Palaeoenvironmental implications of trace fossils in estuarine deposits of the Cretaceous Bluesky Formation, Cadotte region, Alberta, Canada

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Estuarine settings are characterised by numerous physical and chemical stresses that can strongly influence the behaviour of burrowing organisms. Although lowered salinity and fluctuating salinity levels normally represent the chief stresses recognised in bays and estuaries, high sedimentation rates, high current energy, turbidity, and low levels of oxygen in bottom and interstitial waters are known to be significant factors that strongly influence the resultant ichnofossil assemblages. This study builds on earlier research and suggests that the effects of each of these parameters can be observed in the rock record through trace fossil analysis.

The subsurface lower Albian Bluesky Formation in the Cadotte region of Alberta has been interpreted to represent an estuarine deposit. Examination of the trace fossil assemblages from various facies therein suggests that physicochemical stresses were variable across the ancient estuary and mainly constituted the following: (1) low salinity and fluctuating salinity levels, which are interpreted to have contributed to patterns of low ichnofossil diversity and burrow dimunition proximal to the fluvial point source(s) in the upper and central parts of the depositional system; (2) high sedimentation rates and current energy, evidenced ichnologically by sporadic, penetrative bioturbation and the rare preservation of opportunistic sediment stirring, are most significant in the vicinity of the tidal inlet in the lower estuary and in the bayhead delta of the upper estuary; (3) high turbidity associated with the turbidity maximum in tidal channels of the central reaches of the estuary probably inhibited suspension-feeding behaviours locally; and, (4) low levels of dissolved oxygen in quiescent-water embayments and lagoons, often represented in brackish-water deposits as a *Trichichnus*, *Palaeophycus*, and *Diplocraterion* assemblage.

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Key words:

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Introduction

Ichnology is useful for enhancing sedimentological interpretations because it provides information that cannot be derived from analysis of the physical sedimentary structures alone. Ichnological signatures are known to represent composite animal responses to several physical and chemical parameters, including salinity and its fluctuations, strong currents, water turbidity, sedimentation rate, oxygenation, depositional system episodicity, the nature of the available food supply, and temperature locally. Animals also show behavioural responses to changes in substrate cohesiveness and sediment grain size [thorough reviews are provided in Pemberton *et al.* (1992a) and Taylor *et al.* (2003)]. Thus, trace fossil assemblages potentially contain a great deal of information. However, the various animal behaviours indicated by trace fossils represent a complex adaptive landscape; some behaviours are used serially, whereas other ichnofossils might represent a specific faunal response to a particular environmental parameter. Thus, deciphering the information latent in a trace fossil assemblage can present a daunting task.

Due to intense hydrocarbon exploration throughout the last five decades, many sedimentary deposits in the Western Canada Sedimentary Basin (WCSB) have been scrutinised with respect to their ichnological significance. Among the most commonly applied ichnological paradigms in the WCSB is the brackish-water model (Pemberton *et al.* 1982), which strives to characterise brackish-water ichnofossil assemblages. However, the utility of that model has, at times, undermined the general appreciation that trace fossil assemblages are the result of *multiple* physical and/or chemical stresses, and not just those associated with salinity. This paper uses a case study to present an interpretation of the various stresses exerted on the trace-making fauna of a Cretaceous estuary. It is not intended to challenge the brackish-water model, but rather to add to it, suggesting the potential utility of considering various other environmental factors to hone interpretations of ancient estuarine deposits.

Physicochemical stresses in marginal-marine settings

Salinity stress is a prominent environmental parameter in brackish-water settings. Nevertheless, numerous other factors potentially influence associated trace fossil assemblages. The effects of what are considered herein to be the most important in terms of their significance in imparting a signature into the (marginal-marine) rock record are discussed. These include salinity stresses, high sedimentation rates and current energy, excessively turbid conditions, and low oxygenation of bottom and interstitial waters.

Salinity stresses

In the 1970s, researchers working on east coast (Georgia) estuaries of the USA began to recognise the distinguishing characteristics of burrow assemblages made by infaunal organisms in brackish-water settings (e.g. Howard & Frey 1973, 1975; Howard *et al.* 1975; Dörjes & Howard 1975). Howard & Frey (1973) identified specific burrowing activities that were associated with different sediment textures and salinity gradients across marginal-marine depositional systems.

Brackish water is considered to represent water chemistries that are characterised by intermediate salinities, thus representing a continuum between fresh (< 0.5‰) and normal marine (~34‰) water. Trace fossil assemblages associated with sediments deposited in brackish water are typically characterised by one or more diagnostic attribute. A summary of these characteristics was presented by Pemberton *et al.* (1982): (a) a low diversity of trace fossil forms is common, (b) forms present typically represent an impoverished marine assemblage, (c) a dominance of morphologically simple, vertical and horizontal structures, (d) the presence of assemblages dominated by a single ichnofossil species, (e) traces are diminutive relative to fully marine counterparts, and (f) some forms may be found in high densities. Numerous authors have observed a mixed *Skolithos*–*Cruziana* ichnofacies in brackish-water deposits (e.g. Howard & Frey 1975, 1985; Ekdale *et al.* 1984; Frey & Pemberton 1985; MacEachern & Pemberton 1994; Buatois *et al.* 2002). Trace fossils commonly associated with brackish-water deposits include *Gyrolithes*, *Palaeophycus*, *Cylindrichnus*, *Skolithos*, *Planolites*, *Thalassinoides*, and *Teichichnus*.

Work on the McMurray Formation of northern Alberta by Pemberton *et al.* (1982) represents the first successful attempt to recognise and interpret the physical manifestation of salinity stress in ancient ichnofossil assemblages. Throughout the last two decades, several researchers have demonstrated the utility of this palaeoenvironmental tool in numerous study areas (e.g. Frey & Pemberton 1985; Wightman *et al.* 1987; Beynon *et al.* 1988; Ranger & Pemberton 1992; Pemberton *et al.* 1994; MacEachern & Pemberton 1994; Wightman & Pemberton 1997; Hubbard *et al.* 1999; MacEachern *et al.* 1999a; Buatois *et al.* 2002).

Since the initial work in the 1970s there has been a general paucity of ichnological studies in modern brackish-water sedimentary environments (neoichnology). An exception is Gingras *et al.* (1999), who revisited the effects of brackish water on benthic organisms and the concurrent traces they leave in siliciclastic sediments at Willapa Bay, Washington State, USA. The authors complemented the analysis of modern sediments with a Pleistocene data set in their study area, enabling many of the physicological and physical processes responsible for trace fossil suites generated in brackish-water settings to be determined.

In addition to the effect of lowered water salinity, fluctuating salinity levels related to the tidal exchange of marine and brackish (or fresh) water also impart a significant stress on burrowing organisms. Deep burrows (e.g. *Skolithos*, *Thalassinoides* and *Cylindrichnus*) are commonly constructed by organisms to buffer the effects of salinity fluctuation (which can range from fresh to hypersaline) resulting from tidal exchange of water across the tidal flat, precipitation, and discharge of groundwater (Rhoads 1975; Pemberton & Wightman 1992).

Sedimentation stresses

High current energy, water turbidity, and high sedimentation rates are not necessarily directly related. In sedimentary systems that contain large quantities of mobile sand, however, current energy is directly proportional to the degree of shifting a substrate might suffer. Thus, for the purpose of this study (the Bluesky Formation is characteristically sandy in the study area), these parameters are assessed together. Important to palaeoecological interpretations of trace fossil assemblages, the preservation potential of burrows excavated in shallow tiers and by deeper-seated slow-burrowing infauna is significantly reduced by the rapid migration of bedforms in regions dominated by strong currents. Conditions related to the stresses that high sedimentation rates and high current energy impart on burrowing infauna include: (1) high current velocities that limit filter feeding for many soft-bodied organisms. In settings such as the tidal inlet, organic detritus is swept from the sediment–water interface and grazing and other activities on the sea floor are essentially eliminated. (2) Episodic sedimentation associated with storms may bury organisms so quickly that they are unable to readjust to the new sediment–water interface. Such challenging sedimentary conditions are deleterious to the presence of burrowing organisms and normally result in lower burrowing intensities (Howard 1975; Frey & Pemberton 1985). For example, at Willapa Bay, Washington, Gingras *et al.* (1999) noted that (i) low biogenic reworking is observed in intertidal point bars characterised by high sedimentation rates, and (ii) burrowing is strictly limited to organisms able to adapt to rapid sedimentation in these localities, such as amphipods, threadworms and mobile polychaetes (such as *Nereis*).

In estuarine settings, turbidity is a prevalent environmental stress. The area of highest turbidity stress occurs within the turbidity maximum, which is associated with the saltwater wedge where the most intense salinity gradients occur (Meade 1969; Howard *et al.* 1975). The turbidity maximum results from converging fluvially derived freshwater and tidally derived saltwater. This zone of convergence, which often occurs in the vicinity of the middle estuary, is characterised by high rates of clay/organic material flocculation, and the overall accumulation of fine-grained sediments from suspension (Kranck 1981; Rahmani 1988; Allen 1991). The boundary of the saltwater intrusion can fluctuate, significantly impacting burrowing infauna unable to cope with regular environmental changes. Turbid conditions probably exert a significant environmental stress on burrowing organisms, especially filter feeders (Rhoads *et al.* 1972; Rhoads 1973; Ranger & Pemberton 1992; Buatois & López Angriman 1992). However, the effect of the turbidity maximum on burrowing organisms is probably variable. As the turbidity maximum is associated with the landward extreme of saltwater intrusion, it has been suggested that it defines the boundary between marine-dominated assemblages and persistent brackish- to freshwater assemblages (Allen 1991). Therefore, in the central to upper reaches of the estuary, the saline water that permits organisms to live is inherently associated with turbid conditions.

The exclusion of suspension feeding under extremely turbid conditions suggests that burrowing behaviour is biased towards deposit-feeding strategies. In fact, this relationship has been observed in the rock record by numerous authors (Rhoads *et al.* 1972; Buatois & López Angriman 1992; Gingras *et al.* 1998; Coates & MacEachern 1999). In those examples, sedimentary facies that accumulated in turbid waters are dominated by low-diversity trace fossil assemblages, which only record deposit-feeding strategies. Many benthic organisms are thought to adjust their feeding strategies to survive under turbid conditions, and in some cases organisms are suspected to thrive during times of high turbidity (Wilber 1983).

