Journal of Sedimentary Research

Journal of Sedimentary Research, 2009, v. 79, 184–209
Research Article
DOI: 10.2110/jsr.2009.026

HYPERPYCNAL RIVERS AND PRODELTAIC SHELVES IN THE CRETACEOUS SEAWAY OF NORTH AMERICA

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ABSTRACT: **Despite the historical assumption that the bulk of marine "shelf" mud is deposited by gradual fallout from suspension in quiet water, recent studies of modern muddy shelves and their associated rivers show that they are dominated by hyperpycnal fluid mud. This has not been widely applied to the interpretation of ancient sedimentary fluvio-deltaic systems, such as dominate the mud-rich Cretaceous Western Interior Seaway of North America. We analyze two such systems, the Turonian Ferron Sandstone Member of the Mancos Shale Formation, in Utah, and the Cenomanian Dunvegan Formation in Alberta. Paleodischarge estimates of trunk rivers show that they fall within the predicted limits of rivers that are capable of generating hyperpycnal plumes.**

The associated prodeltaic mudstones match modern hyperpycnite facies models, and suggest a correspondingly hyperpycnal character. Physical sedimentary structures include diffusely stratified beds that show both normal and inverse grading, indicating sustained flows that waxed and waned. They also display low intensities of bioturbation, which reflect the high physical and chemical stresses of hyperpycnal environments. Distinct "mantle and swirl" biogenic structures indicate soupground conditions, typical of the fluid muds that represent the earliest stages of deposition in a hyperpycnal plume. Hyperpycnal conditions are ameliorated by the fact that these rivers were relatively small, dirty systems that drained an active orogenic belt during humid temperate (Dunvegan Formation) to subtropical (Ferron Sandstone Member) "greenhouse" conditions. During sustained periods of flooding, such as during monsoons, the initial river flood may lower salinities within the inshore area, effectively "prepping" the area and allowing subsequent floods to become hyperpycnal much more easily. Although shelf slopes were too low to allow long-run-out hyperpycnal flows, the storm-dominated nature of the seaway likely allowed fluid mud to be transported for significant distances across and along the paleo-shelf. Rapidly deposited prodeltaic hyperpycnites are thus considered to form a significant component of the muddy shelf successions that comprise the thick shale formations of the Cretaceous Western Interior Seaway.

INTRODUCTION

General facies models for the interpretation of ancient marine mudstones historically assume that most shelf mud is deposited in quiet water by simple suspension settling (Pettijohn 1975; Bhattacharya and Walker 1992; Nichols 1999; Prothero and Schwab 2004; Boggs 2006). In a landmark paper Rine and Ginsburg (1985) presented one of the first major studies of a high-energy prograding muddy shoreline and inner shelf deposit along the modern Suriname coast. Other major delta complexes, such as the Mekong in Vietnam (Ta et al. 2005), the Atchafalaya in the Gulf of Mexico (Augustinus 1989; Allison and Neil 2003; Rotondo and Bentley 2003), the Po in the Adriatic (Cattaneo et al. 2003 and Cattaneo et al. 2007), the Fly in Papua New Guinea (Walsh et al. 2004), among others (Allison and Nittrouer 1998), show major mud-dominated coastlines and inner-shelf mud belts, typically elongated downdrift of the river mouth. Other oceanographic studies emphasize the importance of rapidly deposited fluid muds in shelf construction (McCave 1972; Nittrouer et al. 1986; Kineke et al. 1996; Kuehl et al. 1996; Kuehl et al. 1997; Kineke et al. 2000; Hill et al. 2007; Liu et al. 2002; Bentley 2003).

Many modern shelf muds are now recognized to have accumulated as prodeltaic deposits. These may be deposited directly from hyperpycnal mud plumes related to times of elevated river discharge during floods (Fig. 1). Rapid flocculation of clays and sediment settling may also occur within an initially low-sediment-concentration hypopycnal plume, causing it to evolve into a hyperpycnal flow (Parsons et al. 2001) (Fig. 1). This can happen quickly, within hours or days of the initial river flood. Storms, fair-weather waves, and tides may also resuspend mud at the sea floor, which subsequently migrates along the shelf as a dilute, hyperpycnal geostrophic fluid-mud belt (Nemec 1995; Kineke et al. 2000; Mulder and Alexander 2001; Bentley 2003; Rotondo and Bentley 2003; Draut et al. 2005). These mudstones typically show distinctly laminated to bedded fabrics with a corresponding lack of bioturbation, reflecting much more rapid sedimentation rates than recorded during pelagic settling of clay from suspension (e.g., MacEachern et al. 2005; MacEachern et al. 2007a). Sediment accumulation rates of up to 20 cm per year have been recorded in the modern Atchafalaya mud belt, compared to less than 1 cm/year in the more distal offshore (Allison and Neill 2003).

Despite these advances in our understanding of mud transport and deposition in modern shelves, most studies of ancient hyperpycnal deposits or of similar "sustained" flow turbidites focus on sandstones

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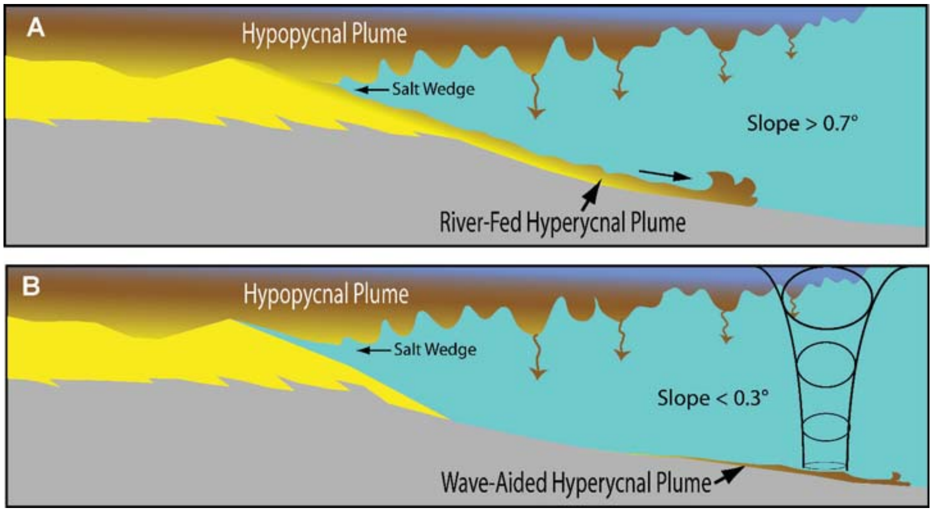

FIG. 1.—Hyperpycnal versus hypopycnal plumes in river mouths. **A)** River-fed hyperpycnal plumes form on slopes > 0.7°. **B)** On lower slopes (< 0.3°), waves or tides are required to generate a hyperpycnal flow. Hypopycnal plumes may also collapse and feed hyperpycnal flows.

rather than mudstones (e.g., Howard 1966; Martinsen 1990; Kneller and Branney 1995; Mutti et al.1996; Mulder and Alexander 2001; Mutti et al. 2003; Plink-Björklund and Steel 2004; Zavala et al. 2006; Petter and Steel 2006). This emphasis on sandy shelf facies reflects the importance of sandy reservoir facies in exploration and production of hydrocarbons. Consequently, there remain relatively few studies that examine the origin of prodelta mudstones on ancient shelves (e.g., Asquith 1970, 1974; Leithold 1993, 1994; Sethi and Leithold 1994; Leithold and Dean 1998; Varban and Plint 2008) although a recent paper by Soyinka and Slatt (2008) documents muddy prodelta hyperpycnites in the Cretaceous Lewis Shale, Wyoming. Other ancient examples of muddy hyperpycnites, nevertheless, remain rare (Bouma and Scott 2004).

We suggest that the lack of described ancient examples reflects the difficulties encountered when working with mud-dominated facies in outcrop and subsurface, rather than the rareness of these features. Given that facies criteria for the identification of modern muddy hyperpycnites have now been proposed, as shown in Figure 2 (Allison et al. 2000; Mullenback and Nittrouer 2000; Allison and Neill 2003; Mulder et al. 2003; Nakajima 2006), it seems appropriate to apply these criteria to the interpretation of the ancient record, as was accomplished by Soyinka and Slatt (2008).

