APPLICATION OF THE ASYMMETRIC DELTA MODEL TO ALONG-STRIKE FACIES VARIATIONS IN A MIXED WAVE- AND RIVER-INFLUENCED DELTA LOBE, UPPER CRETACEOUS BASAL BELLY RIVER FORMATION, CENTRAL ALBERTA

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The early to mid-Campanian Basal Belly River Formation in the Ferrybank, Keystone, and eastern Pembina fields of central Alberta, reflects a mixed wave- and river-influenced deltaic succession with strong storm overprinting. Prodelta deposits consist of mud-dominated heterolithic successions, characterized by a low abundance yet moderately diverse trace fossil assemblage attributable to a "stressed" expression of the *Cruziana* Ichnofacies. Proximal prodelta to distal delta front intervals comprise interbedded sandy siltstones and very fine- to fine-grained sandstones exhibiting convolute bedding and sporadic bioturbation. Trace fossil assemblages range from very low to moderate abundance, and low to moderate diversity; the suites are attributable to a "stressed" expression of the *Cruziana* Ichnofacies. Distal delta front deposits coarsen upwards into fine– to medium-grained sandstones of the proximal delta front. High-energy conditions, coupled with strong storm influences, resulted in erosional amalgamation of tempestites, and led to sporadic distribution of ichnogenera. Proximal delta front intervals are weakly bioturbated, and trace fossil assemblages are characterized by low abundances and low to moderate diversity. Most forms within the sandstone facies represent the structures of deposit-feeding organisms. Suites reflect a "stressed" infaunal community and contain a mixture of elements characteristic of both the *Skolithos* and *Cruziana* ichnofacies. Analysis of more than fifty cored wells has revealed prodelta and delta front deposits that vary markedly along depositional strike. The along-strike variations fit well with the recently proposed asymmetric delta model. The model is based on observations of modern wave-influenced deltas such as the Danube. This study provides an ancient analogue. Continued research will seek to further delineate delta lobe asymmetry and concomitant along-strike facies variations, both attributable to longshore drift and deflection of river-induced stresses downdrift of distributary channel mouths. Organisms are exceedingly sensitive to fluvial influence and this "stress" is reflected in the relatively low diversity and low abundance assemblages that characterize many deltaic successions. Ethological preferences and burrow sizes further reflect the level of "stress" imparted on infaunal organisms within the subaqueous delta environment. Trace fossil suites of river influenced deltaic successions signify a departure from the archetypal ichnofacies characteristic to shoreface successions, and their mapped distributions may serve as a predictive tool for determining distributary channel proximity.

INTRODUCTION

Identification of deltaic successions is conventionally made on the basis of regional correlations and mapping. Nevertheless, there are facies criteria that facilitate identification and differentiation of various deltaic subenvironments, using the integration of sedimentology and ichnology (Coates and MacEachern 1999; MacEachern et al. in press). The ichnology of deltaic deposits is comparatively less well understood than are the ichnological signatures of units deposited in depth-equivalent open shoreface settings. However, a number of previous studies have recognized that deltaic deposits contain "stressed" ichnological assemblages. Examples have been described from the Cadotte Member (Moslow and Pemberton 1988) and the Dunvegan Formation (Gingras et al. 1998), which have been further refined by Coates and MacEachern (1999, this volume). More recently, Bann and Fielding (2004) and (Fielding et al. this volume) documented similar occurrences of stressed ichnological signatures from Permian deltaic successions in the Denison Trough of Queensland, eastern Australia. MacEachern et al. (in press) provides a summary of the ichnological characteristics of deltas.

It has long been recognized that organisms are exceedingly sensitive to their environment. At the mouths of deltas, fluvial input into the marine realm results in a variety of environmental stresses on infaunal organisms. Physico-chemical stresses are largely the result of river-induced processes and increased sedimentation rates. Conditions at the bed are highly variable during and immediately following distributary flood discharges. Fluctuating conditions near the bed may involve hypopycnal-induced water turbidity and/or hyperpycnal-induced salinity and oxygenation changes resulting from phytodetrital pulses, sediment gravity flows, and fluid mud deposition (MacEachern et al. in press). The "stressed" character of the resultant ichnological suites records the dynamic relationship between fluvial influx, tidal flux, storm events, and wave energy. Deltaic successions show marked reductions in bioturbation intensity, sporadic distribution of burrowed intervals, and impoverished assemblage diversities as compared to non-deltaic shorelines (Moslow and Pemberton 1988; Bhattacharya and Walker 1992; Raychaudhuri and Pemberton 1992; Gingras et al. 1998; Coates and MacEachern 1999, this volume; Bann and Fielding 2004; MacEachern et al. in press, this volume). Deposit-feeding behaviors tend to dominate in delta front and proximal prodelta settings. Suspension-feeding behaviors, common to shoreface settings, are generally suppressed, and depending on the degree of fluvial influence, may be completely absent.

Physico-chemical stresses associated with fluvial discharge become increasingly apparent in proximity to distributary mouths; thus it stands to reason that ichnological criteria can be developed for predicting distributary channel proximity within individual successions. Furthermore, strong alongshore drift in wave-dominated and wave-influenced settings acts to extend river-induced stresses considerable distances downdrift from distributary mouths (cf. Bhattacharya and Giosan 2003; MacEachern et al. in press). Consequently, for asymmetric wave-influenced deltas, the ichnological signatures on either side of the distributary mouths will likely display marked differences that reflect the partitioning of the associated environmental stresses.

The objectives of this paper are to: 1) describe the along-strike variation of facies in a mixed wave and river influenced deltaic setting; 2) discuss the application of this data to the recently proposed asymmetric delta model (Bhattacharya and Giosan 2003); and 3) discuss the possibility of developing integrated ichnological and sedimentological criteria for prediction of distributary mouth proximity within wave influenced deltaic successions. As distributary channels commonly constitute the principal deltaic reservoirs, proximity indicators for locating the channels may have profound implications for hydrocarbon exploration and field development.

DESCRIPTION OF STUDY AREA AND PREVIOUS WORK

The Belly River Formation is an eastward-thinning clastic wedge, thickest along the Alberta Foothills and decreasing to its depositional edge in southwest Saskatchewan (Al-Rawahi 1993). The wedge of marine, marginal marine and continental deposits, was laid down during the mid-Campanian, when the Belly River deltas prograded into the Lea Park seaway. The base of the Belly River Formation thus comprises a series of overlapping and offlapping deltaic lobes (Power 1993; Power and Walker 1996). The basal Belly River Formation is an informal term used by workers in the oil and gas industry, and refers to the lower sand-rich, marine to marginal marine units. Above this lies the mud-rich continental deposits that comprise the remainder of the Belly River Formation. In central Alberta, the sandstones, siltstones, and mudstones of the basal Belly River Formation intertongue northeastward with open marine shelf sediments of the Lea Park Formation (Fig. 1). The base of the Belly River Formation is defined as a lithostratigraphic contact, marked by the first major sandstone above the marine shales of the Lea Park.

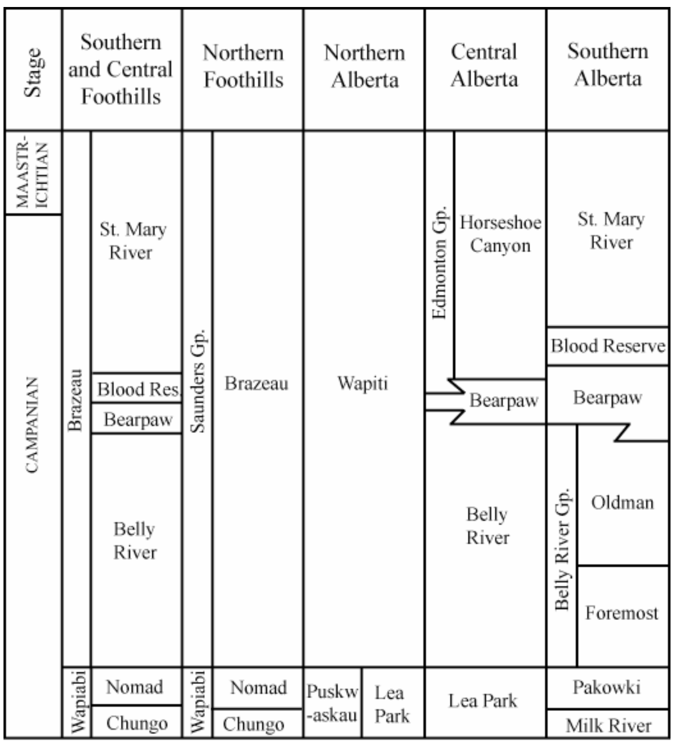

Fig. 1. Lithostratigraphy of the Belly River and Lea Park formations, and stratigraphic equivalents in western Canada (modified after Power and Walker 1996).

Previous work on the basal Belly River Formation mainly focused on regional-scale geometries, depositional architecture and stratigraphic analysis. Wasser (1988) studied the Belly River Formation in the Pembina region and concluded that the deposits were laid down in high-energy (most likely wave-dominated) deltaic and nearshore environments. Hamblin and Abrahamson (1996) interpreted the basal Belly River Formation as a series of stacked, primarily regressive, composite cycles, composed of a central belt of shoreline-related sandstones that pinch out to the east, and flanked by time-equivalent continental deposits to the west. Power (1993; cf. Power and Walker 1996) described the subsurface allostratigraphy and sedimentology of cycles (allomembers) C – H, interpreting each of these as a prograding deltaic shoreline deposit. More recently, Coates (2001) employed detailed sedimentological and ichnological facies analysis of cycles D – G; and interpreted them to represent deposition in mixed wave- / river-influenced delta lobes.

In central Alberta, the basal deposits of the Belly River Formation occur in subsurface and comprise numerous major hydrocarbon fields (Fig. 2). The interval chosen for this study is Allomember G of the basal Belly River Formation. Allomember G forms the main hydrocarbon pool in the Ferrybank, Keystone and eastern Pembina fields of central Alberta. A substantial core and log database exists for this allomember, making it an ideal candidate for a detailed study concerning the facies characteristics and architecture of a wave-influenced delta lobe.