Oxygen stresses

Oxygen deficiency is most characteristic in deep- and/or quiet-water environments, dominated by the slow accumulation of fine-grained sediments. However, marginal-marine sedimentary settings, such as the wave-dominated estuary in the Bluesky Formation, can contain large quantities of terrigenous organic detritus, which, in the process of decomposition, may lower oxygen levels near the sediment–water interface (Leithold 1989; Saunders *et al.* 1994; Coates & MacEachern 1999). Low oxygen concentrations in bottom and interstitial waters influence trace fossil size and diversity; as oxygen content decreases there is a noticeable reduction in the size of the burrows present and the diversity of organisms also decreases (Rhoads & Morse 1971; Savrda & Bottjer 1989; Wignall 1991). A dominance of deposit-feeding burrows that maintain an open conduit to the sediment–water interface is considered characteristic of oxygen-deficient sediments (Ekdale & Mason 1988). Common trace fossil forms in such settings include *Chondrites*, *Zoophycos*, *Teichichnus* and *Trichichnus* (Ekdale & Mason 1988; Savrda & Bottjer 1989; Wignall 1991; Savrda 1992).

Working on the shallow-marine Carmel Formation (Middle Jurassic) in central Utah, de Gibert & Ekdale (1999) interpreted a low-diversity trace fossil assemblage, which included *Arenicolites*, *Chondrites*, *Gyrochorte*, *Lockeia*, *Planolites*, *Protovirgularia*, *Rosselia*, *Scalarituba*, *Skolithos*, *Taenidium*, and *Teichichnus*, to have resulted from greater than normal marine salinities coupled with depletion of oxygen in pore waters. In general, the assemblage consisted mostly of non-specialised ichnotaxa with small burrow sizes dominating the assemblages. The amount of bioturbation was reported to be low.

Brackish-water deposits in the WCSB

Brackish-water deposits are common in Lower to Middle Cretaceous strata of the WCSB. This has been demonstrated by numerous authors using various techniques (e.g. micro-palaeontology: Finger 1983; Mattison & Wall 1993; MacEachern *et al.* 1999a; isotopic analysis: Longstaffe *et al.* 1992; Holmden *et al.* 1997; McKay & Longstaffe 1997; palynology: Wightman *et al.* 1987; MacEachern *et al.* 1999a; organic matter characterisation: Reidiger *et al.* 1997; and ichnology: Pemberton *et al.* 1982; Wightman *et al.* 1987; Beynon *et al.* 1988; MacEachern & Pemberton 1994; MacEachern *et al.* 1999a).

Extensive brackish-water deposits in the Cretaceous record of Alberta are related to the preservation of numerous, marginal-marine sedimentary systems in which salinity gradients (from fresh to marine) were characteristic. The depositional environments were varied and included estuaries, incised valleys, embayments and deltas (Zaitlin *et al.* 1995). Basin physiography is also considered to have been a contributing factor, because the shallow waters of the Western Intracontinental Seaway were probably sensitive to heavy rainfall and runoff from the rising Cordillera, as well as from the topographically emergent Canadian Shield. Tidal forces are known to have been active in the basin (Klein & Ryer 1978; Smith 1988), and would have been responsible for the exchange of saline water into the area.

From an economic perspective, brackish-water deposits in Cretaceous strata of the WCSB are extremely important. Heavy oil deposits in the region are largely encased within associated strata (e.g. Beynon *et al.* 1988; Zaitlin & Shultz 1990; Wightman & Pemberton 1997; Hubbard *et al.* 1999), as are numerous conventional oil- and gas-bearing sandstones (e.g. Brownridge & Moslow 1991; MacEachern & Pemberton 1994; Zaitlin *et al.* 1995; Gingras *et al.* 1998).

Database and previous work

The study area is located in the Cadotte region of the central Alberta plains, between townships 83 and 86 and ranges 15 and 20 west of the fifth meridian (Fig. 1). The Bluesky Formation in the area occurs in the subsurface between 500 and 600 m depth (from the surface). The sedimentological database consists of 81 cored intervals (Figs. 1, 2).

Siliciclastic sediments of the Bluesky Formation are interpreted to represent an ancient wave-dominated estuary (Fig. 3A) (Hubbard 1999; Hubbard *et al.* 1999, 2002). The previously published work provides a well-documented sedimentological and stratigraphical framework into which this ichnological study is integrated. For the purposes of this paper, the Bluesky deposits are separated into three discrete facies divisions reflecting the upper, middle and lower estuary (Fig. 3B).

Upper estuary deposits consist primarily of facies deposited on the bayhead delta, in quiescent bays, and on supratidal and intertidal flats (Fig. 3). The upper estuary represents the head of the estuary most closely related

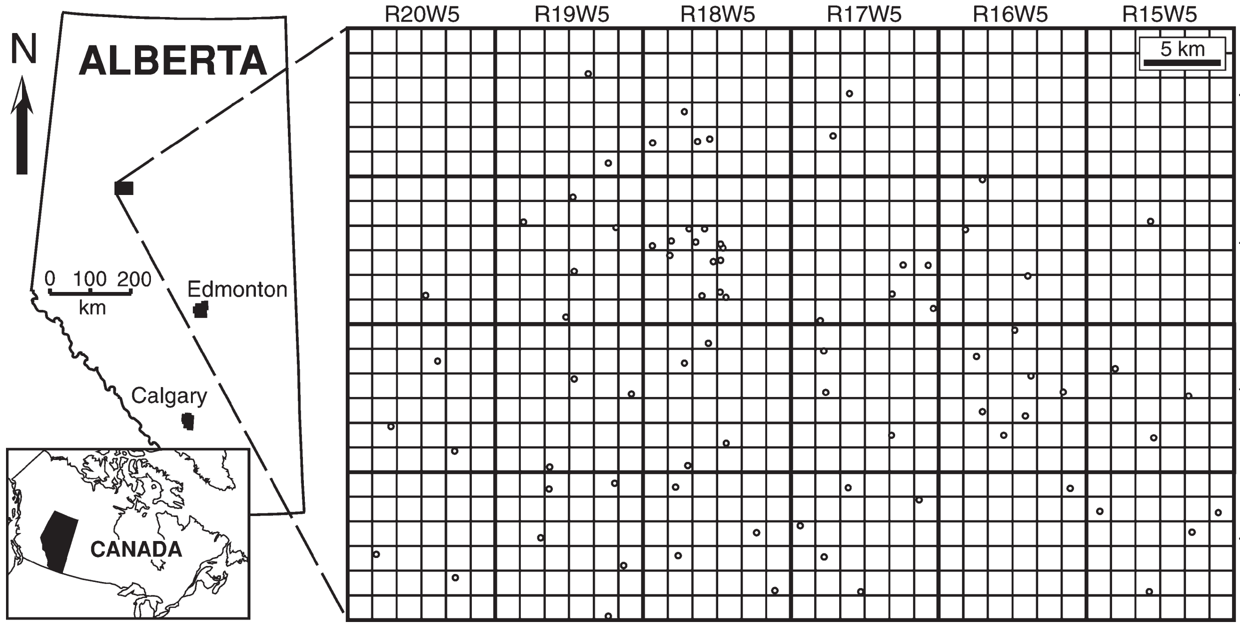

Fig. 1. Location map of the study area and distribution of examined cores (black circles).

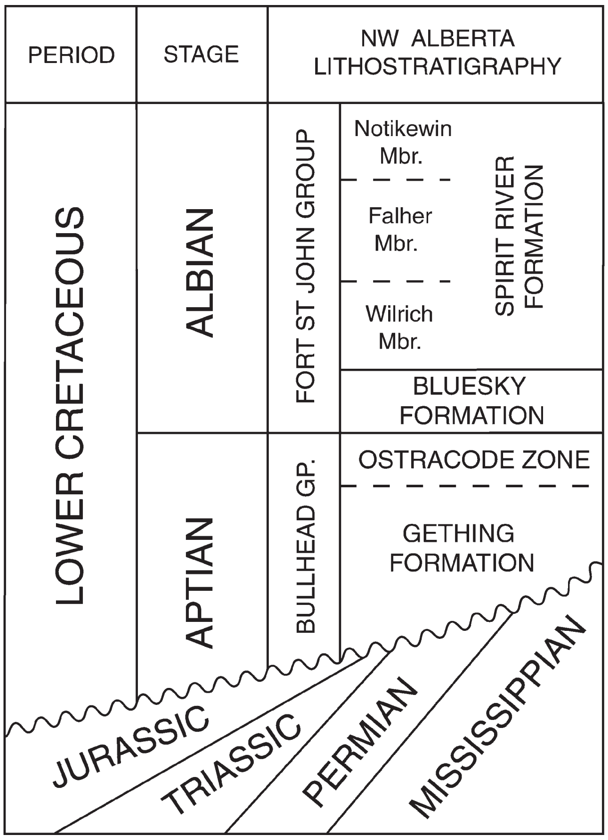

Fig. 2. Subsurface Lower Cretaceous stratigraphic nomenclature for the Cadotte region of Alberta. Not to scale.

to (and including) the fluvial point source. In this region, water salinities are considered to have been low, characterised by fresh to brackish water. Middle estuary deposits include those deposited on tidal flats, in quiescent embayments/lagoons, on the flood-tidal delta, and in back-barrier tidal channels, where brackish water is typical (Fig. 3). The lower estuary represents the marine mouth of the estuary, where water salinities range from brackish to normal marine (> 30‰). Associated deposits are typically sandy in the study area, deposited on tidal deltas, in tidal inlet channels, and/or on the barrier/shoreface complex (Fig. 3).

Trace fossil analysis

Trace fossils overall are abundant and diverse in the study area. Numerous ichnogenera are present, including *Planolites*, *Skolithos*, *Thalassinoides*, *Cylindrichnus*, *Arenicolites*, *Asterosoma*, *Palaeophycus*, *Rosselia*, *Chondrites*, *Subphyllochorda*, *Teredolites*, *Teichichnus*, *Gyrolithes*, *Macaronichnus*, *Helminthopsis*, *Anconichnus*, *Diplocraterion* and *Schaubcylindrichnus*. Roots and fugichnia (escape traces) are also present. Trace fossil diversity within a particular facies is variable, generally not exceeding six diagnostic ichnogenera. The distribution of trace fossils across the study area provides a rationale for the palaeoenvironmental reconstruction of the estuary. Figure 4 provides a summary of the trace fossils present in the Bluesky Formation in the Cadotte region of Alberta.

Upper estuary – observations and interpretations

Herein, the upper estuary is considered to be the part of the ancient deposit that was most strongly influenced by fluvial processes but within the realm of observable tidal reworking. Sediments in the upper estuary accumulated in numerous subenvironments, thereby under various physicochemical conditions. The four subenvironments are: supratidal flat, bayhead delta, intertidal/subtidal flat, and quiescent bay.

