Lower shoreface successions contain suites consistent with a high diversity proximal expression of the Cruziana ichnofacies. The suites include Thalassinoides, Palaeophycus tubularis, Helminthopsis, Phycosiphon, Ophiomorpha irregulaire, Phoebichnus, Chondrites, Terebellina (sensu lato), Skolithos, Asterosoma, Palaeophycus heberti, Teichichnus, Rossella, Rhizocorallium, Macaronichnus, Trichichnus, Zoophycos, fugichnia, and Siphonichnus, in order of decreasing abundance (Fig. 8E). This comprises the largest diversity suite in the studied successions. The suite displays robust burrows. Thalassinoides, for example, may reach 5 cm in diameter, and are passively filled with laminated muddy sandstone (Fig. 8G). These are interpreted as ‘tubular tempestites’ (cf. Tedesco and Wanless 1991). In many cases, a close affinity between the semi-vagile to vagile, shallow- to mid-tier deposit-feeding structure Phycosiphon and dwelling structures Thalassinoides has been observed (Fig. 8E). This may indicate that organic matter in abandoned Thalassinoides dwellings yielded a harvest of microbes, that later attracted the Phycosiphon trace makers (e.g., Bromley 1996). Lower shoreface deposits are overlain by wave-dominated middle shoreface units, displaying suites of the archetypal Skolithos ichnofacies (Fig. 8I). Dominant ichnogenera include the sessile, deep-tier, suspension-feeding structures Ophiomorpha irregulaire, Skolithos, and Arenicolites, as well as the dwelling/deposit-feeding structures Thalassinoides, Phoebichnus, and Palaeophycus tubularis (passive carnivore structures). Subordinate ichnogenera include Chondrites, Helminthopsis, Macaronichnus, Phycosiphon, Terebellina (sensu lato), Diploracerion habichi, Asterosoma, Trichichnus, Siphonichnus, Taenidium, and Rhizocorallium, in order of decreasing abundance. Locally, coal fragments contain Terebolites, but these are probably not in situ. Middle shoreface deposits yielded favorable substrates for suspension feeders. This is indicated by the presence of robust Skolithos, some up to 50 cm in length (Fig. 8K) and others up to 5 cm in diameter (Fig. 8L). Typically, the horizontal branches of Ophiomorpha irregulaire are ramified only along their upper margins (Fig. 8I), as the collapsing pressure acts from top down.

The most characteristic signature of these lower and middle shoreface units is the uniform, high (BI 4-6), and upward-increasing trend of the BI log. This intense bioturbation gives these deposits a mottled appearance with few preserved parallel laminations (Figs. 8E, 8G). This uniform and high BI trend probably indicates a wide colonization window removed from river mouths. This is also supported by the predominance structures of inferred suspension feeders, the activities of which are hindered by heightened water turbidity generated from river discharge (Moslow and Pemberton 1988; Gingras et al. 1998; Coates and MacEachern 1999; MacEachern et al. in press).

Where storm activity is prominent in the shoreface deposits (Sandstone-3 of RR-2; Fig. 6), the ichnological signature is different. Increasing storm activity normally leads to a sporadic distribution of ichnogenera and reduced bioturbation intensities (e.g., Coates and MacEachern 1999). The lower shoreface units contain suites attributable to a distal expression of the Skolithos ichnofacies, grading to suites reflecting a proximal expression of the Cruziana ichnofacies. Middle shoreface deposits display suites that correspond to the archetypal Skolithos ichnofacies (c.f. MacEachern et al. 1999). However, the diversity of ichnotaxa is low with a clear predominance of dwelling of presumed suspension feeding infauna in both the lower and middle shoreface rocks (Fig. 6). Event deposition is highlighted by discrete storm events truncating the fair-weather suite, and generating frozen tiers (Fig. 8A). Upper shoreface deposits do not show any trace fossils, with the exception of some suspected cryptic bioturbation. As a result, sedimentary structures (parallel to low-angle laminations) are well preserved in the deposits (Fig. 8B). Possible scenarios are: 1) the trace fossils have been removed completely by successive periods of storm erosion, and/or 2) burrowing activity was prohibited because of close proximity to a river source creating a harsh environment for infaunal organisms. The general paucity of clear erosion surfaces suggests that the latter scenario is more plausible. Overall, the bioturbated interval of this shoreface deposit displays a non-uniform and upward-decreasing trend of the BI log (BI 0-4) (Fig. 6).