Several well-documented fluvio-deltaic clastic wedges in the Cretaceous Western Interior of North America, such as the Cenomanian-age Dunvegan Formation in Alberta, Canada, and the Turonian-age Ferron Sandstone Member of the Mancos Shale Formation in central Utah (Fig. 3) overlie thick mudstones that generally lack bioturbation and show facies characteristics that resemble modern hyperpycnites. We hypothesize that these deposits represent ancient subaqueous prodelta mud belts, largely built by hyperpycnal flows. Mud-belt migration was likely aided by a high-energy storm regime. Several of these top-preserved delta deposits contain both trunk channel and distributary channel deposits, and have been studied in sufficient stratigraphic detail to establish direct linkages between the rivers and their associated prodeltaic deposits (Figs. 4, 5). Detailed examination of these prodelta mudstones,

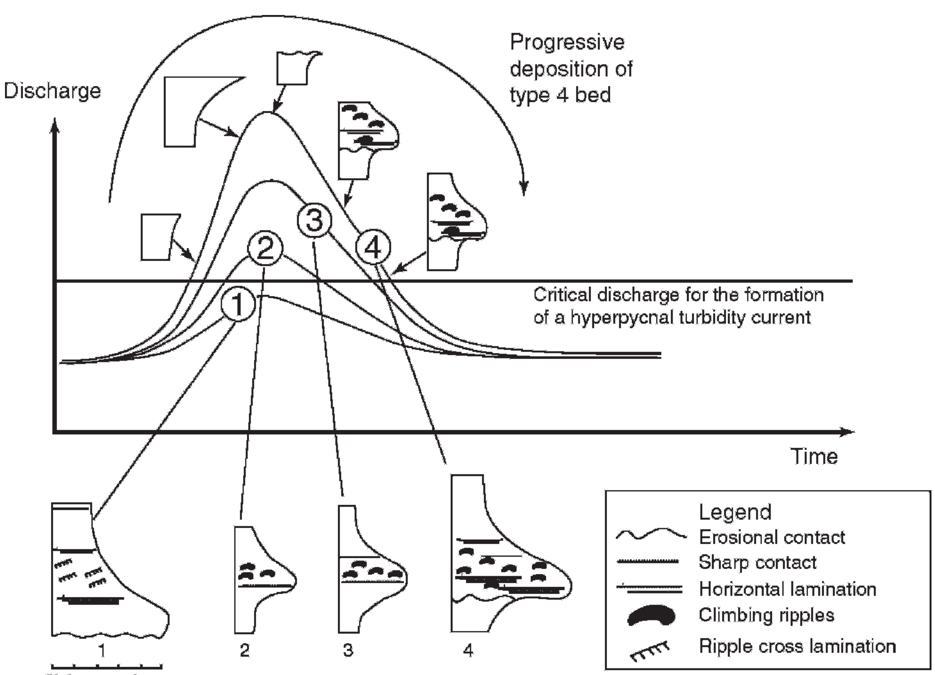

FIG. 2.—Hyperpycnite facies model (from Mulder et al. 2001 and Mulder et al. 2003). Type 1 beds represent classical, surge-type turbidites. Types 2 to 4 show evidence of sustained waxing and waning flows, with the development of inverse and normal grading.

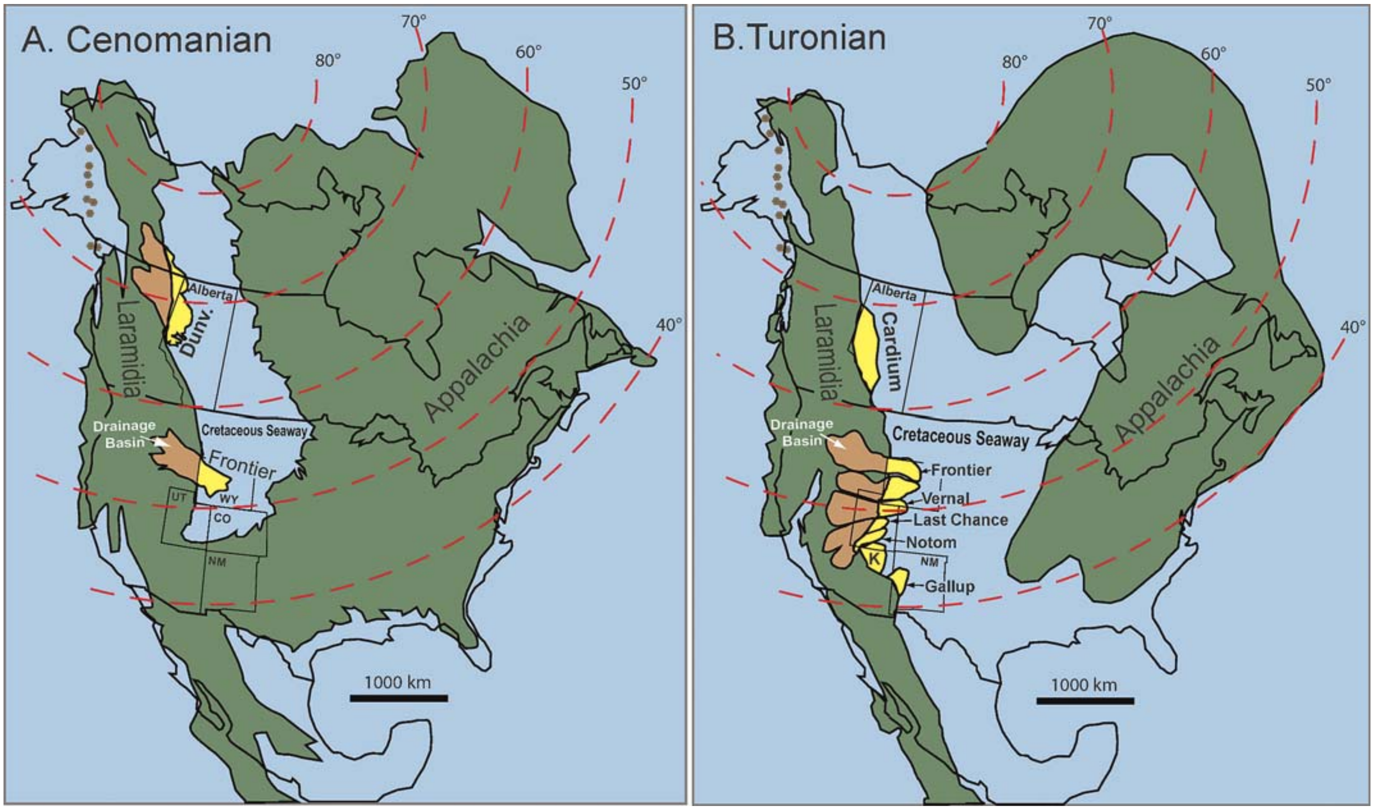

FIG. 3.— **A)** Cenomanian paleogeography of North America showing delta complexes of the Dunvegan Formation in Alberta and the Frontier Formation in Wyoming, and **B)** Turonian paleogeography showing delta complexes of the Ferron Sandstone Member of the Mancos Shale Formation (Notom, Last Chance, and Vernal deltas) in Utah, the Kaiparowits delta (K) in southern Utah, the Frontier Formation of Wyoming, the Cardium Formation in Alberta, and the Gallup Sandstone in New Mexico. Figure based on Williams and Stelck (1975), Bhattacharya (1993), Gardner (1995), Umhoefer and Blakely (2006), Plint and Wadsworth (2003, 2006), and Johnston (2008). Paleolatitudes are from Varban and Plint (2008), after Irving et al. (1993).

especially in cores where details of mud facies are far more easily observed, allow comparison with recently published hyperpycnite facies models and examples.

Purpose of This Paper

The purpose of this paper is two-fold. The first goal is to estimate paleo-discharge volumes of these ancient rivers in conjunction with other paleogeographic and paleoclimatic constraints, in order to evaluate how commonly the rivers that drained the Cretaceous Western Interior Seaway were able to generate hyperpycnal plumes. The second goal is to summarize the facies characteristics (sedimentological and ichnological) of prodelta and "shelf" mudstones preserved within deltaic clastic wedges of the Cretaceous Western Interior Seaway, and to assess what proportion of these wedges are likely to record the deposits of hyperpycnal plumes. Lastly we compare these hyperpycnite deposits with other mudstones in the Cretaceous Seaway such as anoxic laminites.

Aside from their general importance in constructing muddy shelves, muddy hyperpycnites also may be important in the economic assessment of petroleum systems. Hyperpycnites may have lower source-rock potential (at least for oil) and may be significant in the generation of overpressured conditions and the development of mobile shales, which form important traps in major deltaic complexes like the Niger and Mississippi, as well as basins prone to shale tectonics, such as the Black Sea and Caspian Sea.