Supratidal flat deposits

Supratidal flat deposits are moderately to pervasively bioturbated, with a trace fossil assemblage consisting solely of roots (Figs. 4A, 5E, F). Pedogenic slickensides suggest the incipient development of soils, or at least pedogenic alteration in associated lithofacies.

This low-diversity assemblage of traces is typical of supratidal areas, and is well documented from studies of the Georgia marshes (e.g. Howard & Frey 1985). Freshwater input from rain, sporadic storm surges of brackish water into the area, and episodes of desiccation induce inhospitable infaunal living conditions. Where the flats are vegetated, binding of the sediment by roots further discourages the activities of burrowing animals. Furthermore, in tropical climates and during arid periods, supratidal flats may become hypersaline (Howard & Frey 1985; Zonneveld *et al.* 2001).

Bayhead delta deposits

Bayhead delta deposits in the study area consist primarily of sandstone, dominated by physical sedimentary structures indicative of high-energy currents (Hubbard *et al.* 1999). Bioturbation is absent to rare, and where present, is restricted to thin mudstone laminae or interbeds. Trace fossils include moderately abundant *Planolites*, as well as rare *Cylindrichnus*, *Skolithos* and *Thalassinoides* (Figs. 4A, 5C). Individual beds rarely contain a diversity of trace fossils of greater than two ichnogenera; low ichnofaunal diversity is typical of sandy bayhead delta deposits (e.g. MacEachern & Pemberton 1994; MacEachern *et al.* 1999b).

Proximity to the fluvial point source plays an important role in lowering overall salinities in the delta,

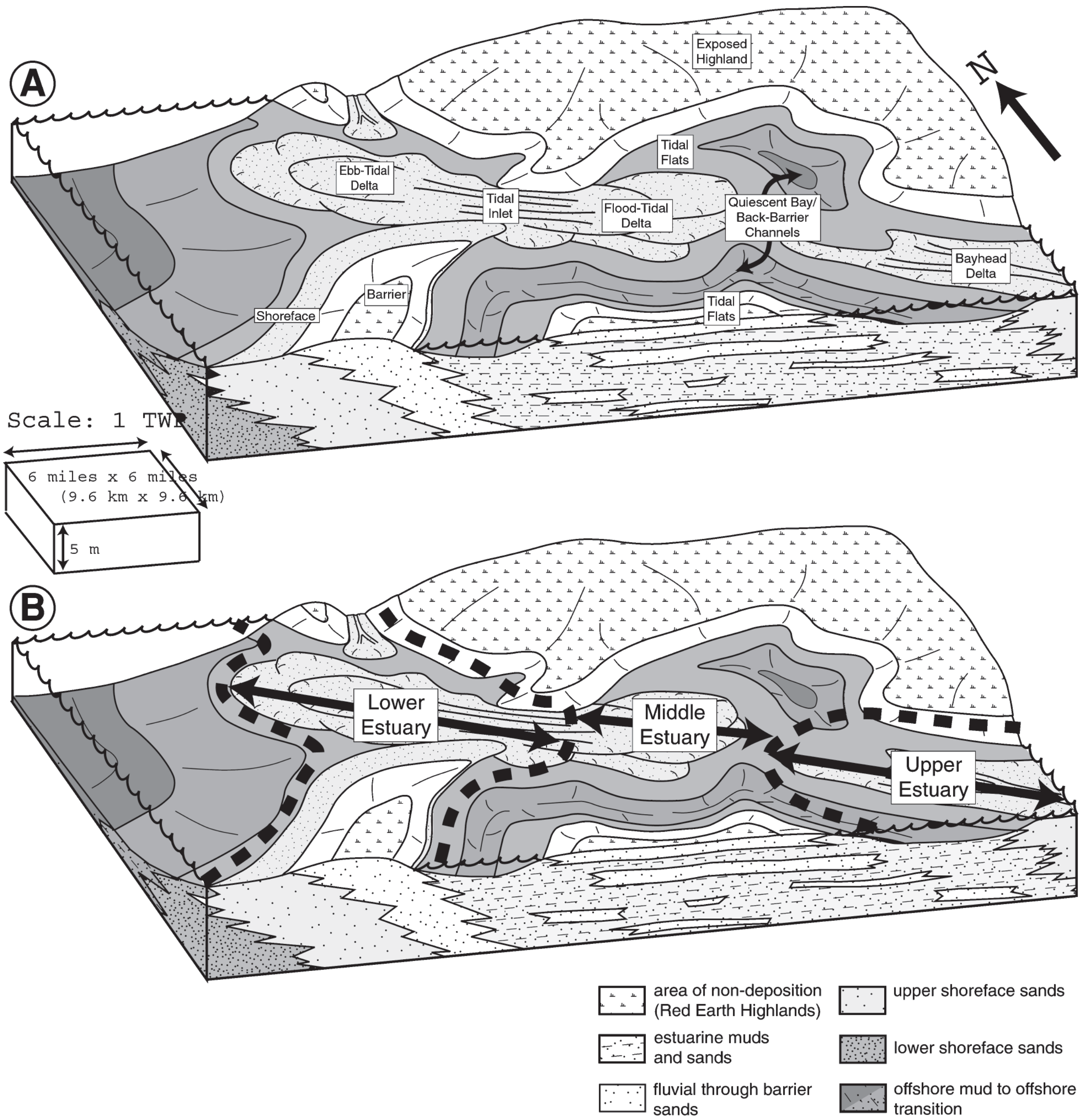

Fig. 3. A: The wave-dominated estuary facies model interpreted for the Bluesky Formation in the Cadotte study area (modified from Hubbard *et al.* 2002). B: Estuarine divisions (upper, middle and lower) as defined in this study.

thereby having the potential to exert a significant environmental stress on organisms (Gingras *et al.* 1998). The observed trace fossil assemblage is, in fact, consistent with salinity-stressed ichnofacies documented from other deposits of similar age, most notably the McMurray Formation of the WCSB (e.g. Ranger & Pemberton 1992). In these deposits, the trace fossil assemblage is dominated by ethologies (behaviours) associated with organisms able to adapt to changing environmental conditions. In particular, *Skolithos*, *Planolites* and *Thalassinoides* are all burrow architectures that, in the modern, can be constructed relatively quickly and are commonly occupied by robust, efficient burrowers. The trace fossil assemblage is thereby interpreted to reflect brackish-water conditions accompanied by energetic currents and high sedimentation rates during deposition; conditions that eliminate the potential for many trace-making organisms to inhabit sediments of the bayhead delta (Nanson *et al.* 2000).

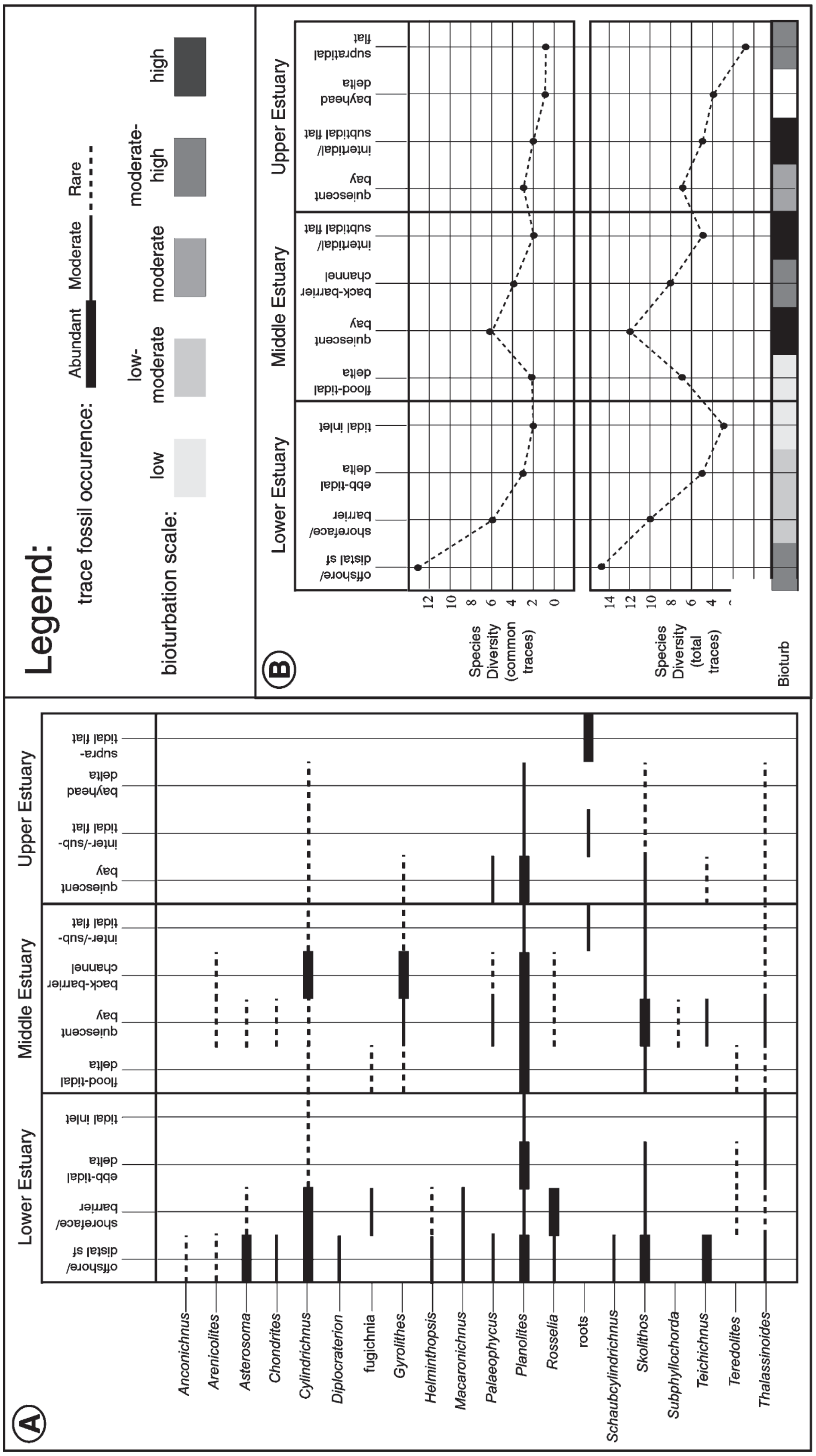

Fig. 4. A: Palaeoenvironmental distribution of trace fossils in the Bluesky Formation. B: Trace fossil diversity (by ichnogenera) for each depositional environment (note that "common" ichnofossils include those that are either abundant or moderately abundant).