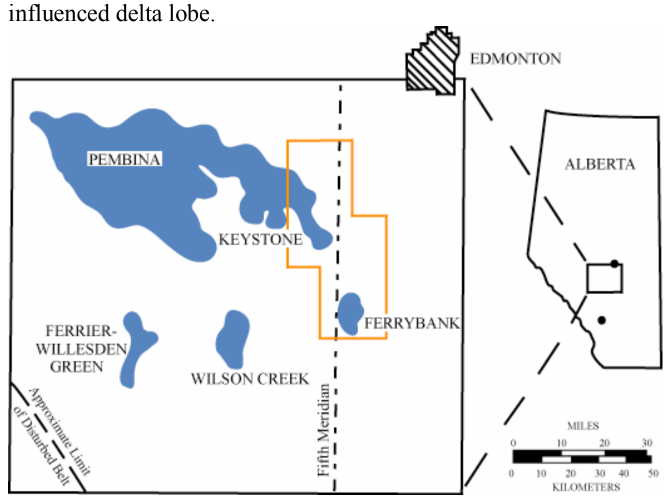

Fig. 2. Location map of the major Belly River hydrocarbon fields in central Alberta. The inset depicts the study area within the Ferrybank and eastern Pembina/Keystone fields (modified after Power and Walker 1996).

THE ASYMMETRIC DELTA MODEL

It has long been recognized that many modern wave-influenced deltas (e.g., São Francisco delta, Brazos delta, and the southern lobe of the Danube delta) show a marked asymmetry in their geometries (plan view shape) and facies associations (Bhattacharya 1999). The "classic" model represents wave-influenced deltas as broad, sandy, arcuate to cuspate (strike-extensive) lobes, and assumes that all sand is derived directly from the associated river (see Elliot 1978; and Bhattacharya and Walker 1992 for a comprehensive review of deltaic facies models). Bhattacharya and Giosan (2003) explained that this classic model is fairly accurate, but only where net longshore sediment transport is negligible at the river mouth. In such cases, wave-influenced deltas resemble, in plan view, the classical symmetric wave-dominated delta with beach ridges more or less equally distributed on either side of the distributary mouth. Thicker, more homogeneous sands are interpreted to have been transported by weak, net sediment drift across the mouth, with deposition occurring on the downdrift portion of the delta lobe. In cases where net longshore transport is high, however, greater sand deposition occurs on the updrift side of the river mouth (Bhattacharya and Giosan 2003). More complex, heterolithic environments are generated downdrift of the mouth due to longshore displacement of fluvial discharge characteristics, resulting in a pronounced asymmetry of the delta lobe (Fig. 3).

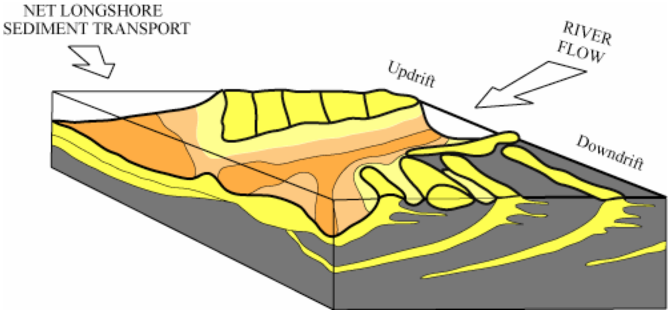

Fig. 3. Block diagram illustrating the inferred three-dimensional facies architecture of an asymmetric delta lobe. A sandy beach ridge plain characterizes the updrift side of the distributary channel, whereas more complex heterolithic environments form downdrift (modified after Bhattacharya and Giosan 2003).

Asymmetric wave-influenced deltas can be divided into an updrift portion, consisting of massive, sandy-beach ridge plains, and a more complex downdrift portion, consisting of muddier environments separated by sandy "shoestring" ridges or bars (Bhattacharya and Giosan 2003). At the distributary mouth of an asymmetric delta, the fluvial effluent (plume) exerts a strong groyne effect, causing updrift retention of the sediment moving along the coast by longshore processes. Amalgamation of longshore-derived sandy beach ridges results in a beach ridge plain on the updrift side of the distributary mouth. At the mouth, sediment is supplied directly by the distributary and deposited subaqueously. These sediments are later reworked by waves into shore-parallel, sandy barrier bars. The formation of a barrier bar creates a protected lagoonal environment, and a river-dominated bayhead delta may prograde subparallel to the coast. The resulting facies formed downdrift are characterized by a succession of elongate sandy ridges separated by heterolithic-prone muddy troughs. The asymmetric delta model thus predicts great proportions of: 1) river-borne muds downdrift, and 2) longshore-derived sands updrift, than has been suggested by the "classic" models for wave-influenced deltas (Coleman and Wright 1975; Galloway 1975).

FACIES DESCRIPTION AND INTERPRETATION

Allomember G of the basal Belly River Formation in central Alberta can be divided into two distinct facies associations (Hansen 2005a,b). Facies Association 1 comprises three distinct facies, whereas Facies Association 2 shows greater variability with four facies. Facies designations are made on the basis of sedimentological and ichnological characteristics. The degree of bioturbation is given as a Bioturbation Intensity (BI) measurement, with 0 defining absent bioturbation, and 6 reflecting complete bioturbation (Fig. 4).

FACIES ASSOCIATION 1 (FA1)

Facies Association 1 consists of three discrete facies (Figs. 5, 6, 7, 8). Each facies is described in terms of the preserved sedimentology and ichnology, followed by an interpretation of the facies association.

Facies 1a: Sparsely bioturbated interbedded siltstone and sandstone facies

Sedimentology: Facies 1a comprises siltstone and clayey siltstone interbedded with very fine-grained sandstone (Fig. 5A). Interbedded sandstones range from millimeter thick laminations to 5 cm thick beds. Bed bases are sharp and generally erosive, and commonly contain mudstone or siltstone rip-up clasts. Sandstone beds consist of oscillation ripple-lamination or wavy parallel lamination. Siltstone and clayey siltstone beds display horizontal laminations. Overall, the facies exhibits minor convolute bedding, rare synaeresis cracks, and very rare current ripples.

BI Value	Visual Representation	Description
0		Bioturbation absent
1		Sparse bioturbation, bedding distinct, few discrete traces
2		Uncommon bioturbation, bedding distinct, low trace density
3		Moderate bioturbation, bedding boundaries sharp, traces discrete with rare overlap
4		Common bioturbation, bedding boundaries indistinct, high trace density with common overlap
5		Abundant bioturbation, bedding just visible, though completely disturbed
6		Complete bioturbation, total biogenic homogenization of sediment

Fig. 4. Schematic representation of Bioturbation Intensity (BI) values. Values are a function of relative degree of burrowing vs. identifiable primary physical sedimentary structures. Modified after Bann et al. 2004, from the original concepts of Reineck (1963) and Taylor and Goldring (1993).

Ichnology: The facies displays an overall scarcity of bioturbation (BI 0 to 2, typically 1), and with the exception of very rare *Cylindrichnus*, the assemblage contains only deposit-feeding and grazing structures (Fig. 5B). Ichnogenera include relatively common *Phycosiphon*, *Planolites*, and *Chondrites*, rare *Helminthopsis* and *Teichichnus*, and isolated *Palaeophycus tubularis*. Escape structures (fugichnia) are locally common within thin sandstone beds. Overall, the facies contains a low abundance, yet moderately diverse trace fossil suite, attributable to a "stressed" expression of the *Cruziana* Ichnofacies (Figs. 7, 8).

Facies 1b: Sporadically bioturbated interbedded sandstone and sandy siltstone facies

Sedimentology: This facies comprises very fine- to fine-grained sandstone interbedded with sandy siltstone. Sandstone beds range in thickness from centimeter-scale to 25cm. Most stratification within these beds consists either of oscillation ripple lamination or wavy parallel lamination (Fig. 5C). Wavy parallel (to subparallel) laminated beds typically display concave-up laminations, though local convex-up laminations are present. Internal laminae, marked by carbonaceous detritus, typically intersect and truncate underlying laminae at low angles (Fig. 5D, E). These are interpreted to be storm deposits consisting mainly of swaley and hummocky cross-stratified sands (SCS and HCS, respectively). Tempestites commonly include small rip-up clasts at the base. Many of these rip-ups are identified as allochthonous *Rosselia* fragments, and reflect the erosional truncation and redeposition of *Rosselia* mudballs and stalks during storm events (Fig. 5D). As with Facies 1a, the succession shows only minor convolute bedding, typically 1-5 cm in thickness. Synaeresis cracks are exceedingly rare.