CRITERIA FOR GENERATION AND IDENTIFICATION OF HYPERPYCNAL FLOWS

Historically, hyperpycnal flows were thought to be common in lacustrine settings but relatively uncommon in marine settings due to the salinity of seawater. It is now recognized that many marine deltas can experience hyperpycnal conditions when sediment concentration is high, especially during exceptional river floods (Mulder and Syvitski 1995; Mulder and Alexander 2001; Plink-Björklund and Steel 2004). Mulder and Syvitski (1995) showed that hyperpycnal flows most commonly occur in sediment-rich, "dirty" rivers, with relatively small drainage basins, and particularly adjacent to high-relief, tectonically active mountains in humid climates, such as we believe characterized the Cretaceous foreland succession of North America. They also show that rivers with average discharge less than 6000 m^3/s routinely generate hyperpycnal flows during large seasonal floods, whereas larger continental-scale rivers, such as the Mississippi or Ganges –Brahmaputra (10^4–10^5 m^3/s) rarely, if ever, become hyperpycnal (Fig. 6).

The ability of a river to generate a hyperpycnal flow can be greatly enhanced if the marine basin is already brackish, such as where estuarine mixing occurs (Felix et al. 2006). In some cases, marine shelves may experience salinity reduction during initial flooding events, which then predisposes the river mouth to generate hyperpycnal flows during subsequent river floods (Warne et al. 2002; Draut et al. 2005; Felix et al. 2006). Such conditions may be met during periods of freshet. Many rivers experience dramatic changes in discharge as a function of seasonal climate changes, as a result of major floods associated with storms, or with snowmelt freshets (e.g., Thomson 1977). As a consequence, many rivers can alternate from hypopycnal to hyperpycnal conditions, even in fully marine settings (Nemec 1995; Mulder and Syvitski 1995; Parsons et al. 2001).

Many rivers produce both hyperpycnal and hypopycnal plumes concurrently (Fig. 1A, Nemec 1995; Kineke et al. 2000). Low-concentra-

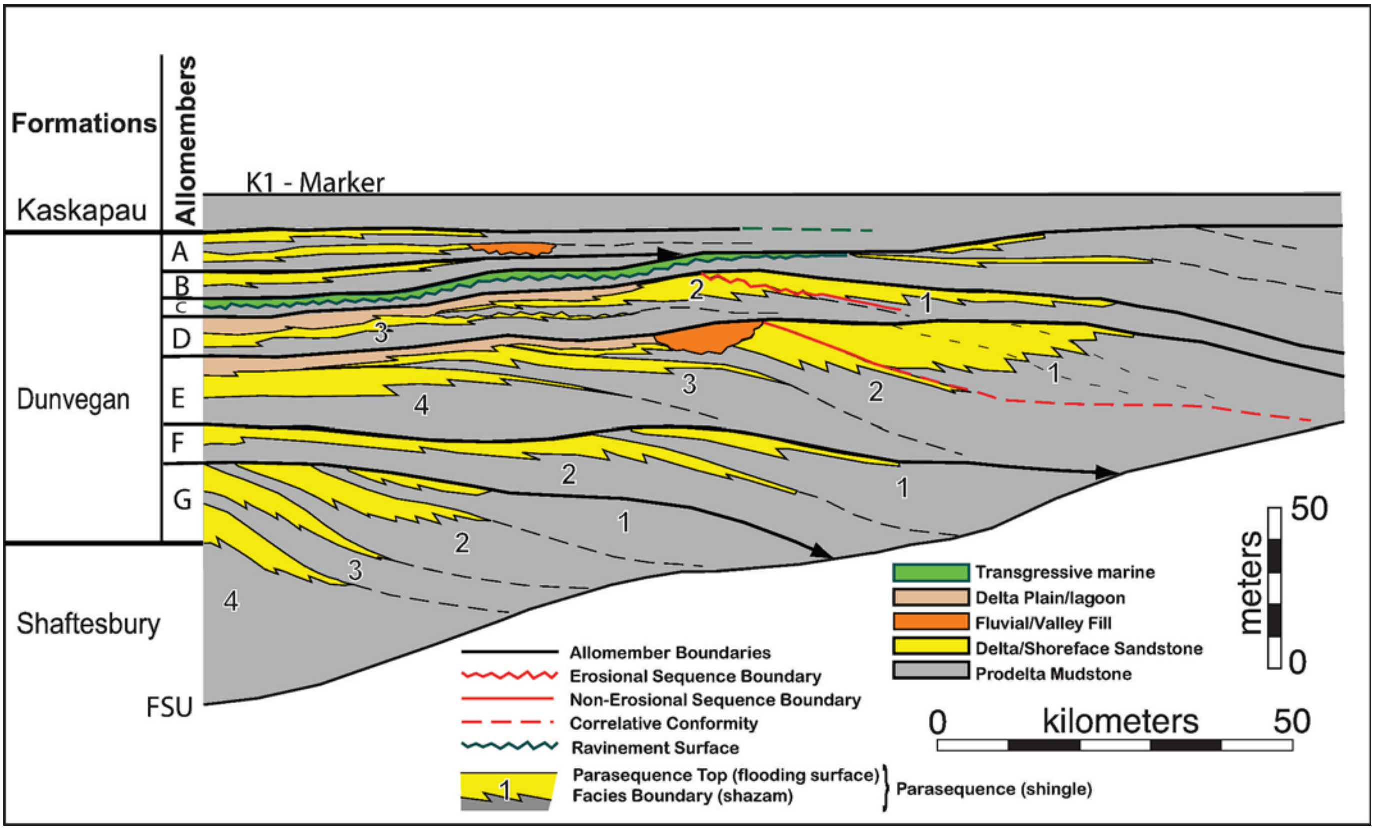

FIG. 4.— Regional cross section across the Alberta Foreland Basin, illustrating the allostratigraphic interpretation of the Upper Cretaceous Dunvegan Formation (from Bhattacharya 1993). The Dunvegan comprises several stacked allomembers (A to G). Each allomember is bounded by a regional transgressive flooding surface. Each allomember internally consists of several smaller-scale, offlapping, shingled parasequences that map as sandy delta lobes and their associated prodelta mudstones. Many delta lobes can be correlated into their updip feeder valleys, such as in Parasequence E1 (Fig. 8).

tion hypopycnal plumes may experience internal settling of sediment, which in turn may evolve into smaller hyperpycnal plumes that descend from the hypopycnal plume onto the seafloor (Parsons et al. 2001; Kineke et al. 2000). Sediment may also partly settle and then become remobilized by waves or tides as sediment-hugging fluid-mud flows, which have also been termed hyperpycnal flows (Fig. 1B). The generation of hyperpycnal turbidity currents, directly fed by rivers, requires slopes greater than 0.7° (Bentley 2003; Friedrichs and Scully 2007) and may be a common phenomena in steep-gradient deltas. In low-gradient deltas with slopes $<$ 0.3°, hyperpycnal flows can be generated where wave or tidal processes add to the turbulence at the seafloor (Fig. 1B), inhibiting near-bed mud from settling and allowing the sediment to migrate across and down-slope as a fluid mud (e.g., Varban and Plint 2008; Friedrichs and Scully 2007; Bentley 2003).

Criteria for Identification of Hyperpycnites

Mulder et al. (2003) have suggested criteria for recognizing the deposits of river-flood-generated turbidity currents, which they term **hyperpycnites** and which includes both sandy and muddy components (Fig. 2). A key criterion is the formation of both inverse and normally graded beds, which reflects the sustained nature of the flow (e.g., Kneller and Branney 1995). Their model suggests that there is a predominance of beds with gradational versus sharp boundaries. Within-bed scour is enhanced in higher discharge events. They suggest that progressive erosion or nondeposition of the inversely graded beds occurs with time and distance from the shoreline. They also suggest that burrowing is typically low and that flora and fauna are primarily allochthonous. The distinction of hyperpycnal deposits formed by intermittent storm suspension versus directly river fed has not been fully elucidated, but we suggest that low-gradient, storm-induced hyperpycnites would likely show a greater preponderance of wave-formed sedimentary structures, such as hummocky cross stratification or oscillatory ripples.

Some of the best-studied modern muddy hyperpycnites are those generated by the Atchafalaya prodelta mud plume (Allison et al. 2000; Allison and Neill 2003; Neill and Allison 2005) and deep-sea hyperpycnites in the Japan Trench (Nakajima 2006). The Atchafalaya mud belt lies within the inner shelf in water depths of about 5 m. The mud belt reaches a maximum thickness of about 2.5 m. Mud dispersal across and along the shelf is aided by wave-generated currents, commonly associated with storms and cold fronts, and a significant proportion of mud migrates onshore and builds the down-drift Louisiana chenier plain (Allison and Neill 2003). Cores from proximal and distal positions in the mud belt show well-developed millimeter- to centimeter-thick sand or silt to clay couplets and are virtually devoid of burrowing (Fig. 7A). Normally graded beds are ubiquitous. Silt and sand layers are sharp based and show localized scour surfaces. Undulating laminations in the sandy layers likely represent wave reworking.