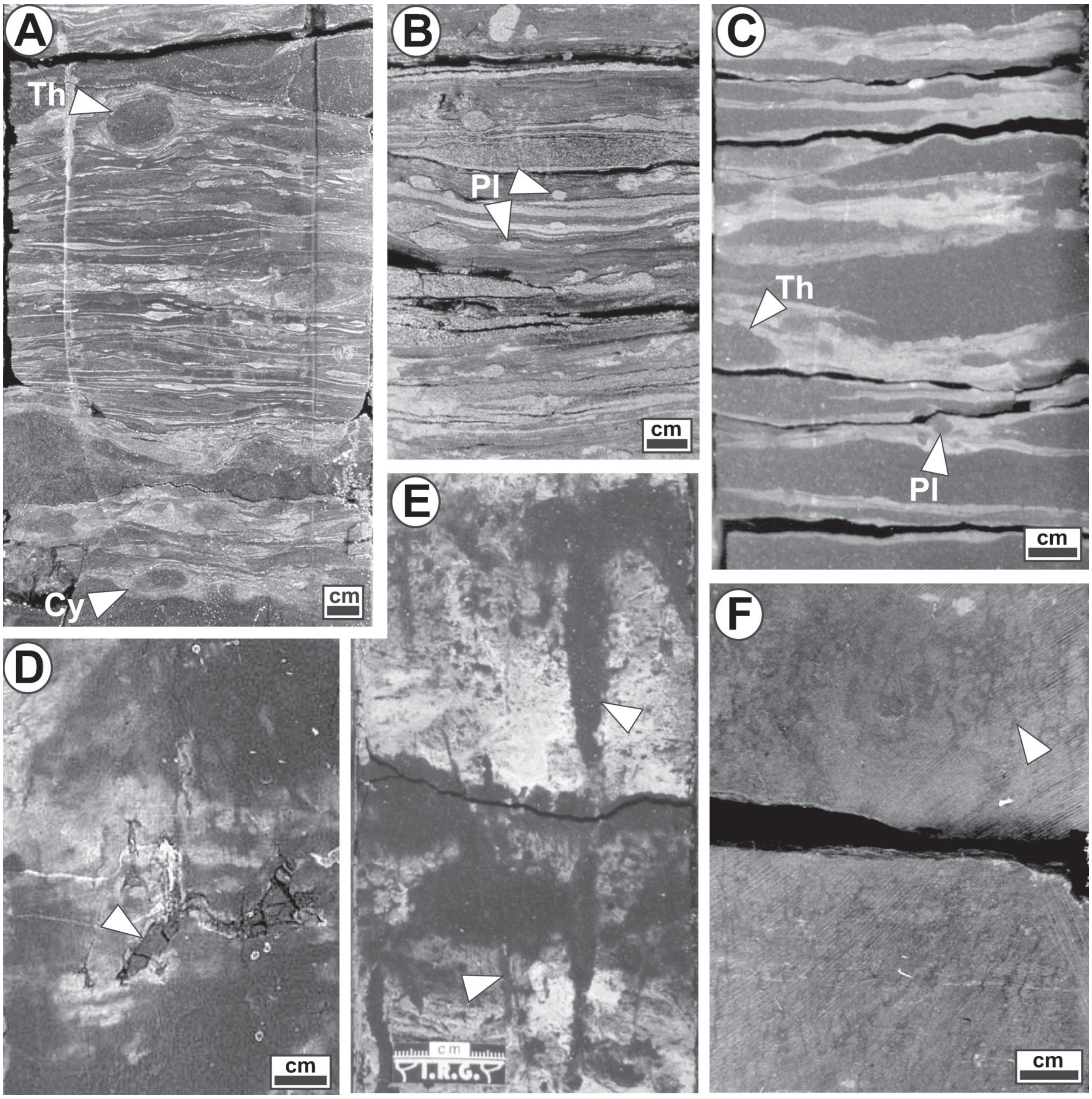

Fig. 5. Trace fossils of the upper estuary in the Bluesky Formation, including *Thalassinoides* (Th), *Cylindrichnus* (Cy), *Planolites* (Pl) and roots (indicated by arrows in D, E, and F). Note that in each photograph, bitumen-stained sandstone is the dark lithology and muddy siltstone is the light lithology. Black mudstone laminae are present in (A) and (B). A, B: Low-abundance and diversity trace fossil assemblages in quiescent bay deposits (core locations – A: 07-09-84-16W5, 654.45 m; B: 06-36-83-16W5, 627.2 m). C: Bioturbated mudstone beds associated with bayhead delta distributary channel point bar deposits (07-30-83-15W5, 645.0 m). D: Intertidal flat, burrow-mottled sandstone and mudstone with coalified roots (06-25-83-15W5, 628.5 m). E, F: Rooted supratidal flat deposits (E: 04-10-85-18W5, 597.5 m; F: 06-33-83-17W5, 625.9 m).

Tidal flat deposits

The facies associated with subtidal and intertidal flat deposition in the upper estuary is characterised by a mottled texture related to extensive biogenic reworking coupled with slow sedimentation rates (Frey & Pemberton 1985; Gingras *et al.* 1999). Individual trace fossils are rarely discernible. Trace fossils recognised include common *Planolites* and rhizoliths, with subordinate *Cylindrichnus*, *Skolithos* and *Thalassinoides* (Figs. 4A, 5D).

This low-diversity trace fossil suite results from reduced salinities, as well as fluctuating currents and sedimentation rates (Weimer *et al.* 1982). Such suites are similar to *Planolites*/*Arenicolites*/*Skolithos* assemblages reported from upper estuarine tidal flats at Willapa Bay, western USA (Gingras *et al.* 1999) and the Bay of Fundy, eastern Canada (Gingras 2002). At those locales, fluctuation in water salinity can also result in the construction of deeper burrow refuges for many organisms, such as thin *Skolithos* produced by capitellid polychaetes, an observation that echoes Rhoads (1975). Notably, sediments on upper estuarine tidal flats are commonly dysaerobic. This is the result of a relatively high proportion of terrestrial organic detritus accumulating in the sediment and local rooting in higher (?supratidal) zones.

Quiescent bay deposits

Quiescent bay deposits of the upper estuary in the Bluesky Formation are typically moderately bioturbated, although vestigial lamination is generally preserved (Figs. 4B, 5A, B). Common *Planolites*, *Palaeophycus* and *Skolithos*, as well as rare *Cylindrichnus*, *Gyrolithes*, *Teichichnus* and *Thalassinoides* characterise the trace fossil assemblage (Figs. 4A, 5A, B). The number of trace fossil forms observed within individual units is typically no more than four. The simple burrow forms common to these deposits, as well as the low-diversity/low-abundance assemblage of trace fossils indicate a stressed environment, capable of only supporting organisms utilising trophic generalist feeding behaviours.

Current energies and sedimentation rates are low in this comparatively sheltered setting. Consequently, the predominant stresses on burrowing organisms probably reflect reduced salinity and possibly escalated turbidity (e.g. MacEachern & Pemberton 1994; MacEachern *et al.* 1999a). Heightened turbidity is inferred, in part, from sedimentological observations, including common mud drapes and intercalated mud beds. Mud linings associated with *Cylindrichnus* and *Palaeophycus*, and the persistence of a deposit-feeding component of the ichnofossil assemblage also support this interpretation.

Middle estuary – observations and interpretations

In the study area, the middle estuary represents all sediments that accumulated within the bay, between the bayhead and mouth. Facies of the middle estuary in the Bluesky Formation include those deposited on intertidal/subtidal flats, in low-energy back-barrier channels, in quiescent bays, and on the flood-tidal delta. Examples of typical trace fossils from facies of the middle estuary are presented in Figs. 6 and 7.

Tidal flat deposits

Subtidal and intertidal flat sediments in the middle estuary are typically completely reworked due to biogenic activity, with few physical sedimentary structures preserved (Fig. 6E, F). Trace fossils are generally unidentifiable. However, *Planolites*, *Skolithos* and roots are moderately abundant (Fig. 6E). *Cylindrichnus*, *Gyrolithes* and *Thalassinoides* are observed rarely (Fig. 4A).

Sediment homogenisation due to extensive burrowing is common to stressed, brackish-water settings, particularly on tidal flats where sedimentation rates are typically very slow (Fig. 4B) (Edwards & Frey 1977; Frey & Pemberton 1985; Gingras *et al.* 1999). Stresses on organisms in the intertidal realm are principally considered to be related to lowered salinity, and short-term fluctuations in salinity levels related to precipitation, discharging groundwater, and tidal influence; suppressed oxygen levels, desiccation, temperature, and predation may also be important locally (Martini 1991; Cadée 1998; Gingras *et al.* 1999). However, food resources (algae) may be plentiful. Typically, the ichnological assemblage associated with this range of stresses and an abundant food resource is characterised by: (1) a sporadic distribution of intensely churned biogenic textures that range between fabrics dominated by a single diminutive ichnogenus and those that result from four or five comparatively robust ichnogenera; and (2) close juxtaposition of horizontal and vertical biogenic structures in high burrow densities.

Tidal channel deposits

Low-energy, back-barrier tidal channel deposits comprise point bar deposits characterised by a prevalence of inclined heterolithic stratification. Bioturbation varies from moderate to high, with finer-grained units typically more thoroughly reworked. The trace fossil suite consists of common *Cylindrichnus*, *Gyrolithes*, *Planolites* and *Skolithos* (Figs. 4A, 6). *Arenicolites*, *Palaeophycus*, *Rosselia* and *Thalassinoides* are also present locally. In many examples, strata from ancient point bar deposits are characterised by monospecific trace fossil assemblages, which are often associated with brackish-water deposits (Fig. 6B, D) (Pemberton *et al.* 1992a). Trace fossil diversities range between two and four ichnogenera in most cases. Most of the ichnofossils descend from muddy horizons, and are defined by muddy fills (Fig. 6A–D).