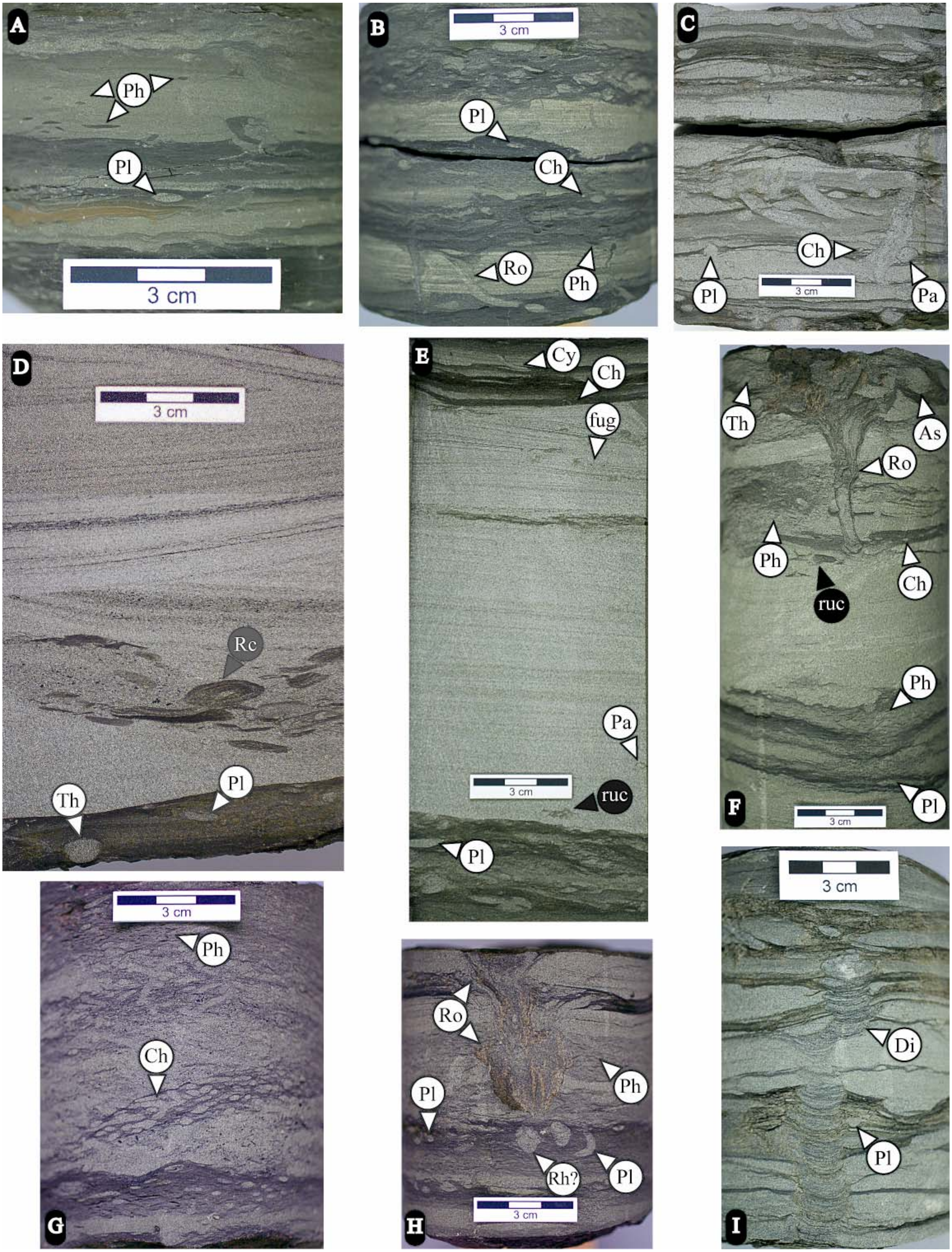
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Fig. 5. (Previous Page) Representative photographs of Facies 1a (A, B) and 1b (C-I) of Facies Association 1 (FA1). **A)** Clayey siltstone interbedded with wavy parallel-laminated, very fine-grained sandstone (BI 1). *Planolites* (Pl), *Phycosiphon* (Ph), well 10-3-43-27W4, 950.0 m. **B)** BI 2. *Chondrites* (Ch), *Rosselia* (Ro), well 7-20-43-27W4, 940.1 m. **C)** Facies 1b. Bioturbated sandy siltstone interbedded with oscillation ripple and wavy parallel-laminated, very fine- to fine-grained sandstone. *Planolites* (Pl), *Chondrites* (Ch), *Palaeophycus tubularis* (Pa), well 6-13-43-28W4, 1032.9 m. **D)** Amalgamated storm deposits with internal laminae truncating underlying laminae at low angles. Note the allochthonous *Rosselia* rip-up clasts (Rc) at the base of the tempestite. *Planolites* (Pl), *Thalassinoides* (Th), well 7-20-43-27W4, 936.3 m. **E)** BI 0-3. *Cylindrichnus* (Cy), *Planolites* (Pl), *Chondrites* (Ch) and *Palaeophycus tubularis* (Pa), fugichnia (fug), well 10-3-43-27W4, 946.9 m. **F)** *Rosselia* (Ro) and *Phycosiphon* (Ph). Well 10-3-43-27W4, 947.3 m. **G)** BI 3. Branched large diameter *Chondrites* (Ch). *Phycosiphon* (Ph) with halos, well 10-3-43-27W4, 948.0 m. **H)** *Planolites* (Pl), *Phycosiphon* (Ph), *Rosselia* (Ro), and possible *Rhizocorallium* (Rh). Well 7-20-43-27W4, 936.4 m. **I)** Interbedded fine-grained sandstone and clayey siltstone, BI 1. *Planolites* (Pl) and *Diplocraterion* (Di) with retrusive spreiten that extends over 10 cm before exiting the face of the core. Well 6-13-43-28W4, 1033.1 m.

Ichnology: The bioturbation intensity is highly variable within this facies, ranging from absent to locally common (BI 0-3), but typically rare to moderate. The trace fossil assemblage consists of locally abundant numbers of *Planolites*, *Chondrites*, and *Phycosiphon*. *Teichichnus*, *Thalassinoides*, *Helminthopsis*, *Rosselia*, and fugichnia are relatively common, with lesser numbers of *Rhizocorallium* and *Palaeophycus* (Fig. 5F-I). Domichnia of inferred suspension-feeding organisms are subordinate in the assemblage, and are only represented by isolated *Diplocraterion*, commonly with extensive retrusive spreiten (Fig. 5I). The moderately diverse yet low to moderate abundance trace fossil assemblage is attributable to a "stressed" proximal to archetypal expression of the *Cruziana* Ichnofacies (Figs. 7, 8).

Facies 1c: Sporadically bioturbated coarsening-upward sandstone facies

Sedimentology: Facies 1c comprises a coarsening-upward succession of upper fine- to lower medium-grained sandstone. The sandstone contains minor muddy or silty laminations locally. The base of the unit is commonly sharp, though rarely erosive. Wavy parallel and oscillation ripple laminations are common in the lower portion of the unit (Fig. 6A), whereas low-angle and trough cross-stratification are the dominant sedimentary structures in the upper part of the unit (Fig. 6B). Apparently structureless (massive) bedding is also present throughout the facies, but is typically most abundant at or near the base of the succession (Fig. 6C). Some intervals of structureless sandstones appear to have a "fuzzy" appearance, possibly reflecting cryptic bioturbation resulting from the meiofaunal disruption of grain arrangements.

Ichnology: Sporadic distributions of ichnogenera are characteristic of the sandstone facies. The bioturbation intensity ranges from absent to moderate (BI 0 to 2) and only a few ichnogenera are present. *Macaronichnus* isp., *M. segregatis*, *Rosselia* and fugichnia are locally common in lower to middle portions of the unit (Fig. 6D, E). Typically, *Rosselia* stalks are in situ, without preservation of mudball tops. Retrusive and protrusive spreiten are commonly associated with the shaft and represent shifting of the burrow up or down (respectively), in addition to spreiten formed as a result of lateral shifting (Fig. 6F). Muddy rip-up clasts, interpreted to be eroded *Rosselia* shafts and mudballs, are common throughout lower portions of the unit. Rare to moderate numbers of *Ophiomorpha* are locally present, typically in association with the other traces (Fig. 6G). Where mudstone or siltstone laminations are present, trace fossils may include isolated *Planolites*, *Thalassinoides*, *Palaeophycus tubularis*, and *Skolithos*. The facies is characterized by a low abundance of burrows, and a low to moderately diverse range of structures that predominantly reflect deposit-feeding behaviors. The assemblage reflects a "stressed" infaunal community comprising a mixture of elements characteristic of both the *Skolithos* and *Cruziana* ichnofacies (Figs. 7, 8).

FA1 Interpretation

The interbedded nature and predominance of wave generated bedforms in Facies 1a and 1b reflects the frequent changes between event (storm) and post-event (fair-weather) conditions. Rare synaeresis cracks and convolute bedding indicate the environment was periodically subjected to salinity variations and rapid sedimentation rates. The significant upward shifting of various infaunal organisms also reflects rapid sedimentation as the tracemaker was required to shift (or re-establish) its burrow in order to stay in proximity to the sediment-water interface: including Diplocraterion with extensive retrusive spreiten, and stacked Rosselia (formed as the tracemaker re-established its burrow following an erosional event and deposition of sediment). The paucity of significant numbers of suspension-feeding traces reflects possible heightened turbidity levels in the water column near the bed. Such conditions serve to clog the filter-feeding apparatus of infaunal organisms, in addition to lowering the overall concentration of food resources. The dominance of deposit-feeding structures, and impoverishment (or exclusion) of *Skolithos* Ichnofacies elements, despite the availability of sandy substrates, is indicative of high water turbidity and is considered to be a diagnostic indicator of deltaic conditions (Moslow and Pemberton 1988; Gingras et al. 1998; Coates and MacEachern 1999; Bann and Fielding 2004; MacEachern et al. in press).

The trace fossil assemblages of facies 1a and 1b depart from the "norm" attributed to offshore environments. Bioturbation within lower to upper offshore deposits is typically intense and fairly uniform, though becoming more sporadic with greater storm influence (Pemberton and Frey 1984; Vossler and Pemberton 1988, 1989; Frey 1990; MacEachern and Pemberton, 1992; Pemberton and MacEachern 1997; Bann et al. 2004). Trace fossil diversity is generally high and characterized by deposit feeding and grazing structures (Howard and Frey 1984; Pemberton and Frey 1984; Vossler and Pemberton 1989). Where thicker tempestites are preserved, suspension feeding / dwelling and escape structures may be associated. These structures are preserved within the top-down bioturbation of tempestites, and reflect the gregarious, opportunistic colonization of sand beds by storm-transported suspension-feeders, from shoreface to offshore locales (Frey 1990; Pemberton et al. 1992; Pemberton and MacEachern 1997). The term "lam-scram" is commonly applied to such laminated-to-burrowed deposits. Offshore assemblages thus reflect distal expressions of the *Cruziana* Ichnofacies to the archetypal. In marked contrast, Facies 1a and 1b are typified by relatively low abundance, and low to moderate diversity trace fossil assemblages attributable to "stressed" expressions of the *Cruziana* Ichnofacies. Despite the abundance of sandstone beds, particularly in Facies 1b, the deposits reflect a paucity of suspension-feeding and dwelling structures.