Muddy hyperpycnites deposited in the Central Japan Sea were deposited 700 km from feeder-river mouths, on the Toyama Fan, at about 3000 m water depth, well below the ability of storm waves to remobilize the sediment (Nakajima 2006). These hyperpycnites comprise sharp-based, centimeter- to decimeter-thick beds that show either normal or inverse grading (Fig. 7B). Beds also show alternating massive to flat-to-undulating lamination, the latter likely reflecting migration of low-amplitude current ripples. Rhythmically stratified beds are interpreted to

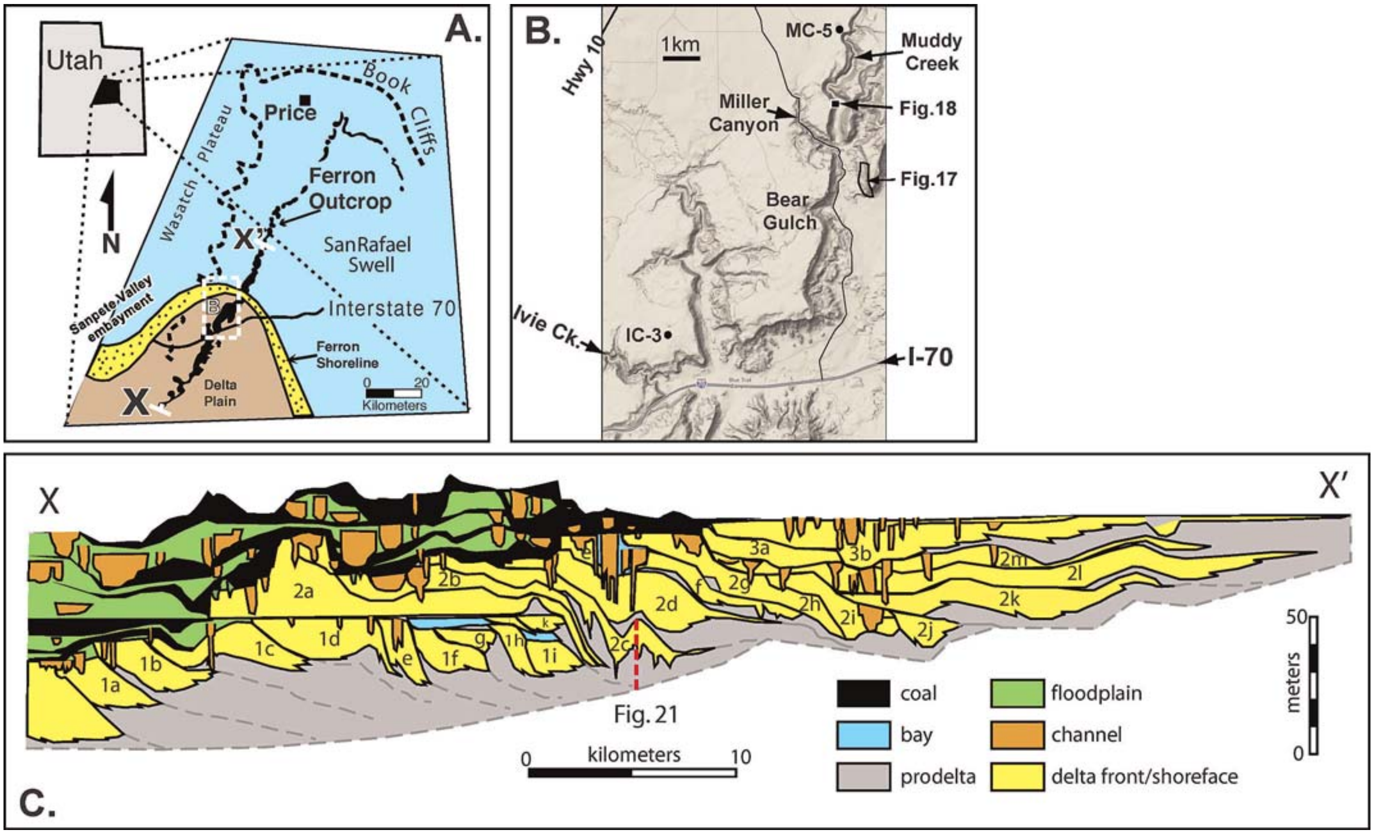

FIG. 5.— **A)** Utah base map showing paleogeography of the Ferron Last Chance Delta and location of regional cross section X–X′. **B)** Close-up of main study area showing location of Ivie Creek Core # 3 (IC-3), Muddy Creek Core # 5 (MC-5), and other locations mentioned in the text. **C)** Stratigraphy of the basal progradational part of the Ferron Sandstone Member. Parasequence sets are numbered and individual parasequences are lettered. Note that Ferron parasequences are numbered from oldest to youngest, opposite of the Dunvegan, wherein the units are numbered from youngest to oldest (see Fig. 4). Modified from Garrison and van den Bergh (2004).

be indicative of long-lived waxing and waning flows. Internal strata show rather diffuse boundaries. Bioturbation is minimal, although the greater water depths of these hyperpycnites compared to the shallow-water examples described above would likely preclude the deep-tier burrowing that is more prevalent in shelf and shallower environments (e.g., Pemberton and MacEachern 1997; MacEachern et al. 2005).

THE DUNVEGAN AND FERRON DELTAS

The synorogenic fluvio-deltaic clastic wedges of both the Turonian Ferron Member and the Cenomanian Dunvegan Formation were deposited into the Cretaceous Western Interior Seaway (Fig. 3), within a foreland basin that developed between the Cordilleran volcanic arc in

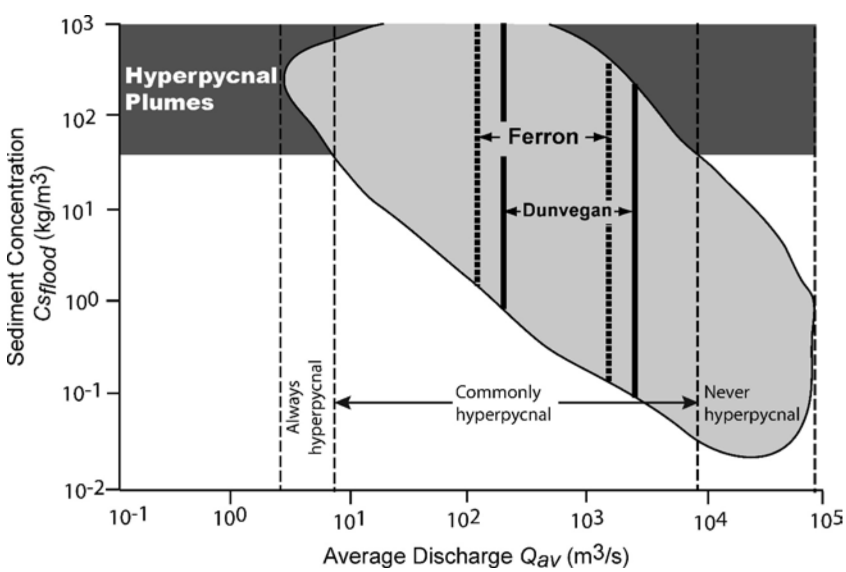

FIG. 6.— Sediment concentration versus average water discharge. Light gray area encompasses range of data for 150 world rivers (after Mulder and Syvitski 1995). Dark gray box shows sediment discharge required for generation of hyperpycnal plumes. Range of discharge for Ferron and Dunvegan rivers suggests that they frequently produced hyperpycnal plumes. Note that hyperpycnal conditions are favored by smaller rivers.