During periods of significant sand deposition and reworking, it is inferred that conditions were unfavourable for infaunal colonisation. Seasonal pulses of increased sedimentation, high water turbidity and potentially lowered salinity may all be related to increased fluvial discharge into the estuary via the distributary network of the bayhead delta. Workers in modern estuaries have explained seasonal variations in levels of bioturbation in this way (Dalrymple *et al.* 1991; Gingras *et al.* 1999, 2002). The observations of the Bluesky Formation, however, may also reflect a taphonomic bias, in that mud-lined burrows are more easily seen, especially in oil–sand intervals. The trace fossil assemblage is dominated by

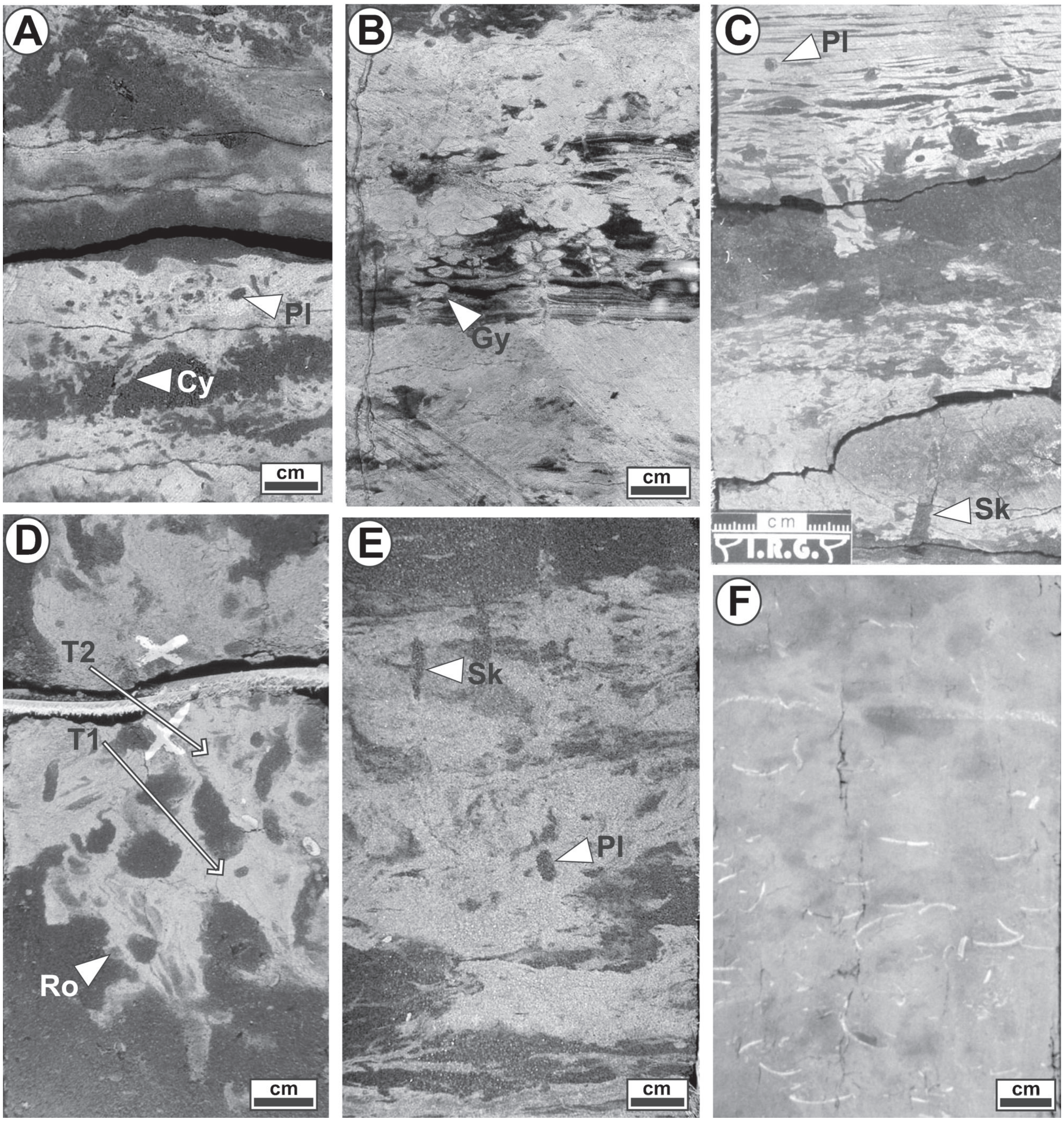

Fig. 6. Trace fossils of the middle estuary (low-energy, back-barrier tidal channels and tidal flats) in the Bluesky Formation, including *Cylindrichnus* (Cy), *Planolites* (Pl), *Gyrolithes* (Gy), *Skolithos* (Sk), and *Rosselia* (Ro). Note that in each photograph, bitumen-stained sandstone is the dark lithology and muddy siltstone is the light lithology. A–C: Heterolithic stratification (mud beds are pervasively reworked) associated with tidal channel (point bar) deposits (core locations – A: 06-33-83-17W5, 633.3 m; B: 05-33-83-19W5, 606.5 m; C: 11-17-83-17W5, 689.0 m). D: Readjustment of a *Rosselia* in tidal channel deposits, probably constructed in response to high sedimentation rates (T1 = time 1; T2 = time 2, after burrow readjustment) (11-17-83-18W5, 625.8 m). E, F: Tidal flat deposits are commonly highly bioturbated. However, individual trace fossil genera are commonly not discernible (E: 12-15-85-18W5, 574 m; F: 04-24-84-16W5, 632.6 m). Note the abundance of pelecypod shells in (F).

simple filter-feeding and interface-feeding structures (e.g. *Cylindrichnus*, *Gyrolithes*, *Skolithos, and Arenicolites*). Deposit-feeding ethologies are simple (e.g. *Planolites* and *Thalassinoides*) and reflect mobile trace makers (e.g. polychaetes and decapods).

Quiescent bay deposits

Facies associated with quiescent bay sedimentation in the middle estuary are characterised by moderate to high levels of bioturbation (Fig. 4B). The trace fossil suite is

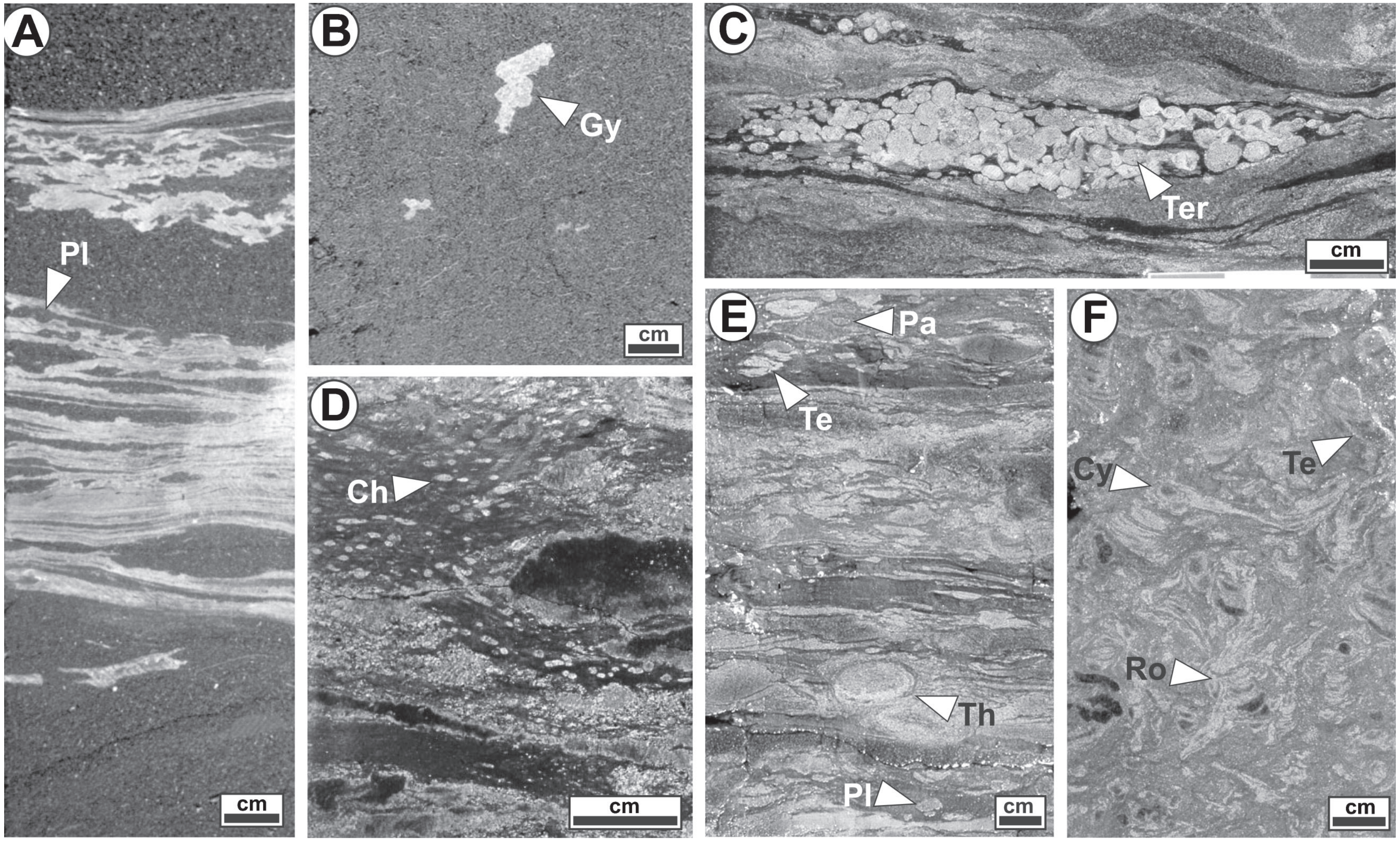

Fig. 7. Trace fossils of the middle estuary (flood-tidal delta and quiescent bay deposits) in the Bluesky Formation, including *Planolites* (Pl), *Gyrolithes* (Gy), *Teredolites* (Ter), *Chondrites* (Ch), *Palaeophycus* (Pa), *Teichichnus* (Te), *Thalassinoides* (Th), *Cylindrichnus* (Cy) and *Rosselia* (Ro). Note that in each photograph, bitumen-stained sandstone is the dark lithology and muddy siltstone is the light lithology. Black mudstone laminae are present in (D) and (E). A, B: Flood-tidal delta distributary channel deposits are characterised by rare, diminutive trace fossils (core locations – A: 04-05-85-17W5, 604.9 m; B: 14-21-85-18W5, 582.44 m). C: Allochthonous coal with pyritised *Teredolites* (10-23-83-18W5, 611.0 m). D: *Chondrites* in deposits interpreted to have accumulated in an oxygen-stressed, quiescent embayment setting (13-22-84-19W5, 566.5 m). E, F: Moderately through to pervasively bioturbated quiescent bay deposits (E: 04-24-84-16W5, 635.5 m; F: 11-17-83-18W5, 627.0 m).

diverse, consisting of common *Planolites*, *Skolithos*, *Gyrolithes*, *Palaeophycus*, *Teichichnus* and *Thalassinoides*, as well as rare *Arenicolites*, *Asterosoma*, *Chondrites*, *Cylindrichnus*, *Rosselia* and *Subphyllochorda* (Figs. 4A, 7D–F). Individual beds rarely contain more than five or six trace fossil forms.