It is important to note that "stressed" trace fossil suites may also be identified from embayment deposits, however the nature of the preserved ichnogenera differ significantly under brackish and fully marine settings. Brackish water and fully marine (offshore) suites generally display high bioturbation intensity, however, bay deposits typically show diminutive trace fossil size and an impoverished diversity (Pemberton et al. 1982; Wightman et al. 1987; Beynon et al. 1988; Pemberton and Wightman 1992). Typical intervals contain

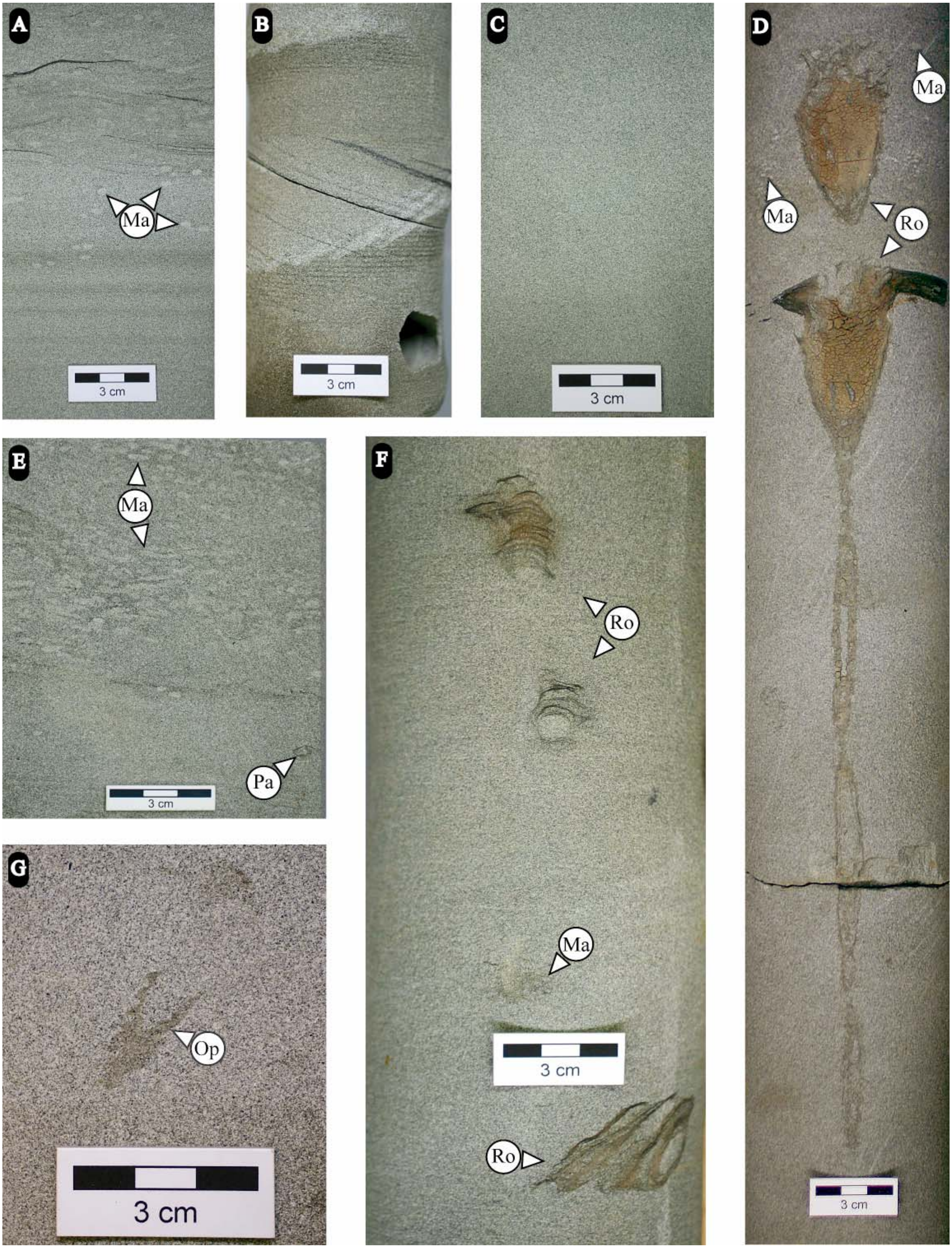
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Fig. 6. (Previous Page) Representative photos of Facies 1c of FA 1. **A)** Wavy parallel and oscillation ripple laminations. Thick beds of wavy parallel laminated sandstone (HCS and SCS) with *Macaronichnus* isp. (Ma). Well 16-1-43-28W4, 952.1 m. **B)** Trough cross-stratification marked by carbonaceous detritus. Well 16-28-43-28W4, 1002.9 m. **C)** Apparently structureless (massive) bedding, possibly due to cryptobioturbation. Well 10-19-43-27W4, 942.2 m. **D)** *Rosselia* (Ro) and *Macaronichnus* (Ma). *M.* isp. (uppermost arrow) and *M. segregatis* (lower arrow pointing to small diameter, gregarious forms). Stacked *Rosselia socialis*, well 10-19-43-27W4, 941.2 m. **E)** Pervasive *Macaronichnus segregatis* (Ma) and isolated *Palaeophycus tubularis* (Pa). Well 02/16-34-43-28W4, 998.6 m. **F)** In situ *Rosselia* stalks (Ro) with lateral and retrusive spreiten. Well 14-24-43-28W4, 982.4 m. **G)** *Ophiomorpha irregulaire* (Op). Well 16-28-43-28W4, 1006.2 m.

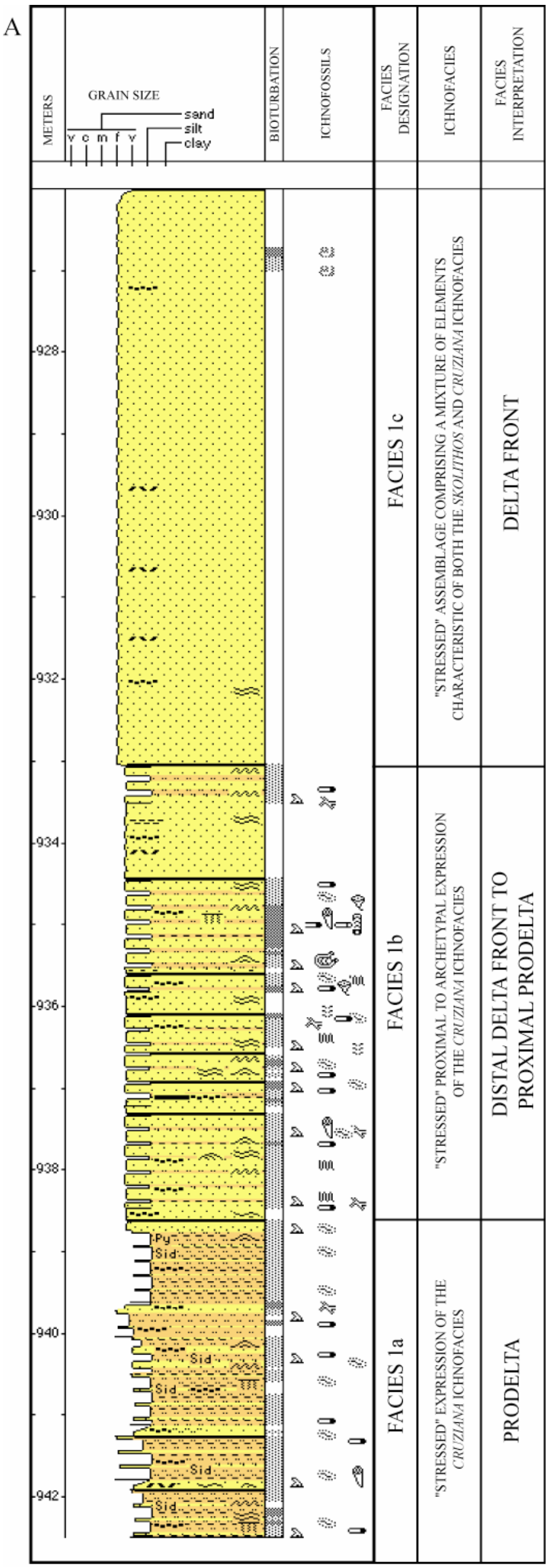

Fig. 7. Litholog of a representative well (08-08-43-27W4) showing the facies of FA1 (column opposite) and legend to lithologs (above).

only 3 or 4 ichnogenera representing opportunistic, simple feeding strategies of trophic generalists. Such ichnogenera are typically pronounced facies-crossers. Comparatively, Facies 1a and 1b comprise relatively low abundance trace fossil assemblages that contain, in addition to simple facies-crossing forms, complex and specialized forms such as *Phycosiphon* and *Rhizocorallium*, reflecting stressed but fully marine (non-brackish) conditions (cf. MacEachern and Pemberton 1994; MacEachern et al. 1999; Bann et al. 2004; Gingras et al. this volume).

Based on the integration of sedimentological and ichnological characteristics, Facies 1a and 1b are interpreted to represent deposition within prodelta and proximal prodelta to distal delta front environments, respectively, of a prograding wave- and storm-influenced delta.

The apparently structureless (massive) sandstone beds at the base of Facies 1c may indicate periods of high sedimentation rates and concomitant slumping. Such processes are commonplace in distal

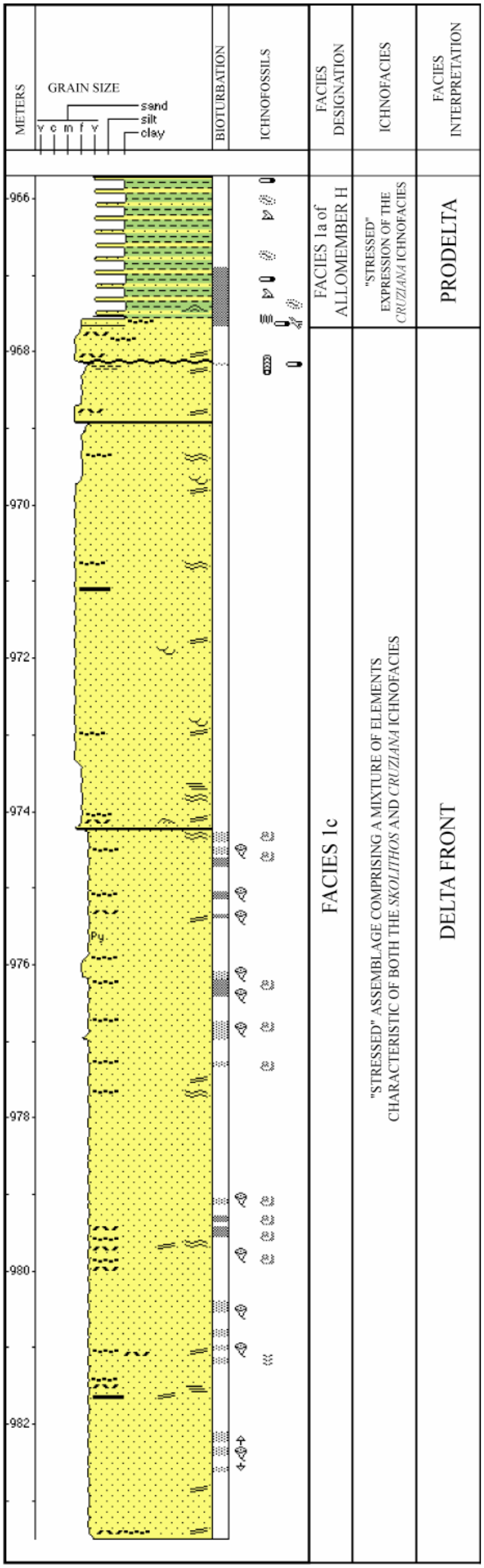

Fig. 8. (Litholog Opposite) Facies 1c of FA1 showing a coarsening-upwards succession. Lower to upper fine-grained sandstones at the base of the succession pass upwards into lower medium-grained sandstone (14-24-43-28W4). Note the variation in diversity and intensity of bioturbation, as well as preserved bedding between Facies 1c of this well as compared to the lower portion of the facies in Fig. 7A.