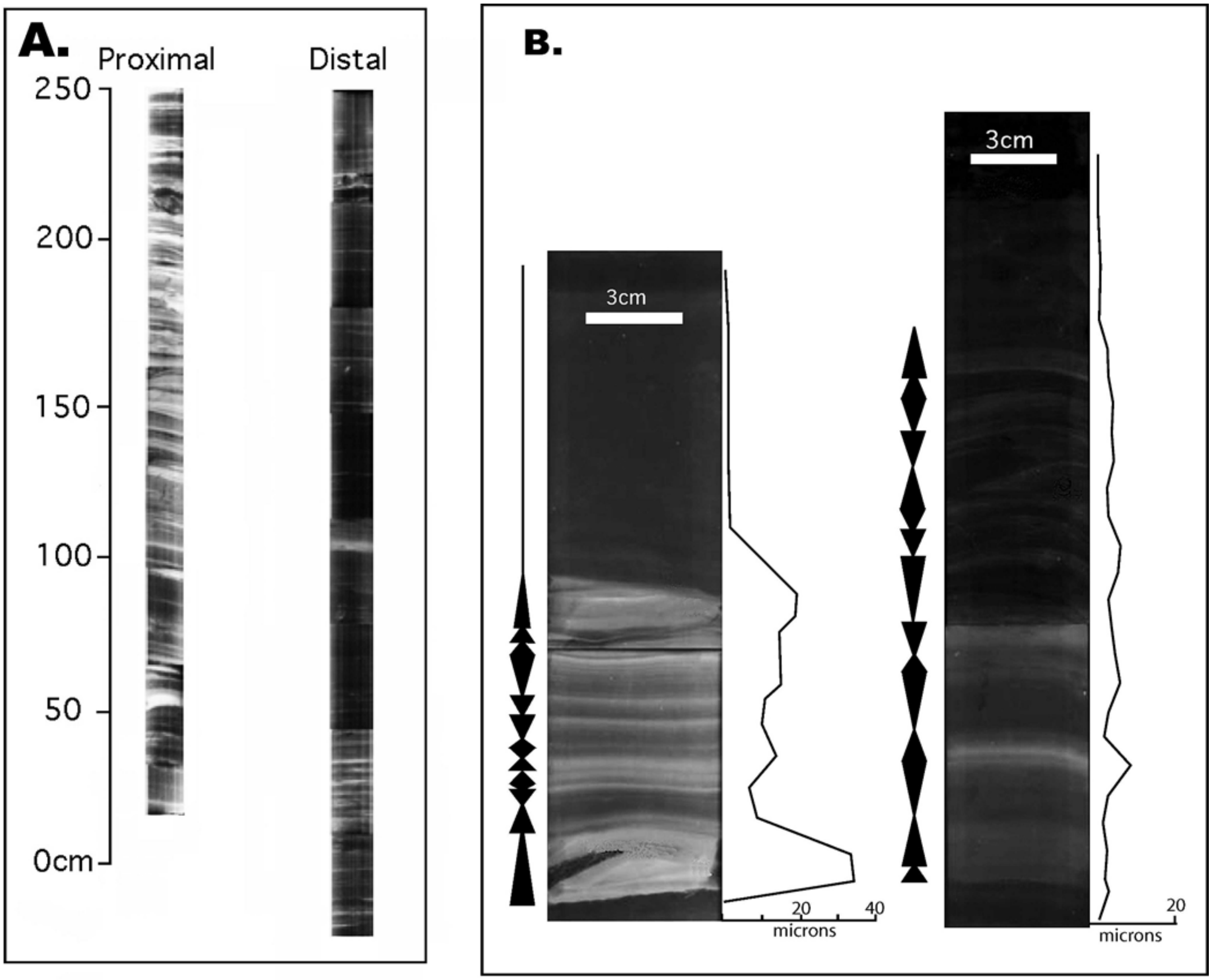

FIG. 7.—X-radiograph photos of prodeltaic hyperpycnites. Lighter color is silt and very fine sand, darker color is clay. **A)** Atchafalaya prodelta hyperpycnites. Note low level of bioturbation and well-developed interbedding (after Allison and Neill 2003). **B)** Japan Trench hyperpycnites (after Nakajima 2006). Triangles indicate normal grading, inverted triangles indicate inverse grading, and diamonds indicate beds that show inverse grading at the base with normally graded tops. Grading is visually estimated from the color grading. Grain-size profile on the right is based on analysis of the sediment as published by Nakajima (2006). Note the diffuse bed and laminae boundaries.

the west and cratonic North America to the east during the Sevier Orogeny (Dickenson 1976; DeCelles and Giles 1996). This seaway never exceeded more than a few hundred meters water depth, but was about 1600 km wide, with a length of about 5600 km. Both stratigraphic units include deltas whose rivers drained an active mountain belt during the humid Cretaceous Greenhouse, conditions ideal for the generation of hyperpycnal conditions (Table 1). The seaway is inferred to have been closed to the south during the Early Cenomanian (Fig. 3A).

Dunvegan

Paleogeographic reconstructions of Plint and Wadsworth (2006) show that the rivers of the Dunvegan Formation drained an area on the order of 500 km by 200 km (100,000 km^2), forming a single, well-integrated, moderate-sized drainage basin (Figs. 3A, 8). The Dunvegan Formation occupied a paleolatitude of about 65–75° N (McCarthy and Plint 1999). Studies of floodplain deposits mainly show hydromorphic, immature paleosols, indicative of generally wet and poorly drained floodplains (McCarthy and Plint 1999). The Dunvegan was, therefore, deposited in a generally humid, cool-temperate climate (McCarthy 2002).

The stratigraphy of the distal marine part of the Dunvegan Formation shows 19 parasequences and 7 allomembers (Fig. 4). The lower parasequences display marked evidence of fluvial domination (Bhattacharya and Walker 1991a, 1991b; Bhattacharya 1991) and downlap onto a prominent, condensed section consisting of dark, greenish black, laminated, unbioturbated fish-scale-bearing, organic-rich bentonitic shales of the Fish Scale Zone. Well-log correlations show a very gradual thinning of these shales to the east. These are interpreted as probable anoxic, condensed-section shales, unrelated to Dunvegan progradation (Bhattacharya and Walker 1991a, 1991b; Bhattacharya 1994).

This paper specifically focuses on the characterization and interpretation of mudstones lying *above* the condensed section, which are deemed to be directly linked with the progradation of the Dunvegan deltaic systems. The muddy facies of each parasequence averages 10–20 m thick and thins

TABLE 1.—*Dunvegan and Ferron regional parameters.*

System	Drainage Area	Latitude	Climate	Prodelta Shelf Slope
Dunvegan	100,000 km^2	65–75°	Humid temperate	0.01–0.03°
Ferron	50.000 km^2	45–55°	Humid subtropical	0.04–0.2°

basinward to 0 m over a distance of 30 to 70 km (Fig. 4), suggesting shelf slopes on the order of 0.01° to about 0.03°. Deposition of most mud occurred within a few tens of meters of the shoreline, and shelf slopes were likely too low to allow development of turbidity currents that were far-traveling.

The parasequences are abundantly cored, allowing detailed description of both prodelta mudstones and delta-front sandstones (Bhattacharya 1991; Bhattacharya and Walker 1991b; Bhattacharya 1993). Plint (2000) and Plint and Wadsworth (2003, 2006) focused on the nonmarine portion of the Dunvegan, and mapped several extensive valley systems that integrated both outcrop and subsurface data (Fig. 8). Their work permits an analysis of the trunk fluvial feeder channels that can be used to estimate paleo-discharge to the deltas.

Ferron

The Ferron Sandstone Member comprises three major depocenters, termed the Vernal, Last Chance, and Notom Delta systems (Fig. 3B; Gardner 1995; Garrison and van den Bergh 2004). Gardner (1995) suggests that owing to segregations caused by major fault lineaments, three drainage basins developed. Gardner (1995) also shows that during Ferron Sandstone deposition the distance to the eroding thrust front was on the order of 100 km. The Ferron drainage basins are each interpreted to have been approximately 500 km long by 100 km wide, suggesting a modest drainage area of about 50,000 km^2.

Paleogeographic reconstruction shows that the deltas of the Ferron Member lay at a paleolatitude of about 45–55° N (Fig. 3B; Sageman and