In the case of Sandstone-6 of RR-2 and parasequence of MC-2, isolated wave-affected deposits alternate with the river-, and tide-affected deposits. In RR-2, the interval from 5.6-2.7 m represents a wave-influenced lower and middle delta front deposit (Fig. 6). The lower delta front contains suites corresponding to a distal to archetypal expression of the Cruziana ichnofacies, with Chondrites, Helminthopsis, Planolites, Terebellina (sensu lato), Phycosiphon, Thalassinoides, Skolithos, Palaeophycus heberti, and Zoophycos, in decreasing order of abundance. On the other hand, middle delta front deposits show suites recording a low diversity, distal to archetypal expression of the Skolithos Ichnofacies, including Palaeophycus...
Fig. 11. – Sedimentological and ichnological graphic logs of MC-2 with interpretations. For legend, see Fig. 5. For location, see Fig. 1C.
of the mixed characterized by suites corresponding to a low diversity expression interval (80-78 m) belongs to middle shoreface deposits, heberti suites that correspond to the archetypal to proximal expression of the River-dominated sedimentation is best developed in MC-2 (Fig. 11). stressful environment. This is consistent with channels, interpreted as probably indicates a narrow colonization window and overall and uniform. This, coupled with the low diversity of ichnotaxa, (found within mud chips) Pickering 1993). Distal expressions of the Leithold 1989; Raychaudhuri and Pemberton, 1992; Wignall and activity (e.g., Rice et al. 1986; Savrda and Bottjer 1987, 1989; conditions through decay of organic matter, reducing biogenic river-dominated systems are thought to generate anoxic bottom water black mudstone also occur. These types of organic-rich mudstones in the gravite beds. Two distinct horizons (1-3 cm thick) of unburrowed unburrowed black mudstone also occur. These types of organic-rich mudstones in river-dominated systems are thought to generate anoxic bottom water conditions through decay of organic matter, reducing biogenic activity (e.g., Rice et al. 1986; Savrda and Bottjer 1987, 1989; Leithold 1989; Raychaudhuri and Pemberton, 1992; Wignall and Pickering 1993). Distal expressions of the Skolithos Ichnofacies are developed in the muddy sandstone unit with penecontemporaneous deformation structures (probably related to growth faults). It is notable that in spite of the deformation, the unit shows a relatively high degree of bioturbation (BI 0-3) with at least six ichnogenera identified that correspond to inferred deposit feeders. This probably indicates that the unit was affected by faulting at a later time, when more proximal cross-bedded sandstones overloaded it. A similar observation of fault initiation was made by Bhattacharya and Davies (2001) in the ‘first cycle’ of the Upper Ferron Sandstone at the Muddy Creek outcrop. The third type of sedimentation is similar to the cyclic sedimentation of the interval of 87-84.5 m of MC-2 (Fig. 11) is also interpreted as a lower delta front, characterized by mixed river/wave-affected deposition. These successions of cyclic event beds (Fig. 12D) show suites reflecting the mixed Skolithos-Cruziana “ichnofacies”, and include Ophiomorpha irregulariae, Palaeophycus tubularis, Thalassinoides, Skolithos, Arenicolites, Planolites, Helminthopsis, Phycosphon, Cylindrichnus, Chondrites, fugichnia, and Palaeophycus heberti, in order of decreasing abundance. Each event bed (average 25 cm thick) truncates the burrows of the preceding bed, and produces frozen tiers. The deepest tier burrows of individual bed comprised only Skolithos, fugichnia, Ophiomorpha, and Palaeophycus tubularis (Fig. 12D). The overall pattern shown by the BI log of this succession is cyclic, non-uniform, and upward decreasing (BI 0-4). Large numbers of dwellings of suspension feeders probably indicate that water turbidity was not elevated, and concentrations were dissipated by subordinate wave activity. This is consistent with the diverse assemblages of ichnotaxa present. The overlying interval from 84.5-80 m (Fig. 11) represents deposition in a river-dominated middle delta front. Overall, the interval is characterized mostly by suites attributable to the archetypal Skolithos Ichnofacies; subordinate suites correspond to the proximal expression of the Cruziana Ichnofacies. Suites include Ophiomorpha irregulariae, Skolithos, Thalassinoides, Palaeophycus tubularis, Helminthopsis, Phycosphon, Cylindrichnus, fugichnia, Cylindrichnus, Helminthopsis, Phycosphon, Planolites, and Bergaerzia, in order of decreasing