portions of the delta front (Elliott 1978). Thick units of unbioturbated, wavy parallel laminated sandstones, in lower portions of the facies, are interpreted as erosionally amalgamated SCS associated with storms. The sandstone facies persistently exhibits a paucity of vertical burrows of suspension-feeders, interpreted to reflect heightened water turbidity near the bed. The generally unbioturbated uppermost coarse-grained portion of the unit, which contains trough cross-stratified layers and current ripples, reflects breaking wave conditions, and is consistent with deposition within the proximal part of the delta front (surf zone equivalent of nondeltaic upper shoreface settings).

The physical characteristics alone do not permit a detailed interpretation of Facies 1c. However, the ichnological aspects of the facies help to preclude the interpretation of a storm-influenced open marine shoreface (nondeltaic strandplain) setting. A number of previous studies have identified criteria for differentiating between wave-influenced shoreface successions from wave- and storm-influenced delta front successions (Coates and MacEachern 2000; Coates 2001; Bann and Fielding 2004; also summarized in MacEachern et al. in press). Distal lower shoreface deposits of nondeltaic strandplain settings are generally characterized by fair-weather beds with trace suites that reflect the high diversity archetypal *Cruziana* Ichnofacies, commonly juxtaposed with event beds containing suites reflecting distal expressions of the *Skolithos* Ichnofacies (e.g. Howard and Frey 1984; Vossler and Pemberton 1989; Pemberton and MacEachern 1997; Bann et al. 2004). Fair-weather and event beds of proximal lower shoreface to middle shoreface deposits contain appreciable numbers of dwelling structures of inferred suspension-feeding organisms, and passive carnivore structures, attributable to the archetypal *Skolithos* Ichnofacies. In contrast, the fair-weather beds of wave-influenced delta front successions host significant numbers of markedly facies-crossing structures of deposit-feeders and passive carnivores. Both the fair-weather and event beds show relatively few structures of inferred suspension-feeding organisms. The heightened water turbidity of deltaic settings excludes most suspension-feeding behavior and instead, delta front successions are dominated by facies-crossing structures made by opportunistic organisms, that employ omnivorous and trophic generalist behaviors (Gingras et al. 1998; Coates and MacEachern 1999, 2000; Bann and Fielding 2004, MacEachern et al. in press). Shoreface and wave-influenced delta front deposits both display sporadic distributions of ichnofossils, but it is only the wave-influenced delta front setting that persistently displays "stressed" trace fossil suites. It is important to note that this difference becomes ever more difficult (or impossible) to recognize with increasing degrees of storm influence (intensity of storm activity and storm frequency), due to the lack of preserved fair-weather suites and reduction of the colonization window (e.g. MacEachern and Pemberton 1992; Saunders et al. 1994; Pemberton and MacEachern 1997).

The Facies 1c succession displays a profound lack of suspension-feeding structures (indicating high water turbidity) and is dominated by the preservation of resilient deposit-feeding structures (*in situ Rosselia* stalks and *Macaronichnus segregatis*) and passive carnivore structures (*Macaronichnus* isp). Very rare thin mudstone beds are locally preserved, are typically burrowed with isolated *Planolites* and *Macaronichnus* isp; and also lack suspension-feeding structures.

Fair-weather suites are only locally preserved and thus, the sedimentary record of the facies is predominantly one of erosionally amalgamated storm deposits. Deep-penetrating structures such as *Rosselia*, *Ophiomorpha*, and *Macaronichnus* have higher preservation potential than shallow tier structures in such storm-dominated settings, and comprise the vast majority of the preserved ichnogenera. Facies 1c is characterized by low abundance and low to moderate diversity suites reflecting a "stressed" infaunal community, and is interpreted to represent the progradation of a delta front with moderate to high storm- and wave-influence.

The coarsening-upwards facies succession of Facies Association 1 is interpreted to represent the progradation of a wave- and storm-influenced delta. Facies 1a and 1b represent deposition within prodelta and proximal prodelta to distal delta front environments, respectively. Facies 1c represents deposition within more strongly storm-influenced, distal to proximal portions of the delta front.

FACIES ASSOCIATION 2 (FA2)

Facies Association 2 consists of four facies (Figs. 9, 10, 11, 12). Each facies is described in terms of the preserved sedimentology and ichnology, followed by an interpretation of the facies association.

Facies 2a: Sporadically bioturbated interbedded clayey siltstone and sandstone facies

Sedimentology: Facies 2a comprises interbedded siltstone and sandstone, lithologically similar to Facies 1a of FA1. However, the Facies 2a siltstones contain greater mud content. The facies also display less oscillatory-generated structures and contains a greater abundance of current ripples, convolute bedding, and synaeresis cracks than Facies 1a. In addition, sandstone beds mantled by dark, thin mudstones are a common characteristic of Facies 2a (Fig. 9A). These mudstones contain abundant organic carbonaceous material, visible on bedding planes as small flakes.

Ichnology: Bioturbation within Facies 2a is highly variable (Fig. 9B, C). Units range from absent to moderate (BI 0-3). The trace fossil assemblage consists of locally abundant *Phycosiphon*, and locally common to moderate *Planolites*, *Chondrites* and *Teichichnus*. The assemblage also comprises rare to isolated *Cylindrichnus*, *Rhizocorallium*, *Helminthopsis*, *Diplocraterion*, *Rosselia*, *Thalassinoides*, *Cosmorhaphe* and *Palaeophycus tubularis* (Fig. 9D). The low abundance, yet moderately diverse trace fossil suite is attributable to a "stressed" expression of the *Cruziana* Ichnofacies (Figs. 11, 12). The trace fossil suites of Facies 1a and 2a are comparable in regards to BI and assemblage diversity, and both record a paucity of suspension-feeding structures.

Facies 2b: Laminated to soft-sediment deformed, clayey to sandy siltstone facies

Sedimentology: Facies 2b consists of clayey to sandy siltstone with fewer sandstone interbeds than Facies 1b. This facies commonly contains thick intervals of convolute bedding, interbedded with thin laminated mudstone units (Fig. 9E). The facies also contains significantly more dark mud beds, synaeresis cracks, and current ripples than Facies 1b (Fig. 9F). Deformed layers commonly overlie, underlie or are intercalated with laminated beds consisting of repetitive normal grading. Undisturbed composite graded bedsets have a pinstriped appearance (Fig. 9G) and may reach thicknesses in excess of 15cm. Individual graded beds and lamina occur on the scale of millimeters to 2cm in thickness.

Ichnology: Facies 2b displays bioturbation intensities that range from absent to rare (0 to 1). Bioturbation is less variable than that of Facies 1b. *Planolites* dominates the ichnological assemblage, and *Chondrites* and fugichnia are locally common. The remainder of the assemblage comprises locally moderate numbers of *Phycosiphon*, *Rhizocorallium*, *Cylindrichnus* and *Teichichnus*, and very rare, isolated *Palaeophycus tubularis* (Fig. 9H, I). The facies consists of a very low abundance, and low diversity assemblage attributable to a highly "stressed" marine expression of the *Cruziana* Ichnofacies (Figs. 11, 12).

Facies 2c: Cross-bedded and current ripple laminated sandstone facies

Sedimentology: Facies 2c consists of mainly upper fine- to lower medium-grained sandstone, which locally coarsens upward to upper medium-grained sand. Mudstone laminae and beds (up to 2 cm in thickness) are locally present. Many of the mudstones are dense, dark in colour, and commonly contain synaeresis cracks (Fig. 10A). Sedimentary structures include trough cross-stratification and current ripple lamination (Fig. 10B, C). Climbing ripples are locally common near the top of the facies (Fig. 10D). Lesser amounts of low-angle stratification, wavy parallel lamination, oscillation ripples, combined flow ripples, and wave-reworked current ripples are locally present throughout the facies. Rip-up clasts, coal fragments and dispersed carbonaceous detritus are common (Fig. 10E). Spherulitic siderite is commonly pervasive in medium-grained, trough-cross stratified sandstone beds (Fig. 10B), and mainly limited to units that are overlain by Facies 2d. Facies 2c units that overlie Facies 2d tend to comprise finer-grained sandstone (for the most part lacking beds of medium-grained sandstone) and typically contain no spherulitic siderite. Facies 2c sandstones commonly fine-upwards into soft-sediment deformed, interbedded sandstone and siltstone (Fig. 10F-H). The fining-upward trend is most evident, though not restricted to units overlain by Facies 2d. In addition, pedogenic slickensides are locally associated with the convolute-bedded, heterolithic units.

Ichnology: The facies is largely unbioturbated (BI averages 0-1 but locally 2-3). Bioturbation is mainly limited to thin mudstone and siltstone beds, and consists of diminutive traces dominated by *Planolites*, with lesser *Chondrites* and *Thalassinoides*, and isolated *Cylindrichnus* (Fig. 10A, C, F, I). Ichnofossils found within the sandy portion of this facies include moderate numbers of escape traces, in addition to rare *Palaeophycus* and *Macaronichnus*. Rooting and adhesive meniscate burrows (AMB) are locally abundant, and are typically found in the interbedded siltstone and sandstone intervals near the top of the facies (Fig. 10G, H). AMB are typically unlined, horizontal to vertical burrows characterized by back-filled menisci (Hasiotis 2002). Isolated *Diplocraterion* may be associated. The unit is characterized by a very low abundance and diversity suite of predominantly deposit-feeding structures, and represents a highly "stressed" assemblage comprising a mixture of elements characteristic of the *Skolithos* and *Cruziana* ichnofacies (Figs. 11, 12).