The trace fossil suite in the Bluesky Formation is similar to that recognised by MacEachern *et al.* (1999a) in the incised valley fills of the central basin deposits in the Cretaceous Viking Formation of Alberta. Supported by micro-palaeontological and palynological data in their study, those suites were interpreted to be highly indicative of deposition in brackish water. In this study, the presence of *Subphyllochorda*, *Asterosoma*, and *Rosselia* suggests that the water chemistries were somewhat more marine.

Flood-tidal delta deposits

Flood-tidal delta deposits in the Bluesky Formation are characterised by sparse bioturbation (Fig. 4B). A low-diversity trace fossil assemblage is present, with diminutive forms common (Fig. 7B). *Planolites* and *Skolithos* are most commonly observed, restricted to thin mudstone beds (Fig. 7A). Other trace fossils include *Cylindrichnus*, fugichnia, *Gyrolithes*, *Thalassinoides* and *Teredolites* (Fig. 4A). The occurrence of *Teredolites* is restricted to wood fragments and coaly debris, and is probably not *in situ* within tidal delta sandstones (Fig. 7C). Trace fossil diversity within a single unit is low, ranging from one to two ichnogenera.

Along with high sedimentation and low salinity, turbid water may also contribute to reduced burrowing activity in settings such as tidal deltas. Trace fossil diversity is directly affected by turbidity as filter-feeding strategies may be hindered due to excessive sediment in the water column (Wilber 1983; Moslow & Pemberton 1988; Gingras *et al.* 1998; Coates & MacEachern 1999).

Lower estuary/marine – observations and interpretations

Subenvironments of the lower estuary, as defined in this study, specifically include the tidal inlet, ebb-tidal delta, shoreface/barrier and offshore/distal shoreface. There is a paucity of core data in the westernmost part of the study area (Fig. 1); consequently, offshore/distal shoreface deposits are poorly constrained. These deposits preserve complex facies architectures, and features from different cores suggest deposition in lower shoreface, offshore transition or offshore settings, based on the generalised shoreline profile model defined by Reading & Collinson (1996). The other lower estuarine deposits are more extensively cored, and are sandier overall (Hubbard *et al.* 2002).

Tidal inlet deposits

Upper flow regime conditions are interpreted to have persisted in the tidal inlet, based on the presence of pervasive horizontal planar parallel to low-angle cross-beds in these facies (Hubbard *et al.* 2002). Consequently, bioturbation is low to absent in associated units (Fig. 4B). The only trace fossils observed in tidal inlet deposits are *Planolites*, *Thalassinoides* and *Cylindrichnus* (Figs. 4A, 8F).

Trace fossil diversities are low, in part due to high currents and sedimentation rates in tidal inlet settings (e.g. MacEachern & Pemberton 1994; Savrda *et al.* 1996). It is likely that physical processes overshadowed the effects of other potential stresses on the community of burrowers. The paucity of trace fossils observed in tidal inlet sandstones of the Bluesky Formation is consistent with research in the Georgia estuaries of the eastern USA, which concluded (Howard & Frey 1973) that burrows are rare to absent in coarse sands deposited by energetic currents in the lower estuary.

Ebb-tidal delta deposits

Bioturbation in ebb-tidal delta deposits is low to moderate overall, and predominantly associated with mudstone intervals (Fig. 4B). The low-diversity trace fossil suite consists of common *Planolites*, *Skolithos* and *Thalassinoides*, as well as rare *Cylindrichnus* and *Teredolites* (Figs. 4A, 8E).

Ebb-tidal delta deposits are rare in the rock record, and their inaccessibility in the modern has resulted in a general paucity of information about their facies characteristics, especially with regard to burrowing organisms. No more than three trace fossil forms were observed in individual units interpreted to have been deposited in ebb-tidal deltas. Such a reduced diversity suggests stressed environmental conditions. Variable sedimentation rates, salinity fluctuations, brackish water, and heightened water turbidity are all likely to have contributed to the hostile environment indicated by the trace fossil assemblage.

Shoreface/barrier deposits

Sandy shoreface/barrier deposits are predominantly characterised by low to moderate bioturbation intensities (Fig. 4B), although biogenic reworking is pervasive in some facies (Fig. 8G). Robust, mud-lined *Cylindrichnus* and *Rosselia* are commonly present in bitumen-stained barrier sandstones of the Bluesky Formation (Fig. 8H, I). These vertical burrows predominantly represent domiciles of filter-feeding organisms, and the trace fossil assemblage is assigned to the *Skolithos* ichnofacies (*cf.* Pemberton *et al.* 1992a). Other common traces include fugichnia, *Macaronichnus*, *Planolites* and *Skolithos* (Fig. 4A).

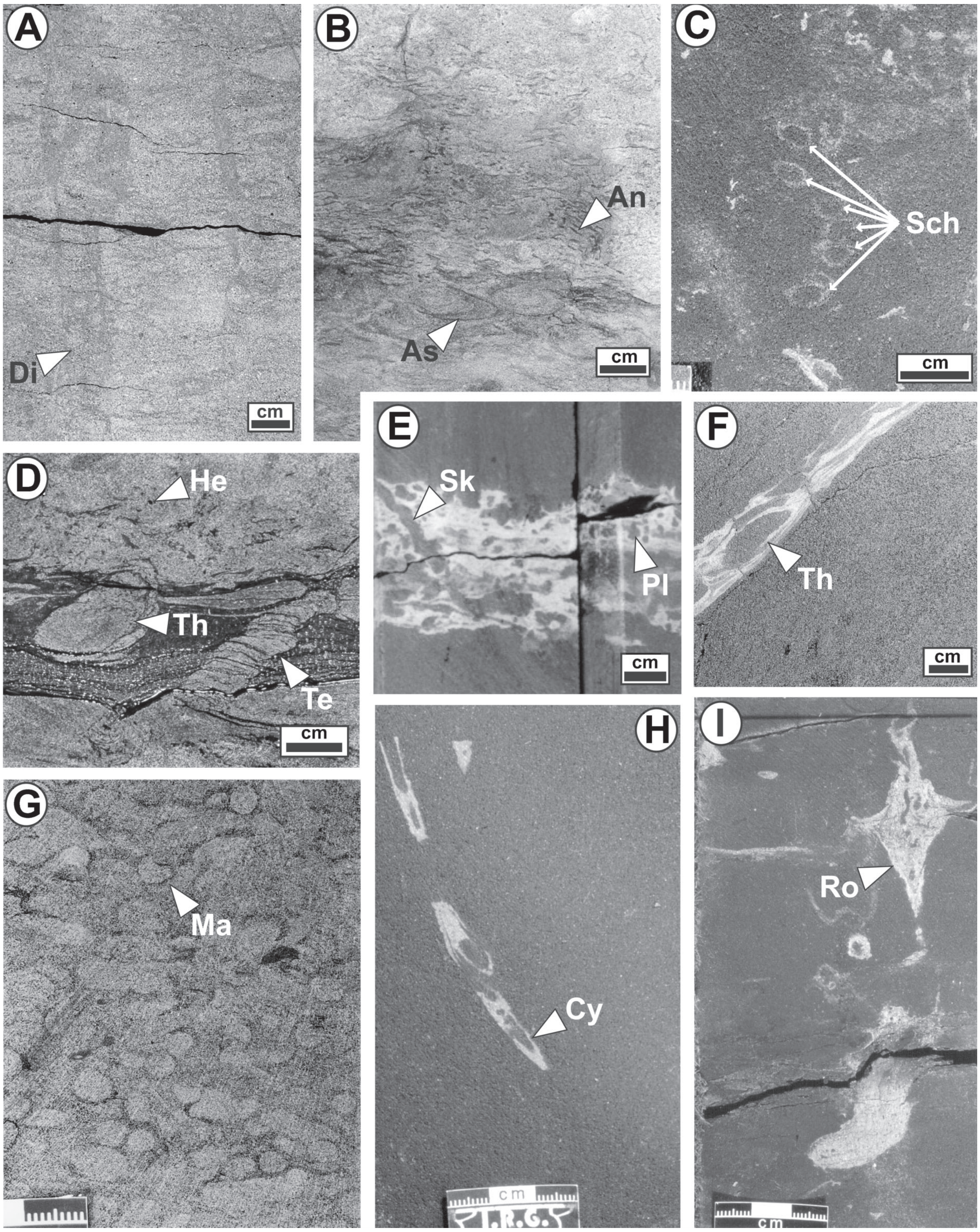

Fig. 8. Trace fossils of the lower estuary in the Bluesky Formation, including *Diplocraterion* (Di), *Anconichnus* (An), *Asterosoma* (As), *Schaubcylindrichnus* (Sch), *Macaronichnus* (Ma), *Helminthopsis* (He), *Teichichnus* (Te), *Thalassinoides* (Th), *Skolithos* (Sk), *Planolites* (Pl), *Cylindrichnus* (Cy) and *Rosselia* (Ro). Note that in each photograph, bitumen-stained sandstone is the dark lithology and muddy siltstone is the light lithology. Black mudstone laminae are present in (D). A–D: Offshore/distal shoreface deposits are characterised by diverse trace fossil assemblages, commonly associated with complex feeding and dwelling structures (core locations – A: 16-08-84-20W5, 525.1 m; B: 16-08-84-20W5, 529.8 m; C: 04-10-85-20W5, 520.2 m; D: 13-17-83-20W5, 572.8 m). E: Complete reworking of a mudstone bed in an ebb-tidal delta deposit (04-10-85-20W5, 554.9 m). F: Bioturbation is rare in tidal inlet deposits, restricted primarily to mudstone interbeds (note that the angle of bedding is exaggerated as the core is from a deviated well) (09-16-85-18W5, 627.75 m). G: Upper shoreface sandstone completely reworked by *Macaronichnus* (14-02-84-20W5, 553.1 m). H, I: Robust, mud-lined trace fossils in deposits of the fossil barrier–bar complex (H: 11-17-83-18W5, 627.2 m; I: 14-11-83-20W5, 600.5 m).