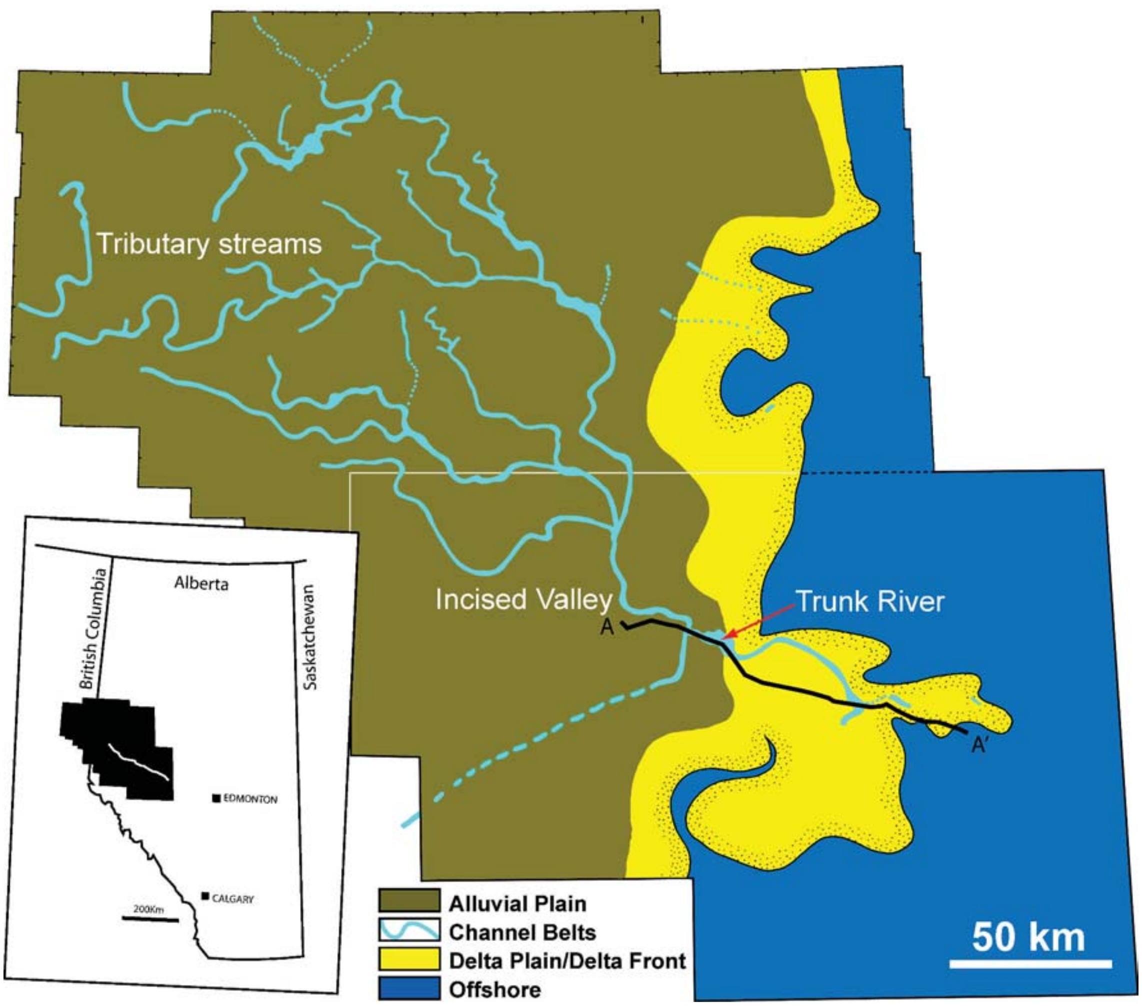

FIG. 8.—Map of valleys and lowstand deltas in Allomember E of the Dunvegan Formation (after Plint and Wadsworth 2003). Cross section A–A′ (Fig. 10) is shown on the main paleogeographic map. Inset map of Alberta shows location of regional cross section shown in Figure 4.

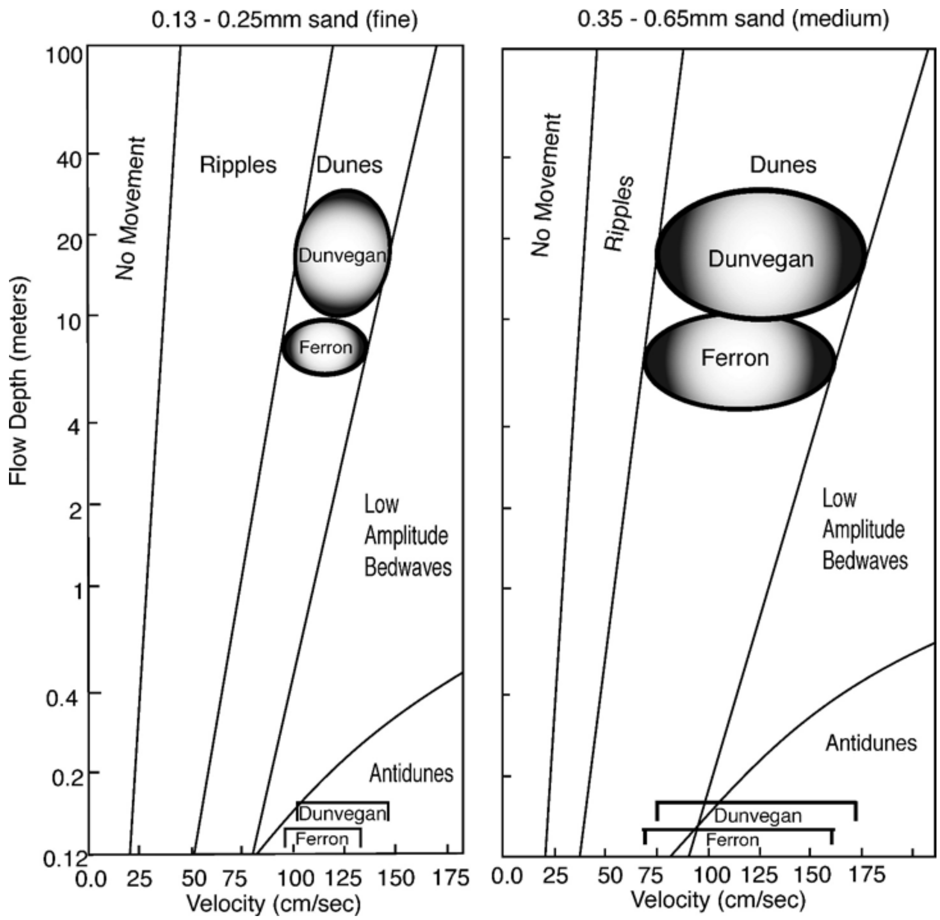

FIG. 9.—Bedform phase diagrams showing velocity versus depth for fine- and medium-grained sandstones. Velocity–depth estimates of rivers of the Dunvegan Formation and Ferron Member are also plotted (modified after Bhattacharya and Tye 2004 and Rubin and McCulloch 1980).

Arthur 1994; Dean and Arthur 1998). Abundant coals and immature paleosols attest to wet, poorly drained floodplains, and a humid, tropical to subtropical climate. Milankovitch-frequency climate fluctuations have been hypothesized to control variations in sediment supply and oxygenation in the seaway (Sethi and Leithold 1994; and Plint 1991).

Garrison and van den Bergh (2004), following on the earlier stratigraphic schemes of Ryer (1984), Gardner (1995), and Barton (1994), subdivided the Turonian-age Ferron Member into 42 parasequences, which are organized into 14 parasequence sets and three sequences (Fig. 5). Fluvial feeder systems can be linked stratigraphically to their down-dip shoreline and shelf successions. Superb outcrop exposures of the fluvial sandstones facilitate estimates of original channel widths and depths, which are needed to estimate paleo-river discharge (see Bhattacharya and Tye 2004 and other papers in Chidsey et al. 2004).

The parasequences downlap onto fossiliferous, condensed section mudstones that cap highly bioturbated sandstones and mudstones of the underlying Clawson and Washboard lentils within the Tununk Shale Member of the Mancos Formation (Fig. 5). This paper focuses primarily on the characterization and interpretation of the less thoroughly bioturbated mudstones lying above this condensed section. The cross section (Fig. 5) shows that the muddy facies of each parasequence thin and downlap from a maximum of about 20 m to 0 m over distances of 5–30 km, suggesting that shelf slopes were on the order of 0.04° to 0.2°, far too low to generate long distance turbidity currents. In general, prodeltaic mud is deposited within about 30 km of the shoreline.

PALEO-DISCHARGE ESTIMATES

Recent advances in paleohydrology (e.g., Leclair and Bridge 2001; Bhattacharya and Tye 2004) permit estimation of the paleo-discharge of associated river channels in the proximal parts of both the Dunvegan Formation and Ferron Member. Combining velocity estimates with channel width and depth estimates allows calculations of water discharge (Bhattacharya and Tye 2004). These can be compared to theoretical estimates, in order to assess how commonly flows might have been hyperpycnal.

Velocity was estimated using the bedform-phase diagrams of Rubin and McCulloch (1980), who showed that specific bedforms (e.g., ripples

TABLE 2.—*Channel dimensions and discharge.*

System	Depth (D) m	Width (W) m	Area 0.65(W*D) m^2	Dominant bedform	Dominant grain size	Velocity (U) m/s^2	Discharge $Q = A*U$ m^3/s
Ferron	9	174	1017	3D dune	Fine-coarse	1.5	1525
Dunvegan	16	170	1768	3D dune	Fine-medium	1.6	2829
Dunvegan	28	150	2730	3D dune	Fine-medium	1.7	4641