Facies 2d: Variable heterolithic facies

Sedimentology: Facies 2d is the most variable of the facies in that it ranges from heterolithic intervals of shale and sandstone, through shale with minor sandstone lenses or laminae, to a mixture of both, with or without convolute-bedded siltstone units. Sedimentary structures include both current and oscillation ripple lamination. Oyster shells are common and are typically found at the base of the shale intervals, where sandstone tends to comprise a minor component (Fig. 10J). In addition, a number of plant fossils were identified on the bedding planes of oyster-bearing units.

Ichnology: The ichnology of Facies 2d is also highly variable. Bioturbation intensities range from BI 0-3. *Planolites*, *Chondrites*, *Thalassinoides*, and *Rosselia* are locally common in the sandier upper portions of shale-dominated intervals (Fig. 10K, L). Where heterolithic intervals of clayey siltstone and sandstone are found, a relatively more abundant and diverse trace fossil assemblage is preserved. Ichnofossils in these units include *Palaeophycus*,

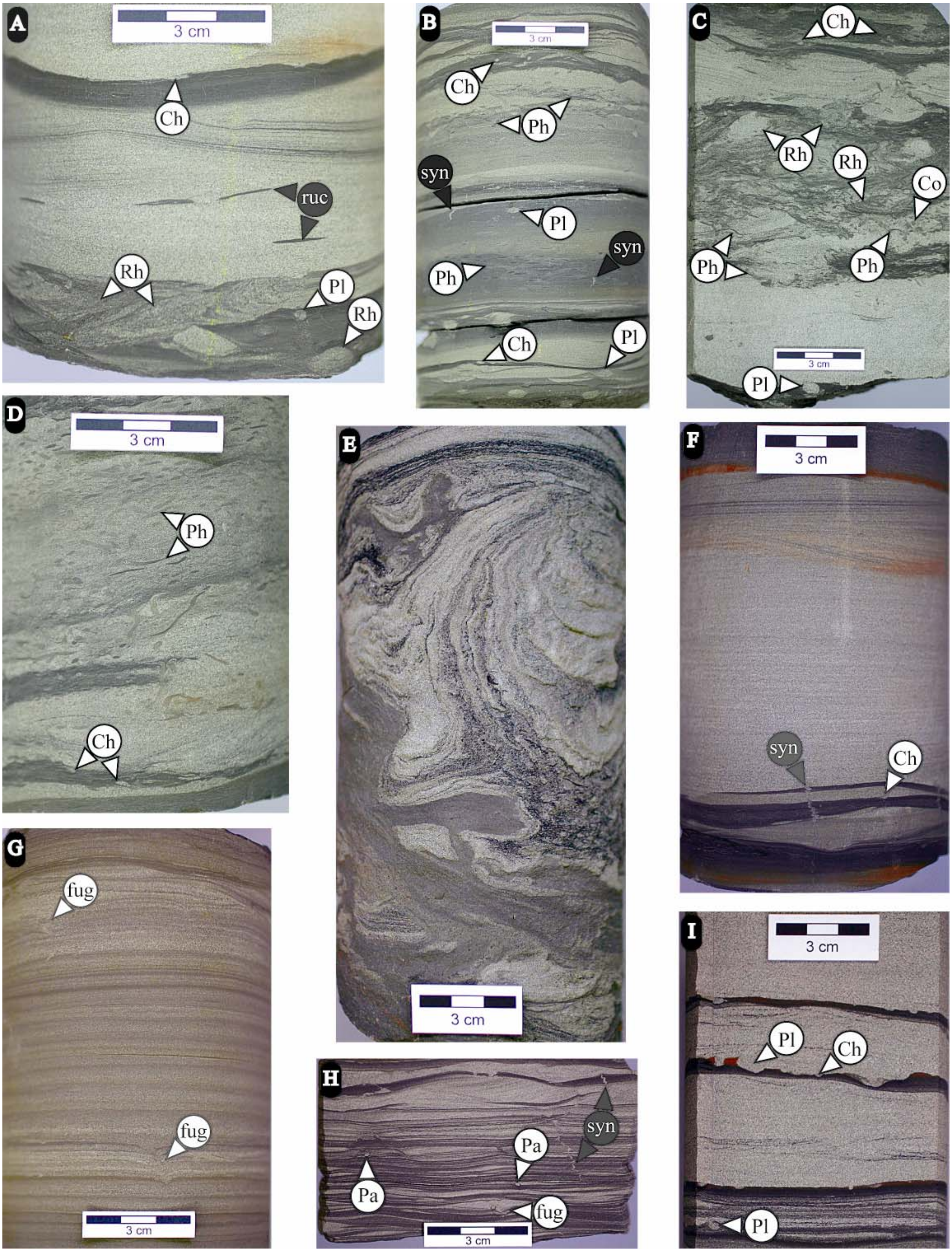
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Fig. 9. (Previous Page) Representative photographs of Facies 2a (A-D) and 2b (E-I) of Facies Association 2 (FA2). **A)** Thin event beds (tempestites) mantled by dark mudstone beds. Note how the mudstone bed truncates the underlying laminae of the tempestites, indicating a probable hyperpycnal origin to the muds (sediment-gravity flow transported along the bed). *Chondrites* (Ch) and rip-up clasts (ruc). BI of 3 in the lower beds. *Rhizocorallium* (Rh) and *Planolites* (Pl). Well 3-35-46-2W5, 1024.9 m. **B)** BI 1, *Phycosiphon* (Ph), *Planolites* (Ph), and *Chondrites* (Ch). Synaeresis cracks (syn). Well 3-35-46-2W5, 1023.4 m. **C)** BI 3. *Phycosiphon* (Ph), *Cosmorhaphe* (Co), *Planolites* (Pl), *Chondrites* (Ch) and *Rhizocorallium* (Rh). Well 6-31-46-1W5, 983.8 m. **D)** Facies 2a. *Phycosiphon* (Ph) and *Chondrites* (Ch). Well 3-35-46-2W5, 1025.5 m. **E)** Facies 2b. Thick intervals of convolute bedding. Note the flame structures near the top of the photo, well 7-20-46-1W5, 1002.7 m. **F)** Synaeresis cracks (syn) and *Chondrites* (Ch). Well 16-15-47-2W5, 959.6 m. **G)** Repetitive graded bedding. BI 0-1 with rare fugichnia (fug). Well 3-35-46-2W5, 1021.4 m. **H)** Interbedded sandstone and muddy siltstone with oscillation ripples, wavy parallel laminations, and synaeresis cracks (syn). Isolated and diminutive *Palaeophycus tubularis* (Pa) and fugichnia (fug). Well 6-31-46-1W5, 977.2 m. **I)** Possible hyperpycnal mud drapes with *Planolites* (Pl) and *Chondrites* (Ch). Note the faint current ripple laminations in the lower sandstone bed, well 10-9-47-2W5, 1019.7 m.

Helminthopsis, *Phycosiphon*, *Cylindrichnus*, *Teichichnus*, *Rhizocorallium* and *Asterosoma* (Fig. 10M, N). Rooting and adhesive meniscate burrows are locally common in the siltstone horizons. The facies is characterized by low to moderate abundances of traces and a low to moderate diversity assemblage. The trace fossil assemblage in this facies consists predominantly of deposit-feeding structures, and reflects a "stressed" community of infaunal organisms that are characteristic of both the *Skolithos* and *Cruziana* ichnofacies (Figs. 11, 12).

FA2 Interpretation

Current-generated structures and synaeresis cracks are common to Facies 2a and 2b, and reflect a strong fluvial character with recurrent salinity fluctuations. These are probably associated with heightened river discharge, related to flooding or high precipitation events (freshets). Increased fluvial influx may result in muddy to sandy sediment-gravity (hyperpycnal) flows that move along the bed as dense freshwater plumes. Where mud-laden flows reach the prodelta, a freshwater lens would lie above the bed for a short period of time, and the resultant salinity contrast may facilitate the formation of synaeresis cracks (MacEachern et al. in press). Composite graded bedsets reflect rapid sedimentation and abundant convolute bedded intervals indicate numerous episodes of slumping and dewatering, possibly also as a result of freshet-induced hyperpycnal flows. The close association of soft-sediment deformed beds, composite graded bedsets, and dark, organic-rich mudstone beds with synaeresis cracks, suggests that salinity reductions may have been concomitant with phytodetrital pulses and hyperpycnal-emplaced turbidites (cf. Rice et al. 1986). The organic mudstones show very little biogenic reworking and indicate that their emplacement, at least temporarily, may have resulted in dysaerobic conditions that hindered opportunistic colonization of both the fluid mud and the underlying sand (Leithold 1989; Raychaudhuri and Pemberton 1992; Leithold and Dean 1998; Coates and MacEachern 1999; Bann et al. 2004; MacEachern et al. in press).

Facies 2a and 2b comprise, respectively, a moderate to highly "stressed" marine expression of the *Cruziana* Ichnofacies, reflecting the fluctuating environmental conditions associated with fluvial input. Facies 2a contains a relatively more diverse and abundant trace fossil assemblage than Facies 2b, and is interpreted to represent deposition in a prodelta setting, more distant and less directly impacted by fluvial stresses than Facies 2b. Facies 2b contains a more highly impoverished trace fossil suite and more sporadic distribution of traces than Facies 2a, reflecting the influence of markedly stronger fluvial stresses. Based on the integration of sedimentological and ichnological characteristics, Facies 2a and 2b are interpreted to represent deposition within prodelta and proximal prodelta to distal delta front environments, respectively, of a prograding river-dominated delta.