Macaronichnus is known to be a useful indicator of highly oxygenated surface waters and sediments, common to a narrow range of environments, including the upper shoreface, foreshore and estuary channel bars (e.g. Clifton & Thompson 1978; Curran 1985; Saunders *et al.* 1994). Rarer trace fossil elements present in shoreface/barrier deposits of the Bluesky Formation include *Asterosoma*, *Helminthopsis*, and *Thalassinoides*, as well as *Teredolites* in transported wood clasts (Fig. 4A).

Distal shoreface/offshore transition deposits

Offshore/distal shoreface deposits in the study area are divided into two dominant lithofacies: (1) fine-grained siltstone/mudstone and (2) sandstone. Moderate to high bioturbation intensities are characteristic of these facies, with high diversities of trace fossil forms common (up to eight ichnogenera in some units). The trace fossil assemblage in fine-grained units includes *Asterosoma*, *Cylindrichnus*, *Chondrites*, *Helminthopsis*, *Palaeophycus*, *Planolites*, *Skolithos*, *Teichichnus* and *Thalassinoides*. This assemblage is assigned to the *Cruziana* ichnofacies, consisting mainly of deposit-feeding structures.

Common trace fossils present in the sand-rich facies include *Asterosoma*, *Cylindrichnus*, *Diplocraterion*, *Helminthopsis*, *Palaeophycus*, *Planolites*, *Rosselia*, *Schaubcylindrichnus*, *Skolithos*, and *Teichichnus* (Figs. 4A, 8A–C). Locally present are *Anconichnus*, *Arenicolites* and *Macaronichnus*. The high diversity of burrows and the predominance of vertical, cylindrical and U-shaped burrows lead to the assignment of the assemblage into the *Skolithos*, or mixed *Skolithos–Cruziana* ichnofacies, deposited in the lower shoreface to offshore environment (cf. MacEachern & Pemberton 1992; Pemberton *et al.* 1992b). Unbioturbated beds associated with this facies are characterised by oscillation ripples and hummocky cross-stratification, suggesting the working of sediments by fair-weather and storm waves.

Discussion

Estuaries comprise a complex association of sediments, deposited in various subenvironments (Howard & Frey 1973). The different physicochemical stresses on burrowing organisms throughout an estuary are numerous, including lowered salinity, fluctuating salinity, high current energy, increased sedimentation rates, high water turbidity, and reduced oxygenation of bottom and interstitial waters. These palaeoenvironmental factors, as a whole, shape the trace fossil assemblage that is ultimately preserved in the rock record (Rhoads *et al.* 1972; Pemberton *et al.* 1992a). Discerning the effects of these stresses on the assemblage is difficult, however, especially if it is conceded that the burrowing behaviour of an organism is also strongly influenced by sediment texture (e.g. Howard & Frey 1973; Taylor *et al.* 2003). Nevertheless, ichnological patterns are evident across the Bluesky Formation estuarine complex in the study area (Fig. 4). Ichnofabrics were influenced by the relative intensities of the various primary palaeoenvironmental stresses that were active across the depositional system (Fig. 9). A summary of the effects of various stresses on infaunal organisms and their reflections in the rock record is

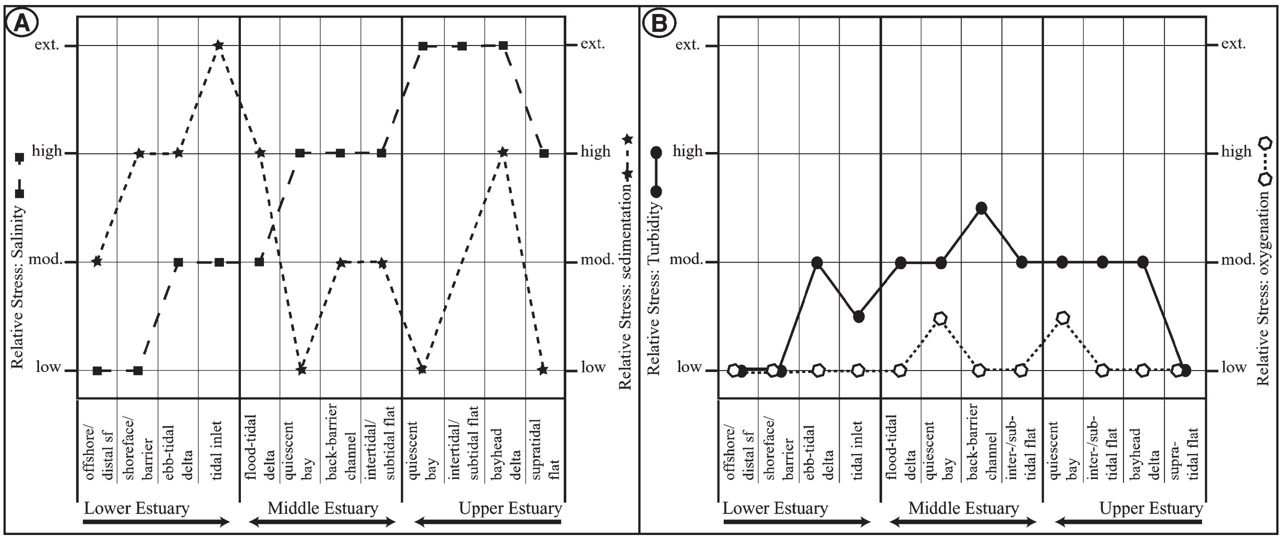

Fig. 9. A: Interpreted relative stresses on burrowing organisms due to lowered salinity and high sedimentation rates in the various subenvironments of the wave-dominated estuary studied. These are based on the observations made and interpretations discussed in this paper. Note that stresses related to lowered salinity increase towards the fluvial point source. B: Interpreted relative stresses on burrowing organisms due to high water turbidity and low oxygenation of bottom and interstitial waters.

presented below, based on observations made in this study.

The ichnological signature of rapid sedimentation and strong currents

Widespread coarse-grained deposits and the prevalence of sedimentary structures indicative of upper flow regime conditions lead to the interpretation that numerous facies of the estuary studied were deposited under energetic conditions (Hubbard *et al.* 2002). Accordingly, high current energy and sedimentation rates are interpreted to have limited burrowing activity in tidal inlet channels, on proximal tidal or bayhead deltas, and at the bases of back-barrier tidal channels.

In lower estuarine subenvironments, such as the tidal inlet where strong currents and rapid sedimentation are characteristic, burrows are absent despite the fact that most other (inferred) environmental parameters would be ideal for organisms to flourish (e.g. upper brackish to normal marine salinities, and oxygenated water and sediment). It is therefore interpreted that in the tidal inlet, high current energies and sedimentation (as well as migrating bedforms locally) comprise the primary stresses on burrowers. The significance of this environmental parameter is underscored by the fact that tidal inlet deposits are characterised by the least diverse trace fossil assemblage in the entire lower and middle estuary (Fig. 4B).

It is more difficult to assess the relative importance of the different environmental parameters in the bayhead delta area. There, strong currents and heightened sedimentation probably imparted a significant effect on the burrowing infauna (Fig. 9). However, persistent freshwater, as well as turbid water, inputs are probably also key factors in controlling the behaviour and abundance of trace-making organisms locally (Fig. 9). Based on the data collected, there is no way of deciphering the relative influence of individual physicochemical parameters in the ancient bayhead delta of the Bluesky Formation. Rare fugichnia and a relatively uniform distribution of trace fossils suggest that episodic sedimentation resulting from storms was minor during the accumulation of Bluesky Formation deposits.

Circulation in wave-dominated estuarine settings is associated with a null zone in the central estuary where tidal and fluvial currents converge and muddy facies accumulate in the turbidity maximum (Allen 1991; Dalrymple *et al.* 1992). Facies of the Bluesky Formation potentially influenced by turbidity include those deposited on the distal flood-tidal delta, tidal flats, and the bayhead delta, as well as in quiescent bays and low-energy back-barrier tidal channels (Fig. 9). As discussed, burrows of deposit feeders normally predominate in sediments accumulating in turbid environments, as filter-feeding organisms may not be able to cope with excessive material in the water column (Moslow & Pemberton 1988; Buatois & López Angriman 1992; Gingras *et al.* 1998). Trace fossils interpreted as the burrows of filter-feeding organisms such as *Skolithos*, *Gyrolithes* and *Cylindrichnus* persist across most of these middle to upper estuary facies, however, suggesting that, overall, turbidity may not have been a major stress in the fossil estuary (Fig. 4).

The ichnological signature of oxygenation stress

In the estuarine deposits studied, stresses on trace-making organisms due to lowered oxygen are considered to have been low overall (Fig. 9). Most subenvironments are characterised by sandy substrates, interpreted to have been associated with effective water circulation resulting from tidal currents, wave energy and fluvial input. Facies in the Bluesky Formation, associated with potentially low levels of oxygen in bottom or interstitial water, include rare mudstones deposited in quiescent embayments/lagoons (Fig. 7D). Ekdale & Mason (1988) suggested that deposit-feeding burrows with open connections to the sediment–water interface (e.g. *Chondrites* and *Zoophycos*) are typical of facies associated with extremely low oxygen levels in interstitial and bottom waters. Other than in central bay facies, burrows recording this behaviour are rare to absent (Fig. 4A).

It is likely, however, that burrow assemblages associated with dysaerobic sediment differ from those of poorly oxygenated sedimentary environments (as in de Gibert & Ekdale 1999). Modern shallow-water assemblages associated with anoxic sediments comprise simple burrows that connect to the sediment–water interface, including diminutive *Trichichnus*, *Palaeophycus*, *Arenicolites*, and *Diplocraterion* (Gingras *et al.* 1999; Gingras 2002). Thus, dysaerobic ichnofossil assemblages should show a range of behaviours from simple, unusually small burrows to the more complex *Chondrites–Zoophycos* assemblage. In any case, the latter assemblage is strongly associated with more marine conditions of deposition (Ekdale & Mason 1988; Wignall 1991; Savrda 1992). However, the *Trichichnus*, *Palaeophycus*, *Arenicolites*, and *Diplocraterion* assemblage may represent the brackish-water equivalent of a dysaerobic open-marine ichnofacies.

The ichnological signature of salinity stress

For the most part, the strata examined in this study show that salinity stress is the dominant biologically limiting factor in the estuary deposits. The diversity and size of trace fossils systematically decrease along the length of the fossil estuary, from facies associated with freshwater input in the region of the bayhead delta to facies deposited in the region of the tidal inlet. Also, previous tenets of the brackish-water model (e.g. Howard & Frey 1973, 1975; Dörjes & Howard 1975; Pemberton *et al.* 1982; Wightman *et al.* 1987; Beynon *et al.* 1988; Pemberton & Wightman 1992; MacEachern & Pemberton 1994; Gingras *et al.* 1999; Buatois *et al.* 2002) apply well to this marginal-marine Bluesky Formation deposit. These include: impoverished marine assemblages; vertical and horizontal structures present; monospecific horizons; somewhat diminutive trace fossils; locally prolific population densities; and the presence of the mixed *Skolithos*–*Cruziana* ichnofacies. The ichnological patterns documented across the ancient deposit and their potential importance are discussed below.