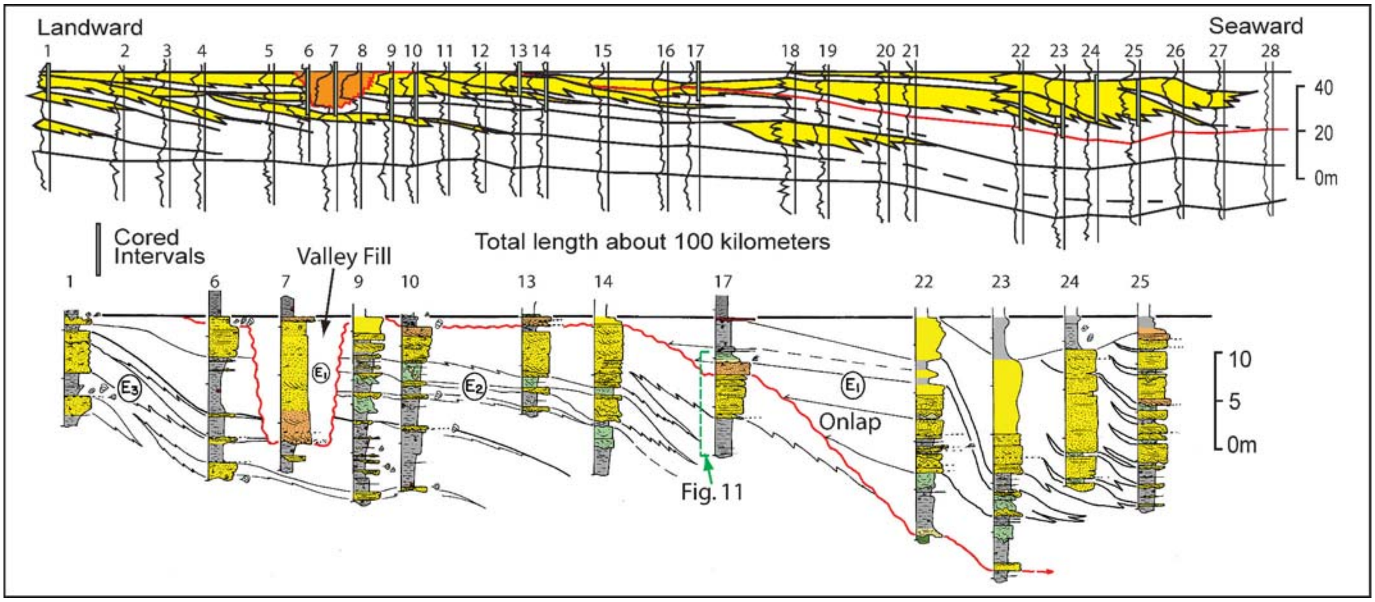

FIG. 10.—Well log (SP and Gamma) and core cross section through Allomember E of the Dunvegan Formation. Where the core does not cover the entire allomember, the lithology has been estimated from the well log, as shown in the top parts of cored wells 9, 14, 22, 23, 24, and 25. Core photos from well 17 are shown in Figures 11 and 12. Location of cross section A–A′ shown in Figure 8. Cross sections modified after Bhattacharya (1993). See Bhattacharya (1993) for well locations and log types.

and dunes) are stable within specific ranges of flow velocity, flow depth, and grain size (Fig. 9). Grain size, bedforms, and flow depth can all be directly measured or estimated from core or outcrop data, thus allowing velocities to be estimated. For example, the observation of dominantly dune-scale cross-stratification within both systems can be used to determine average flow velocities, provided that sediment caliber and water depth are known.

Within the clastic wedges examined, rivers confined to valleys are candidates for the largest-scale trunk channels. In general, Mulder and Syvitsky (1995) show that the larger the river, the more difficult it is to produce a hyperpycnal plume. We thus focus on estimating the discharge of the largest rivers. If they fall within the range of rivers that easily produce hyperpycnal plumes, then we assume that the smaller rivers and delta distributaries would have even greater propensity to generate hyperpycnal plumes.

Details of channel and bar dimensions are readily available from published facies architectural studies (e.g., Plint and Wadsworth 2003, Barton et al. 2004, Corbeanu et al. 2004, and Garrison and van den Bergh 2004, 2006) and can be used to estimate channel widths and depths (Table 2).

Estimations of Discharge for Ferron and Dunvegan Rivers

Data from preserved story thicknesses, bar thicknesses, and dune-scale cross-set thicknesses suggest that the largest Ferron rivers were about 9 m deep (Barton et al. 2004; Bhattacharya and Tye 2004; Corbeanu et al. 2004; Garrison and van den Bergh 2004, 2006). The grain sizes of Ferron channels vary between fine to medium sand, although pebbly sandstones are found in the most proximal portions of some intervals. Widths of channels (as opposed to channel belts), as estimated from strike-oriented cliff exposures (Table 2), range from a few tens of meters to a maximum of 174 meters (Garrison and van den Bergh 2004, 2006). Channel belts reach a maximum width of several kilometers.

Plotting the Ferron data on the 3D bedform phase diagram of Rubin and McCulloch (1980) suggests peak river flood velocities (U) of about 1.5 m/s for the largest (9 m deep) channels (Fig. 9). A rectangular channel would yield a maximum cross-channel area (A) of about 1500 m^2 for the largest (174 m wide) Ferron rivers. Given that the channels are curved, the actual area is probably closer to $0.65(A) = 1000$ m^2 (Table 2). Corresponding discharge ($Q = A \times U$) of the largest trunk Ferron rivers is calculated to have been about 1500 m^3/s. Given the tectonic and climatic setting, coupled with the intermediate channel sizes, the Ferron rivers are predicted to have produced common hyperpycnal flows (Fig. 6).

Data on ancient rivers of the Dunvegan Formation (Bhattacharya 1991; Plint and Wadsworth 2003) show trunk channel depths of about 10 m, with widths of between 100 and 150 m, although a few larger rivers up 28 m deep have been documented. The Simonette valley, an incised trunk river associated with the most highly river-dominated lobe within Allomember E of the Dunvegan Formation (Bhattacharya 1991), shows a maximum thickness of about 15 meters, suggesting that flood-river depths were generally less than this. Subsurface isolith mapping shows that the valleys ranged from 2 km to 5 km wide. Photomosaic interpretation of a large tributary feeder valley to the Simonette Valley (Plint and Wadsworth 2003) shows a cross-sectional width of about 170 m and a depth of about 16 m.

Sediment calibers within the lower reaches of the Simonette Valley range from fine- to medium-grained sand (except for intraformational mud clasts, and shell and plant debris) and the dominant sedimentary structure is dune-scale cross stratification. The Rubin and Mculloch (1980) plot suggests that velocities of < 1.6 m/s were likely (Fig. 9). Assuming a maximum cross-sectional width of about 170 m, a maximum water depth of 16 m, and a velocity of 1.6 m/s, a discharge of 2829 m^3/s can be estimated for the Simonette channel, which is somewhat larger than that of the Ferron, but still lying within the range of rivers that are frequently hyperpycnal (Fig. 6, Table 2). The average discharge volumes of the 10-m-deep, 150-m-wide rivers would be on the order of 1500 m^3/s, similar to the largest Ferron rivers. Even the deepest Dunvegan rivers show a discharge of 4641 m^3/s (Table 2).

Comparison of paleo-discharge estimates of both the Dunvegan and Ferron rivers, using the criteria presented by Mulder and Syvitski (1995), indicates that both systems likely produced hyperpycnal plumes with some regularity (Fig. 6). The generally humid climate and proximity (<