Facies 2c comprises sandstone that is characterized by abundant current-generated structures, reflecting an exceedingly strong fluvial character. Trough cross-stratified and large-scale ripple-laminated beds commonly display abundant spherulitic siderite marking the internal stratification, suggesting that the sediments were derived from soils on the delta plain (cf. Leckie et al. 1989). During floods, and during autocyclic migration of channels, the low-lying areas of the delta plain are inundated and the spherulitic siderite contained within the soils is liberated, making them available for transportation to the delta front. Dark (organic-rich) mudstone laminae and thin beds are locally common, and quite possibly represent hyperpycnal muds that flowed across the bed during periods of high fluvial discharge, but they may also represent mud drapes from hypopycnal flows (deposition of flocculated clay from a buoyant mud plume). The sandstones and mudstone interbeds display an exceedingly low abundance of burrowing and a low diversity trace fossil assemblage, reflecting stressed environmental conditions. Pedogenic slickensides, abundant rooting, and the presence of adhesive meniscate burrows (AMB) in the upper portion of the facies provide evidence of subaerial exposure and incipient soil formation. Beetle larvae and adult soil bugs are the suspected tracemaker of AMB (Hasiotis 2002). The backfill menisci formed as the insect shifted within the substrate, perhaps feeding on plant roots and organic matter within the upperparts of soils, and thus the trace represents both locomotion and feeding behaviors.

Facies 2d overlies or is intercalated between units of Facies 2c. The oyster-bearing succession (Facies 2d) likely reflects brackish water conditions and is interpreted as representing deposition within a quiet bay or lagoon setting, along the lower delta plain. The sedimentology and ichnology of this facies varies drastically from place to place, the main controlling factor likely being the proximity to bayhead deltas. The depositional environment attributed to Facies 2c depends on the stratigraphic context of the units. Where Facies 2c underlies Facies 2d, the units are interpreted as delta front deposits that were subsequently overlain by the deformed sandy siltstones and immature soils (of the upper portion of Facies 2c), during continued progradation of the delta lobe and subsequent subaerial exposure on the delta plain. Where Facies 2c overlies Facies 2d, it is interpreted to likely represent a number of variable depositional environments typical of the lower delta plain, including bayhead deltas (that shed into the bays / lagoons of Facies 2d) and tidal channels.

Facies Association 2 is interpreted to represent the progradation of a river-dominated delta. Facies 2a and 2b represent deposition within prodelta and proximal prodelta to distal delta front environments, respectively. Facies 2c (underlying Facies 2d) represents deposition within distal to proximal portions of the delta front. Facies 2d and Facies 2c (that overlies Facies 2d) represent lower delta plain deposits.

DISCUSSION

The progradation of both deltaic and non-deltaic shorelines produces coarsening-upwards successions. Strandplain deposits are identified using an integrated ichnological and sedimentological model,

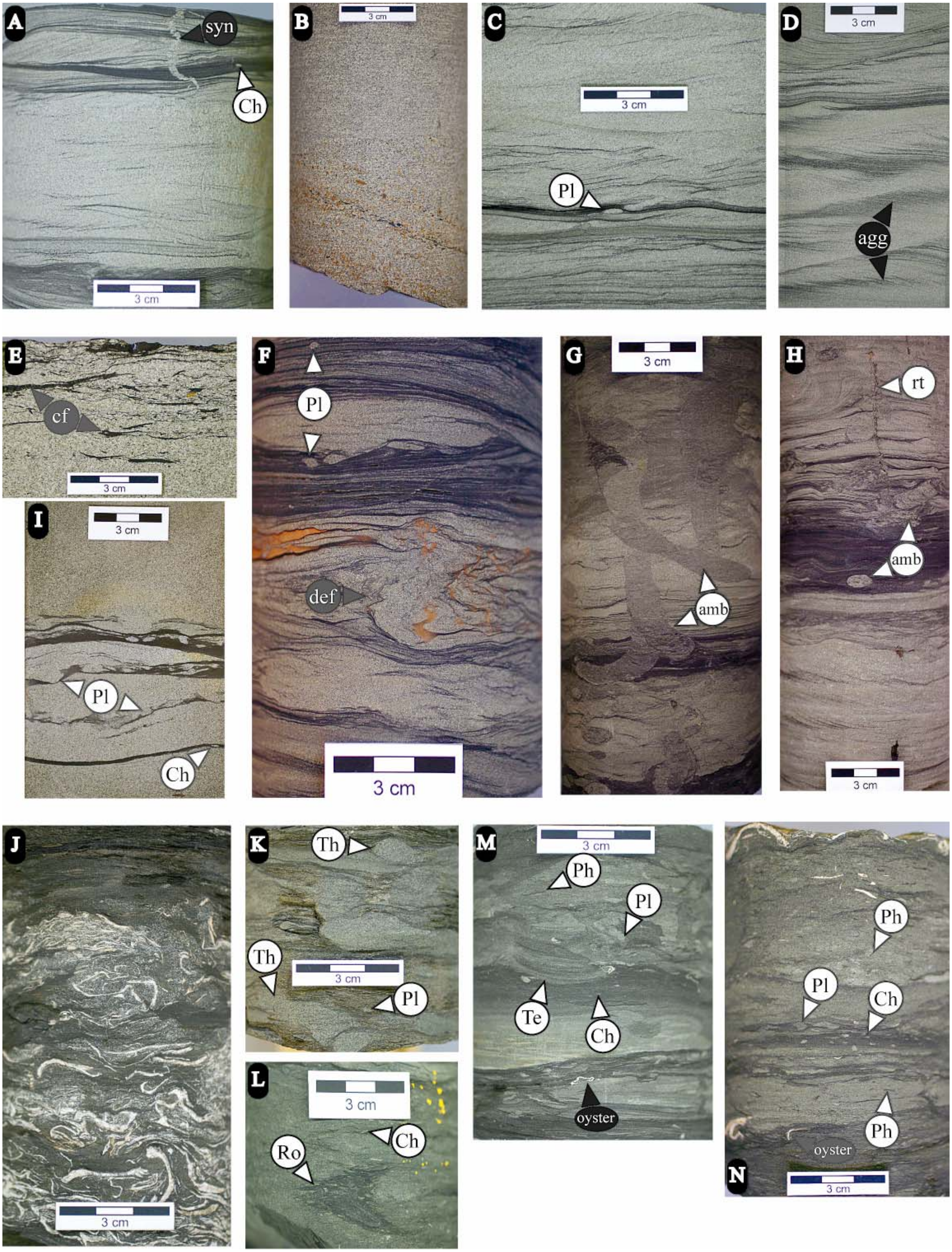
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Fig. 10. (Previous Page) Representative photographs of Facies 2c (A-I) and 2d (J-M) of Facies Association 2 (FA2). **A)** Dark mudstones and current ripple-laminated sandstone beds, locally displaying synaeresis cracks (syn). BI 0-1, *Chondrites* (Ch). Well 6-1-47-2W5, 964.3 m. **B)** Trough cross-stratification marked by carbonaceous detritus and dispersed spherulitic siderite, well 2-15-47-2W5, 971.2 m. **C)** Current ripple-laminated sandstone. BI 0-1, *Planolites* (Pl) Well 14-35-46-2W5, 1000.0 m. **D)** Aggradational current ripples (climbing ripples). Well 10-9-47-2W5, 1015.1 m. **E)** Sandstone beds containing coal fragments, carbonaceous detritus and siltstone / mudstone rip-up clasts. Also note the dispersed spherulitic siderite. Well 8-27-46-2W5, 1016.7 m. **F)** Interbedded fine-grained sandstone and siltstone. Soft-sediment deformation. *Planolites* (Pl). Well 4-11-47-2W5, 970.9 m. **G)** Adhesive meniscate burrows (amb). Well 12-22-46-2W5, 946.5 m. **H)** Root traces (rt) and adhesive meniscate burrows (amb). Well 8-22-46-2W5, 988.0 m. **I)** *Planolites* (Pl) and *Chondrites* (Ch). Well 2-6-46-1W5, 981.2 m. **J)** Facies 2d, mudstone or sandy mudstone with abundant fossilized oysters. BI 0. Well 8-22-46-2W5, 987.4 m. **K)** Bioturbated sandier portion of the facies. *Thalassinoides* (Th) and *Planolites* (Pl). Well 4-11-47-2W5, 968.0 m. **L)** *Rosselia* (Ro) and *Chondrites* (Ch), well 7-20-46-1W5, 995.6 m. **M)** Heterolithic clayey siltstone and fine-grained sandstone with a BI 1-3. *Teichichnus* (Te), *Planolites* (Pl), *Phycosiphon* (Ph) and *Chondrites* (Ch). Well 6-16-46-1W5, 995.4 m. **N)** BI 2, *Chondrites* (Ch), *Phycosiphon* (Ph) and *Planolites* (Pl). Well 6-16-46-1W5, 995.2 m.

whereas deltaic successions are conventionally identified on the basis of detailed mapping of sand body geometries. More recently, studies have recurrently identified deltaic deposits as containing "stressed" ichnological assemblages. The integration of sedimentological and ichnological characteristics of deltaic deposits has led to more reliable determinations of the relative degree of influence imposed by river, tidal, wave, and storm influences.

A number of recurrent sedimentological characteristics have been identified in deltaic successions. Convolute bedding is a common feature to deltaic prodelta and distal delta front deposits, and is most abundant within river-dominated successions, where thick soft-sediment deformed units are commonly interstratified with undeformed units consisting of repetitive graded bedsets. Synaeresis cracks, formed as a result of salinity fluctuations, and current-generated structures tend also to be most abundant within river-dominated settings. Finally, dark organic mudstone drapes probably indicate hyperpycnal emplacement, and comprise significant numbers in river-dominated deposits. FA1 contains only minor amounts of convolute bedding, synaeresis cracks, current-generated structures and dark, organic mudstones, and no appreciable thicknesses of repetitive graded beds, indicating a lesser degree of river influence than the subaqueous deltaic deposits of FA2.

The determination of the relative degree of river, tide, wave, and storm influence can be further refined with the integration of ichnological characteristics of prodelta and distal delta front environments. The interaction of various delta front processes results in a variety of physico-chemical stresses being imposed upon infaunal organisms, and this is reflected in the "stressed" trace fossil assemblages of most deltaic successions. "Stressed" ichnological suites are characterized by impoverished trace fossil assemblage diversities, low (though variable) degrees of bioturbation (BI generally averaging 0-3), and sporadic distribution of ichnogenera throughout the deposits. Ethologies are overwhelmingly dominated by grazing and deposit-feeding behaviors, with an abundance of facies-crossing forms. The deltaic signal is especially strong in sandy substrates, where very low numbers of suspension-feeding structures are found, despite the availability of sandy substrates.