abundance. There is a clear predominance of Ophiomorpha irregulariae in this interval. Four types of sedimentation patterns are recognized. The first type constitutes trough cross-stratified sandstones, which show only Ophiomorpha and Skolithos (BI 0-2). A second overlying type comprises a thin muddy sandstone unit with penecontemporaneous deformation structures (probably related to growth faults). It is notable that in spite of the deformation, the unit shows a relatively high degree of bioturbation (BI 0-3) with at least six ichnogenera identified that correspond to inferred deposit feeders. This probably indicates that the unit was affected by faulting at a later time, when more proximal cross-bedded sandstones overloaded it. A similar observation of fault initiation was made by Bhattacharya and Davies (2001) in the ‘first cycle’ of the Upper Ferron Sandstone at the Muddy Creek outcrop. The third type of sedimentation is similar to the cyclic sedimentation of the interval of 87-84.5 m, and shows a mixture of inferred suspension-feeding and deposit-feeding structures (BI 0-2). The fourth and final type records rapid sedimentation of aggrading to high-angle climbing ripples, and contains only Ophiomorpha, Skolithos, and Thalassinoides (BI 0-1). The entire interval from 84.5-80 m reflects a non-uniform and low trend of the BI log (BI 0-3), which indicate a narrow colonization window related to episodic and rapid deposition during major river floods. Nonetheless, the overall ichnotaxa diversity is moderate to high. Suspension-feeding/dwelling ethnologies of Ophiomorpha and Skolithos predominate in this interval, which may indicate that the trace-makers avoided the turbid water column, and managed to filter feed by staying inside their burrows and circulating water through them (e.g., Bromley, 1996). It is also likely that Ophiomorpha, thought to be produced by shrimp, may not represent suspension feeding structures, as modern shrimps are passive carnivores, detritus feeders, and scavengers. The last
Fig. 12.—Ichnological signatures of MC-2. See Fig. 11 for the litholog of this well. A) River-dominated prodelta deposits consisting of interbedded mudstones and sandstones with non-uniform bioturbation (BI 1-3), 91.9 m depth. Sandstones show ripple cross-lamination with small-scale collapse structures (related to growth faults). Trace fossils include *Chondrites* (Ch), *Thalassinoides* (Th), *Palaeophycus tubularis* [Pa(tb)], *Planolites* (Pl), *Zoophycos* (Zo), *Asterosoma* (As), *Phycosiphon* (Phy), fugichnia (fu), and *Palaeophycus heberti* [Pa(hb)]. Note two size groupings of *Chondrites*, one with tube diameters of 1 mm, and the other, 0.5 mm. B) River-dominated lower delta-front sandstones (BI 2) with climbing ripple cross-lamination (lower part) and parallel lamination (upper part), 90.2 m depth. Trace fossils include *Ophiomorpha irregulare* [Op(ir)], *Ophiomorpha nodosa* [Op(no)], fugichnia, and *Planolites*. C) Wave-dominated lower shoreface deposits showing uniform and extensive burrowing (BI 5), 89 m depth. Trace fossils include *Ophiomorpha irregulare* [Op(ir)], *Ophiomorpha nodosa* [Op(no)], *Palaeophycus tubularis* [Pa(tb)], *Helminthopsis* (He), *Phoebichnus* (Pho), *Chondrites* (Ch), *Macaronichnus* (Ma), *Terebellina* (Ter), fugichnia (fu), *Asterosoma* (As), and *Rosselia* (Ro). D) River/wave-dominated lower delta-front event bed showing upward-increasing BI, 85.3 m depth. Trace fossils include *Ophiomorpha irregulare* [Op(ir)], *Thalassinoides* (Th), *Skolithos* (Sk), *Palaeophycus tubularis* [Pa(tb)], *Helminthopsis* (He), *Phycosiphon* (Phy), fugichnia (fu), and *Planolites* (Pl). E) River-dominated middle delta-front deposits of parallel laminated sandstone, showing diverse but low intensity bioturbation (BI 2), 81.1 m depth. Trace fossils include *Asterosoma* (As), *Cylindrichnus* (Cy), fugichnia (fu), *Ophiomorpha irregulare* [Op(ir)], *Skolithos* (Sk), *Helminthopsis* (He), *Phoebichnus* (Pho), and *Bergaueria* (Be). F) Wave-dominated middle shoreface deposits showing uniform burrowing (BI 5), 78.4 m depth. Trace fossils include *Palaeophycus tubularis* [Pa(tb)], *Ophiomorpha irregulare* [Op(ir)], *Helminthopsis* (He), *Asterosoma* (As), *Cylindrichnus* (Cy), and *Planolites* (Pl).
river-dominated interval (78.1-76.6 m) in MC-2 comprises upper delta-front deposits. This interval shows a non-uniform trend and very low values (BI 0-1) of BI on the log, including only Ophiomorpha irregulare. Like before, this BI trend is characteristic of river-dominated processes.