Ichnological variation across the estuary

Through the comparison of deposits from estuarine subenvironments with similar physical conditions, the effects of chemical variability across the depositional system can be assessed. In other words, if it can be established that physical processes are similar on tidal flats in the middle and inner estuary, it can be inferred that physical differences in the sedimentary facies are due primarily to hydrochemical changes in the depositional waters. In this section, ichnological comparisons of: quiescent bay deposits of the upper and middle estuary, and of the offshore; tidal flat deposits of the upper and middle estuary; and mudstone laminae associated with bayhead, flood-tidal and ebb-tidal deltas are attempted, in order to assess the relative effect of salinity stress.

Quiescent deposits: embayment and offshore

Facies that accumulated predominantly through quiet-water sedimentation, such as embayment and offshore deposits, potentially preserve the best evidence for recognising the effects of ancient salinity levels (MacEachern *et al.* 1999a). This is true mostly due to the reduced impact of some of the other stresses in these environments (Fig. 9). In the upper estuary, where water salinity is lowest proximal to the fluvial point source, *Planolites*, *Palaeophycus* and *Skolithos* represent the only commonly recurring trace fossils in the quiescent bay (Fig. 4A). The secondary components of this assemblage consist of four other ichnogenera. In the same depositional setting in the middle estuary, the recurring suite comprises six forms: *Planolites*, *Skolithos*, *Gyrolithes*, *Palaeophycus*, *Teichichnus* and *Thalassinoides* (Fig. 4A). Secondary components of this assemblage include six other ichnogenera. At the marine end of the system in the offshore, the diversity of trace fossils is much higher, with recurring elements consisting of *Asterosoma*, *Cylindrichnus*, *Planolites*, *Skolithos*, *Teichichnus*, *Chondrites*, *Helminthopsis*, *Palaeophycus*, and *Thalassinoides* (Fig. 4A). In this setting, the complete assemblage also consists of up to six other, rarer components.

Some key observations can be summarised from the above information regarding salinity levels and the palaeoenvironment. The first is related to the diversity of trace fossils in the Bluesky Formation. At Willapa Bay, Washington, Gingras *et al.* (1999) documented the effects of lowering salinity on organism diversity and size from modern point bar sediments. They observed that species diversity and the size of the largest burrows decreased as salinity decreased up estuary (Fig. 10). The same trend is evident in similar curves plotted for the estuarine system present in the study area (Fig. 4B). Perturbations in these curves are associated with subenvironments where salinity stress was probably not the primary stress on burrowing organisms, such as in the tidal inlet (Fig. 9). Furthermore, the observation made by Gingras *et al.*

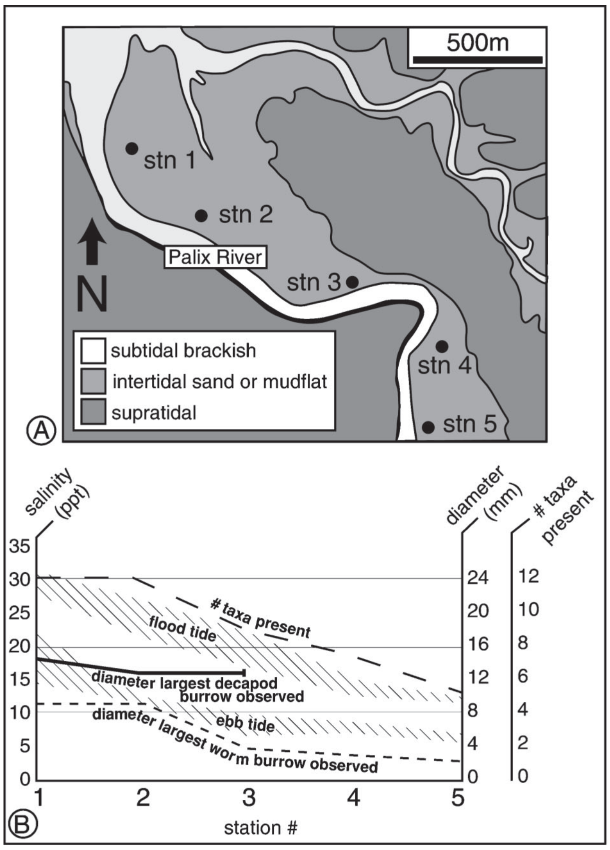

Fig. 10. A: Depositional environment map of the Palix River, Willapa Bay, Washington (western USA). At this location, observations of water salinity, burrowing organisms, and burrows were made at each of the five observation stations present. B: The diversity and size of burrowers/ burrows decreases upriver where salinity is lowest. The flood- and ebb-tidal cycles are shaded, as they represent a range of values at each station (modified after Gingras *et al.* 1999).

(1999) regarding the largest burrow sizes is consistent with the observations in the Bluesky Formation. In the study area, the most robust, common burrows in quiescent bay deposits of the upper estuary are small *Planolites* and *Palaeophycus*, with diminutive *Thalassinoides* rarely present. In the middle estuary, relatively larger burrows are common, including more robust *Thalassinoides*. In the offshore deposits, robust *Thalassinoides*, *Rosselia*, *Teichichnus* and *Cylindrichnus* are all present in moderate to high abundance (Fig. 4A).

Trophic generalists, or organisms able to adapt their feeding strategy in response to changing environmental conditions, have been considered to be diagnostic of brackish-water settings (Wightman *et al.* 1987; Beynon *et al.* 1988; Pemberton & Wightman 1992). In associated environments, adaptation by an organism generally results in the construction of simple horizontal or vertical burrows. Consequently, in an area transitory between fresh and marine water, burrow morphologies are increasingly complex towards the marine end of the system (e.g. Howard *et al.* 1975). This is the case observed in sediments of the Bluesky Formation. Relatively simple trace fossils, including *Planolites*, *Palaeophycus* and *Skolithos* (Fig. 4A), dominate quiescent bay deposits of the upper estuary. Middle estuary quiescent bay deposits are characterised by a trace fossil assemblage consisting of slightly more complex forms, which include *Gyrolithes*, *Teichichnus* and *Thalassinoides* (Fig. 4A). The most complex feeding and dwelling structures in quiescent deposits in the Bluesky Formation are associated with facies deposited in the offshore, including *Asterosoma*, *Chondrites*, *Helminthopsis*, and *Schaubcylindrichnus* (Fig. 4A).

Tidal flat deposits

The utility of trace fossils from tidal flat deposits in providing an adequate data set for the analysis of salinity stress is negated by their similarity throughout the depositional system, and that in all cases associated facies are pervasively bioturbated (Fig. 4B). The mottled texture does not promote the identification of individual trace fossils and, thus, comparing ichnofossil diversities is not possible. Unfortunately, bioturbation intensity in these deposits does not necessarily aid in the palaeoenvironmental analysis of the fossil estuary. Complete bioturbation of a sediment substrate can result from reworking by a diverse assemblage of organisms in normal marine conditions, or through the work of a highly abundant, low-diversity assemblage of burrowers under extremely stressful conditions (Pemberton & Wightman 1992).

Intertidal flats are shaped by a host of stresses not encountered by subtidal sediment dwellers. These additional stresses include temperature fluctuations, wind and solar desiccation, a fixed oxygen supply, and increased predation. Thus, salinity is not necessarily the principal shaping parameter of the tidal flat deposits. The presence of all of these stresses on intertidal flats throughout the fossil estuary leads to the striking similarity in the ichnological character of the associated units.

Lower estuary and bayhead delta deposits

In environments dominated by sand, sandstone laminae sets are commonly separated by thin mudstone beds reflecting fluctuations in flow strength (Figs. 5C, 6A, 7A, 8E, F). As the sandstones are lacking in features unique to any one depositional environment (e.g. low- or high-angle cross-bedding or trough cross-bedding), palaeoenvironmental interpretation may be greatly enhanced through the careful analysis of the preserved mudstone interbeds (MacEachern *et al.* 1999a).

A comparison of bayhead delta sediments of the upper estuary, flood-tidal delta sediments of the middle estuary, and ebb-tidal delta sediments of the lower estuary is evaluated, focusing on the mudstone interbeds present in each facies (Fig. 4B). In each of the three environments, it is notable that the sandstone facies show no signs of biogenic reworking. The diversity of commonly recurring ichnogenera within mudstone beds across the estuary increases from the upper estuary (bayhead delta – one common ichnogenus) to the middle estuary (flood-tidal delta – two common ichnogenera), and then to the lower estuary (ebb-tidal delta – three common ichnogenera) (Fig. 4B). In each subenvironment, the common trace fossils are simple structures constructed by trophic generalists, probably indicative of salinity-induced stress, which was prominent during periods of waning flow. The increasing diversity of trace fossil forms towards the lower estuary, albeit slight, suggests that salinity-induced stresses were greatest at the landward end of the estuary. The only common trace fossils observed in the upper estuary are diminutive *Planolites,* consistent with observations on maximum burrow size distribution made by Gingras *et al.* (1999) (Fig. 10). The largest burrows observed in all of the deltaic deposits are *Thalassinoides*, which are common only in ebb-tidal delta deposits of the lower estuary.

Summary and conclusions

Estuaries are characterised by numerous stresses on potential trace-making organisms, including low salinities, fluctuating salinity levels, high water turbidity, high current energy, rapid sedimentation rates, and low oxygen levels in bottom and interstitial waters. Although the effects of these stresses are difficult to differentiate, doing so is important in order to understand the palaeoenvironmental conditions in ancient estuarine settings. These factors shape the trace fossil assemblage that is ultimately preserved in the rock record.

Trace fossils in the Cretaceous Bluesky Formation of Alberta provide important palaeoenvironmental information, thereby enhancing subsurface facies mapping and interpretation. Burrowing organisms in the ancient, wave-dominated estuary were particularly influenced by lowered salinities in the middle to upper parts of the system, and by high current energies and rapid sedimentation rates in both the lower and upper extremes of the system. Other factors suspected of contributing to the trace fossil assemblages include high suspended sediment volume in the middle to upper estuary associated with the turbidity maximum, fluctuating salinity levels in intertidal areas, and reduced oxygenation of bottom and interstitial waters locally.

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