Although both river-dominated and wave- and storm-influenced deltaic successions show "stressed" ichnological suites, the wave-influenced deltaic setting is characterized by relatively more diverse and abundant trace fossil assemblages. Waves act to buffer fluvial effects in wave-influenced deltas and the resultant deposits typically contain more of the "classic shoreface" character, in terms of the sedimentology and ichnological signals. Trace fossil assemblages in river-dominated settings reflect a much greater degree of physico-chemical stress. The deltaic ichnological signals are most prevalent in the proximal prodelta to distal delta front deposits of both river-dominated and wave-influenced deltaic successions. FA2 consists of less diverse, less abundant (overall), and more sporadically distributed trace fossil suites than FA1, reflecting the significantly higher stress levels imposed upon the FA2 infaunal communities.

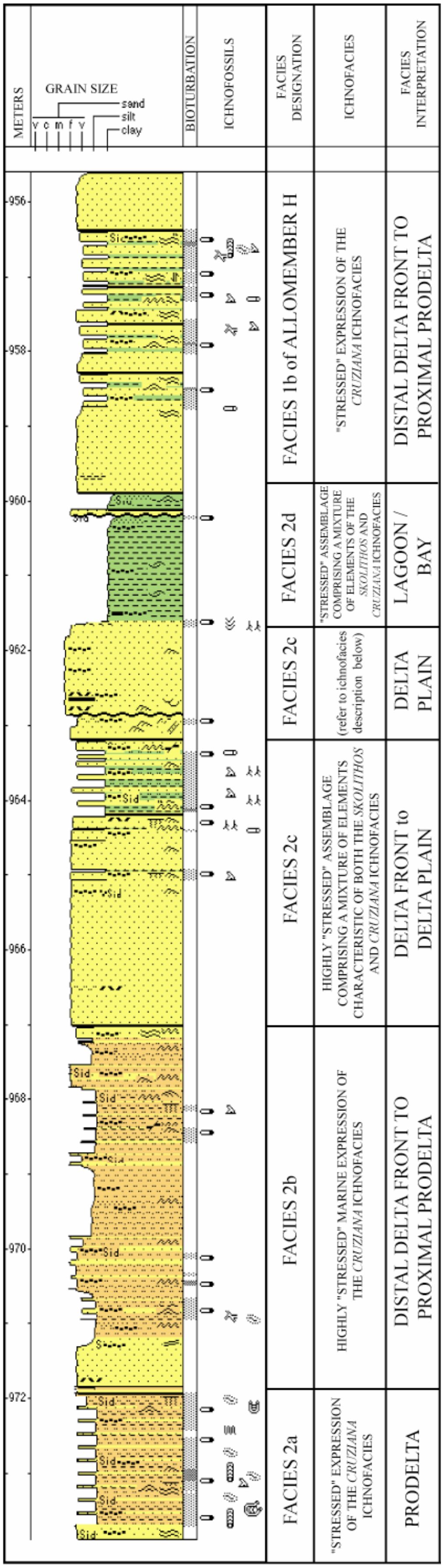
Along depositional strike of the Allomember G delta, FA1 is limited to more northerly locations and FA2 is located only to the south. The along-strike facies variations have major implications for interpretation and architecture prediction of the delta lobe. Bhattacharya and Giosan (2003) developed a model to explain the three-dimensional geometry and facies architecture of a number of modern asymmetric, wave-influenced deltas characterized by strong longshore drift. Their model indicates that a strong groyne effect generated at the distributary mouth tends to impede sediment drift. As a result, amalgamated beach ridges accumulate on the updrift side of the distributaries, whereas more heterolithic units develop downdrift where the succession is more river-dominated. The formation of barrier bars downdrift creates protected lagoonal environments that act as sediment traps for fine-grained sediment. Lagoonal sediments may show a strong riverine component, particularly if linked to secondary bayhead deltas that accumulate subparallel to the coast behind barrier bars.

CONCLUSIONS

Allomember G of the basal Belly River Formation is characterized by facies that contain "stressed" ichnological assemblages that depart from the ichnological signals characteristic of strandplain successions. Such assemblages are consistent with a deltaic signal.

The facies can be easily subdivided into two facies associations, based on ichnological and sedimentological variations. FA1 and FA2 are interpreted to represent deposition in an overall wave- and storm-influenced delta; however, deposits of FA2 contain characteristics more consistent with deposition in a river-dominated deltaic setting.

The facies associations that comprise Allomember G fit well into the asymmetric delta model of Bhattacharya and Giosan (2003). The facies architecture of FA1 matches the high sand content and strong wave-influence expected along updrift portions of the delta. Reduced river influence in the updrift facies is reflected by more pervasive bioturbation, higher trace fossil diversities and greater ethological range. Vertical dwelling structures of inferred suspension/filter feeding infauna are more common within FA1. In contrast, the facies architecture of FA2 is consistent with the heterolithic nature and river-dominated influences that would be expected downdrift of distributary channel mouths. The increase in environmental fluctuations and thus physico-chemical stresses on infaunal communities in downdrift portions of the delta front, is reflected by the dominance of current-generated structures, normally graded bedding, soft-sediment deformation, synaeresis cracks, and inferred hyperpycnal mudflow deposits. In addition, bioturbation is less pervasive than in the updrift facies and trace fossil assemblage diversities show greater impoverishment. The structures of inferred suspension-feeding organisms are conspicuously less evident in the downdrift facies. Furthermore, the occurrence of bay/lagoonal and bayhead delta deposits completes the expected stratigraphic architecture of a downdrift portion of an asymmetric wave-influenced delta.



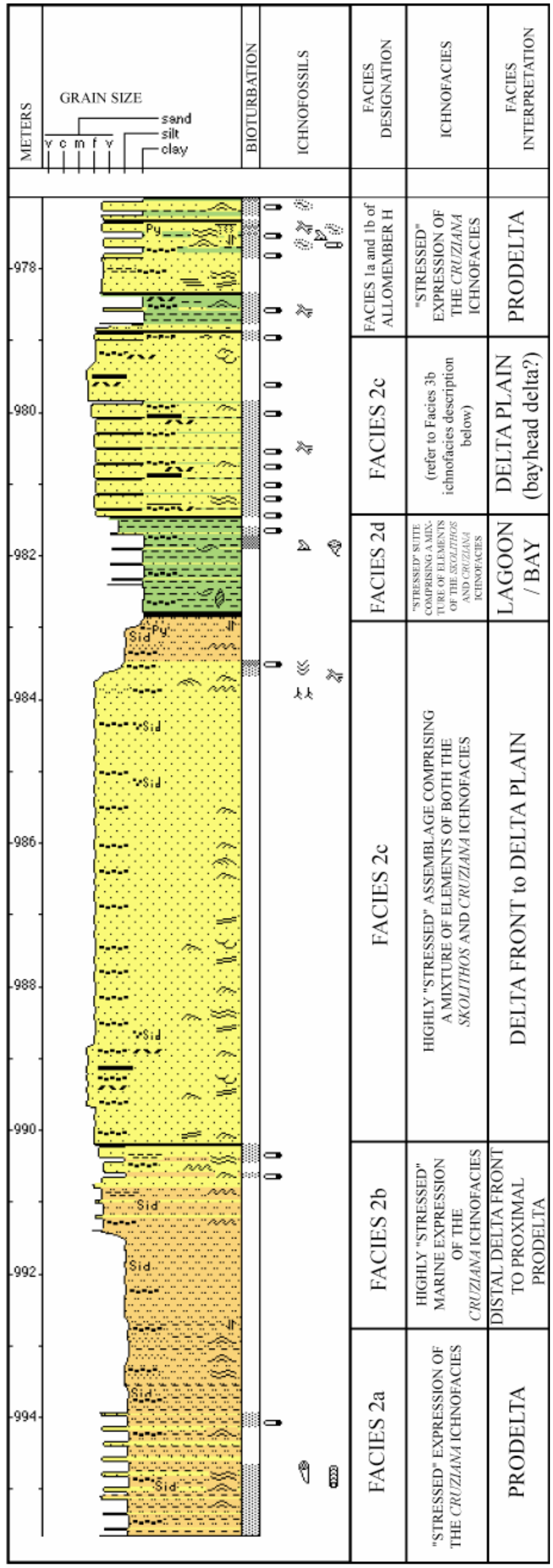


Fig. 11. Litholog of well 06-01-47-02W5 showing facies of FA2.

Fig. 12. (Previous Page) The facies of FA2 show a greater degree of variability from well to well than the facies of FA1. This variability is highlighted when comparing the Figure 11 facies succession with that of another representative well (02-06-46-01W5). The prodelta to distal delta front successions (Facies 2a and 2b) are rather comparable, both comprised of numerous intervals of convolute-bedded strata. However, the 06-01 well shows a higher degree of river influence suggested by the higher quantity of current ripple laminated beds and synaeresis cracks. The successions are characterized by highly 'stressed' trace fossil assemblages, though locally variable with respect to BI and diversity. Facies 2c that lies above Facies 2d is interpreted as bayhead delta deposits. The unit consists of abundant thin, dark-colored mud drapes. These are probable hyperpycnal-induced deposits that were transported along the bed during high discharge events (freshets).

FUTURE WORK

The asymmetric delta model is based on observations of modern wave-influenced deltas. This is the first study to apply the model directly to an ancient system. Continued research seeks to further delineate delta lobe asymmetry and concomitant along-strike facies variations, both attributable to longshore drift and deflection of river-induced stresses downdrift of distributary channel mouths. Infaunal organisms are exceedingly sensitive to fluvial influences, and thus, the ethological preferences, trace fossil abundances and assemblage diversities are a direct reflection of imposed environmental stresses. It thus follows that mapping distributions of bioturbation intensity and assemblage diversity, may serve as a predictive tool for determining distributary channel proximity. Understanding the facies architecture and spatial distributions of wave-influenced deltas may have important implications for predicting and mapping reservoir quality. Recognition of ancient asymmetric delta lobes may therefore, potentially lead to more efficient and predictable reservoir exploitation.

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