Tidally affected deposits—Tidally affected sedimentation is observed only in Sandstone-6 of the Wall Creek Member in RR-2 and RR-7 (Figs. 6, 9). In RR-7, the interval from 7.5-3 m is interpreted as a tide-dominated middle delta-front deposit. The interval shows a low diversity trace fossil suite, reflecting a proximal expression of the Cruziana Ichnofacies to a distal expression of the Skolithos Ichnofacies (Figs. 10C,10D). Suites contain Asterosoma, Ophiomorpha irregulare, Palaeophycus tubularis, fugichnia, Chondrites, Helminthopsis, Planolites, Skolithos, and possible cryptic bioturbation, in order of decreasing abundance. The margins of Ophiomorpha irregulare are more or less uniformly lined with pellets in all sides (Fig. 10D), indicating a highly shifting substrate. Deposit-feeding structures are mainly found within intercalated muddy horizons (Fig. 10C). Some mud chips contain Chondrites, but these are probably not in situ. Overall, the interval is characterized by non-uniform and low BI trend (BI 0-2). The topmost interval of RR-7 and RR-2 reflects mixed tide/river-affected, upper delta-front deposits. The interval shows suites corresponding to a low diversity expression of the archetypal Skolithos Ichnofacies, with Palaeophycus tubularis, Skolithos, fugichnia, Macaronichnus, Ophiomorpha irregulare, Planolites, and possible cryptobioturbation, in order of decreasing abundance. Suites show impoverished numbers. Visibility of Macaronichnus is enhanced in the cemented horizons of rippled sandstones. Notably, mud drapes and mud clasts are almost devoid of burrows (Fig. 10F). In general, the interval is characterized by non-uniform and very low (BI 0-1) trend of the BI log. This BI trend probably indicates a narrow colonization window resulting from comparatively high rates of tidal sedimentation. The low diversity of ichnotaxa may reflect high magnitudes of salinity fluctuations associated with tidal periodicities.

ICHNOLOGICAL SIGNATURES: PARASEQUENCE DEPOSITION AND THEIR BOUNDING DISCONTINUITIES

Overall ichnological signatures, particularly the BI trend, of individual parasequences (sandstones) is distinctive, depending to what extent they are affected by wave, storm, river, and tidal processes. Ichnological signatures also change characteristically across initial marine flooding surface.

PARASEQUENCES

In general, wave-dominated deposits host the most diverse and climax signatures of trace fossils. When protected from storm erosion, tidal modification, and direct river input, these deposits (Sandstone-3, 4, and 5 of RR-2) could show maximum activity of trace makers (Figs. 6, and 7). All of these parasequences show characteristic uniform and upward-increasing trends of BI with overall high values (BI 2-6). This is probably due to a wide colonization window (e.g., Bromley 1996) where the slow sedimentation rate facilitates a homogeneous and thorough modification of the substrate. This condition was likely coupled with high oxygen availability and normal salinities, aided by wave agitation. Overall ichnotaxa diversities are high, with a mixture of grazing, foraging, deposit-feeding, and suspension-feeding structures. Each of these ethologies is dominant in offshore, lower shoreface, and middle shoreface, respectively. It is notable that when BI values reach six, only a few traces (deep tier) are readily identifiable (Fig. 8F). This situation should not be confused with low diversity suites. In these parasequences, some robust ichnogenera are observed (Figs. 8G, 8K, and 8L), which also support an unstressed condition during colonization. Although thin storm beds with hummocky cross stratification (HCS) have been observed sporadically in these wave-dominated successions, the BI trends are not obliterated, probably due to low frequency and reduced intensity of storms.

In storm-dominated intervals (e.g., Sandstone-3 of RR-2), the ichnological signatures are different and probably taphonomically biased. Rapidly deposited testes predominate in the lower shoreface deposits, whereas middle and upper shoreface units show a strong signature of storm erosion and amalgamation (e.g., MacEachern and Pemberton 1992; Pemberton et al. 2002; Coates and MacEachern 1999). This is the case for Sandstone-3. As a result, this sandstone shows a non-uniform and upward-decreasing BI trend (Fig. 6). The upper shoreface is almost entirely devoid of burrows (Fig. 8B), which probably indicates either a taphonomic bias resulting from storm erosion, or a narrow colonization window related to heightened sedimentation rates.

Ichnological signatures are also distinctive when in close proximity to distributary channels (e.g., Sandstone-6 of RR-2 and RR-7, and the parasequence of MC-2). In general, these two parasequences are characterized by an upward-decreasing and non-uniform trend of BI log. Most importantly, each of these parasequences shows discrete intervals of river-, wave-, storm-, and tide-dominated sedimentation, giving rise to different ichnological signatures. Wave-dominated intervals of these parasequences are characterized by uniform trends and relatively high values of BI (mostly 3-5) with a diverse suite (up to 13 ichnotaxa) (Figs. 12C, 12F) – signatures similar to those of wave-dominated deposits described earlier. River-dominated intervals show the most non-uniform trend of BI (BI 0-4), varying from low diversity (1) to high diversity (up to 11) of ichnotaxa. Seasonal fluctuations of sedimentation rate (i.e., fluctuating colonization window) and suspended sediment concentration (water turbidity) near distributary mouths probably generate an alternating high-stress and low-stress environment for the trace makers. As a result, infauna shows highly variable distributions and abundances in the deposits. In the studied successions, tide-dominated intervals show the most ‘stressed’ ichnological conditions, with non-uniform trends and generally low values of BI (0-2). Salinity fluctuations, continuously shifting substrates, narrow colonization windows (related to diurnal-scale tidal periodicities), and the development of fluid-mud layers are probably the dominant factors in controlling the trace-maker distributions, abundances, and ethologies.

In RR-2 and MC-2, retrogradational transgressive deposits that are associated with a relative rise in sea level, commonly lie above the progradational parasequences. In general, when relative sea level begins to rise, waves become the dominant process during deposition as distributary channels are being abandoned. Therefore, all of the transgressive deposits in this study display ichnological signatures (Fig. 8I) comparable to those of unstressed (e.g., wave-dominated) deposits. The resulting signatures are characterized by diverse suites of ichnotaxa, coupled with uniform and high trend of the BI log (BI 3-4). In RR-2, these deposits also show an upward-decreasing trend of BI values.

BOUNDING DISCONTINUITIES

A marked change of ichnological signatures has been observed across the bounding discontinuities reflecting the initial (first) marine flooding surfaces related to relative rise of sea level. In the study intervals, TS (transgressive surface) or TSE (transgressive surface of erosion) cap the progradational parasequences. A sharp change in BI values occurs at these discontinuities. The change is generally towards higher BI values if the underlying parasequence shows upward-decreasing BI, but is towards lower BI if the underlying parasequence shows a trend of upward-increasing BI. TS generally indicate comparatively gradual deepening of the sea, and mark the turnaround from progradation to retrogradation. In the studied successions, this gradual deepening of relative sea level is characterized by a gradual upward shift of ichnofacies from the
archetypal *Skolithos* Ichnofacies below the TS to distal *Skolithos* / proximal expressions of the *Cruziana* Ichnofacies above the TS (e.g., parasequence of MC-2 and Sandstone-5 of RR-2). On the other hand, the TSE demarcates rapid or abrupt changes of relative sea level (Fig. 8C), accompanied by sharp upward shifts of ichnofacies from the archetypal *Skolithos* Ichnofacies to the archetypal *Cruziana* Ichnofacies across this surface (e.g. Sandstone-3, and 4 of RR-2). When marine transgression reaches its highest position, an MxFS (maximum flooding surface) develops, after which, the ensuing depositional system starts to prograde. Therefore, this surface normally demarcates the boundary between transgressive deposits below and prograding parasequences above. Ichnological signatures do not show any sudden changes across the MxFS. Notably, the BI trend (BI 3-4) also does not break across MxFS.

CONCLUSIONS

1. Deltaic deposits of the Turonian Western Interior Seaway, show marked variations in ichnological signatures, dependent on the relative dominance of wave, storm, river, and tidal processes.

2. BI (bioturbation index) logs, when plotted beside lithologs and integrated with ichnological suites interpreted within the ichnofacies paradigm, can significantly assist in understanding the bed-scale as well as parasequence-scale variations of trace maker’s behaviors in the deposits. Four basic morphologies have been identified that describe the trend of the BI log – uniform, non-uniform, upward-increasing, and upward-decreasing (Fig. 4).

3. Wave-dominated deposits, when protected from frequent storm erosion, show the most diverse, climax trace fossil signatures, with “uniform and high” trends of BI (averaging to 4). This is probably due to broad colonization window, coupled with persistent wave agitation, which helps to minimize water turbidity, and optimize the distribution of oxygen, salinity, temperature, and organic matter in the water column, as well as in the substrate.

4. High storm frequency may preclude or obliterate trace fossil distributions in the deposits, by reducing the colonization window and/or eroding the fair-weather suites. The resulting ichnological signatures reflect “non-uniform” and “upward-decreasing” trends of the BI log.

5. River-dominated intervals show the most “non-uniform” trends and highly variable values of BI (ranges from 0 to 4), displaying a low-diversity to moderately high diversity of ichnotaxa. These probably reflect seasonal to centennial fluctuations of sedimentation rate and water turbidity in the vicinity of the distributary mouth. Such setting favors alternations from high-stress to low-stress conditions for trace makers.

6. Tide-dominated deposits show the most ichnologically ‘stressed’ conditions, with “non-uniform and low” trend of BI (0-2), resulting from salinity fluctuations, continuously shifting substrates, narrow colonization window associated with tidal periodicities, and development of fluid-mud layers.

7. Individual parasequences are characterized either by upward-increasing or upward-decreasing trends of BI. BI values and trace fossils suites change significantly across marine flooding surfaces that cap progradational parasequences. However, there is no trend break on the BI log across maximum flooding surfaces (MxFS).

8. Individual parasequences can show various proportions of river-, wave-, storm-, and tide-affected facies, each characterized by distinct ichnological signatures. We suggest here that different parts of a delta complex may experience different degrees of wave, storm, tide, and river influence during a single phase of progradation, and indeed, may evolve from one type to another over time. Consequently, many deltaic successions may not be simply classified as end-member types (i.e., ‘wave-dominated’, river-dominated, or ‘tide-dominated’).

9. Ichnological analyses, particularly trend analysis of BI log, of ancient successions can help in identifying the intervals deposited under specific dominant process, in a depositional system. This would facilitate in the delineation of its evolutionary history, as well as in the reconstruction of its paleogeography.

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