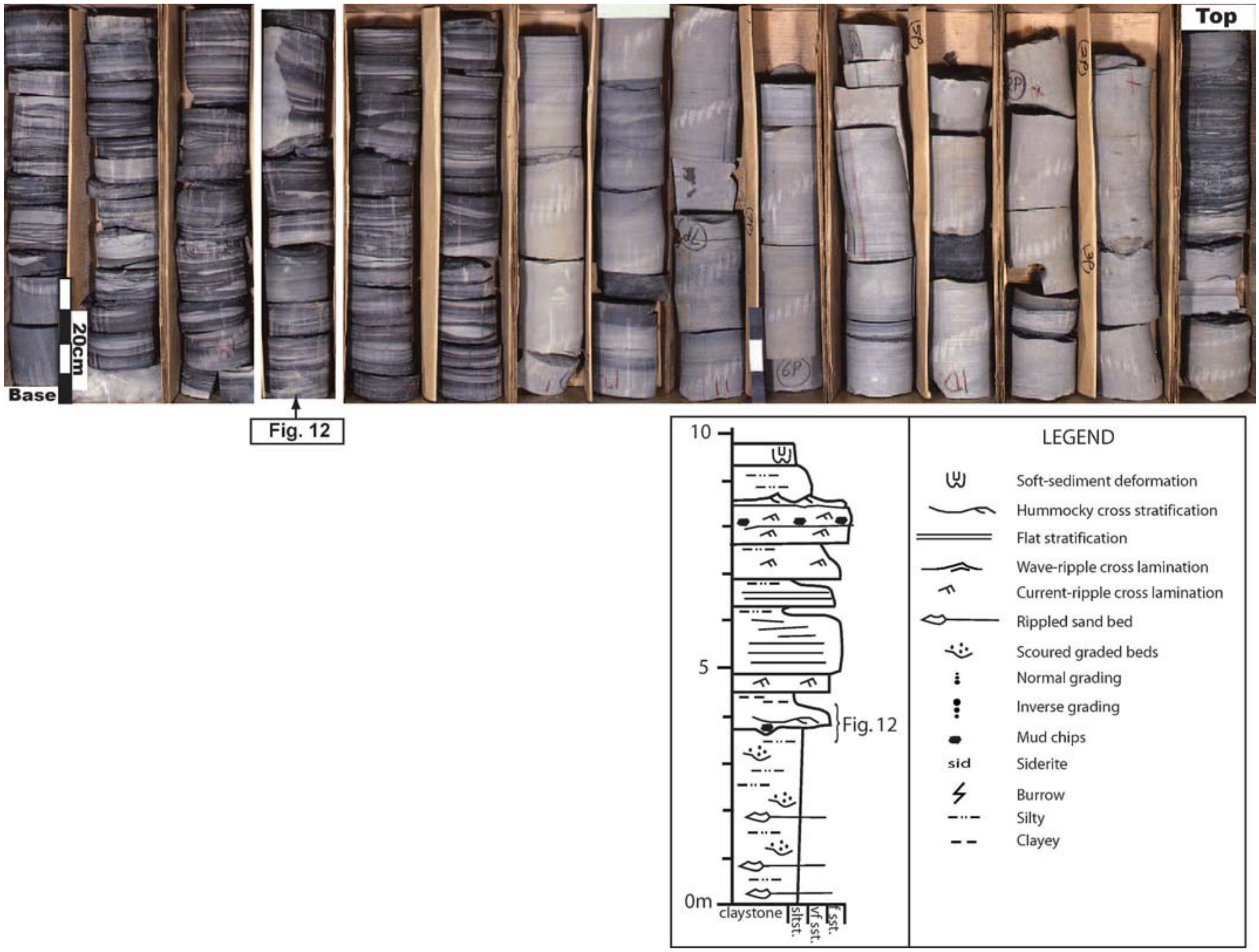

FIG. 11.—Core photos and measured section through prodelta and delta-front succession of well 17 in Figure 10. Core is read from base at lower left to top at upper right. Core location: Trilogy et al., Saxon well 16-10-61-25W5M, 2244–2262 m; lower 10 meters only is shown.

200 km) to an active mountain belt would also have enhanced the ability of these rivers to achieve hyperpycnal states. The relatively small drainage basins, which are an order of magnitude smaller than continental-scale rivers like the Mississippi and Ganges–Brahmaputra, would also have ameliorated the generation of hyperpycnal plumes (Bhattacharya and Tye 2004; Mulder and Syvitsky 1995).

The shallow-ramp versus shelf–slope setting may also have resulted in brackish-water conditions and estuarine mixing in the nearshore zone, and would have enhanced the ability of the rivers to produce hyperpycnal flows (Slingerland et al. 1996). Depending upon how reduced the nearshore salinities were, the ability of the larger Dunvegan Rivers to generate hyperpycnal flows may have been enhanced by an already brackish-water seaway.

Low slopes would certainly have inhibited the development of long-traveling, ignitive turbidity currents, but the generally stormy nature of the seaway, as indicated by the ubiquity of hummocky cross-stratification in both shoreface and deltaic successions (e.g., Howard and Frey 1984; Pemberton and Frey 1984; Ryer 1984; Plint 1988; Frey 1990; Bhattacharya and Walker 1991a, 1991b; MacEachern and Pemberton 1992; Pemberton and MacEachern 1997; Garrison and van den Bergh 2004, 2006; van den Bergh and Garrison 2004), may have allowed storms to maintain hyperpycnal flows, following the mechanisms suggested by Bentley (2003), Wheatcroft (2000), Mutti et al. (2003), and Freidrichs and Scully (2007).

DUNVEGAN AND FERRON RIVER-DOMINATED DELTA-FRONT AND PRODELTA DEPOSITS

Dunvegan Facies

General descriptions of the prodelta and delta-front deposits of river-dominated deltas in the Dunvegan Formation were first described by Bhattacharya and Walker (1991a) and Bhattacharya (1991). A standard grain-size card was used to visually estimate grain sizes down to lower very fine sandstone (62 microns). Silt and clay were visually estimated, based upon color and texture. The prodelta mudstones form units that range from a few tens of centimeters to as much as 20 meters thick (Figs. 4, 10, 11). The mudstones lie at the base of coarsening-upward facies successions (parasequences), which were interpreted as prograding fluvial- or storm/wave-dominated delta fronts and shorefaces (Figs. 4, 10, 11). Originally, Bhattacharya and Walker (1991a, 1991b) interpreted these mudstones to have formed as passive, suspension-sediment fallout deposits.

In detail, the prodelta mudstone facies show an abundance of centimeter-thick, normally graded siltstone and very fine-grained

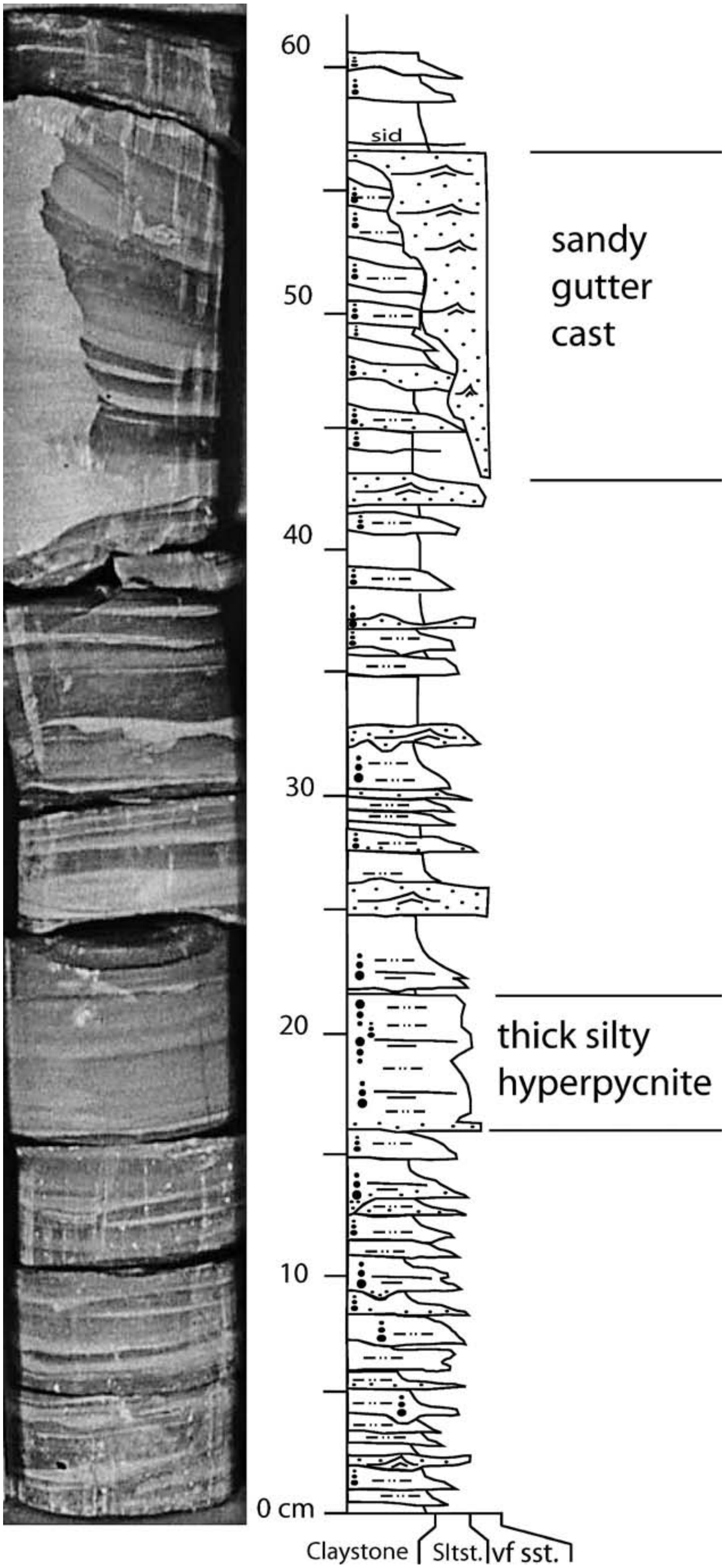

FIG. 12.—Photo and measured section of core column outlined in red in Figure 12 (Well 17 in Figure 12). Core shows centimeter-thick interbeds of normal and inversely graded prodeltaic mudstones, siltstones and very fine-grained sandstones. Storm-produced sandy gutter cast at 57 cm along with numerous wave-rippled sandstone interbeds suggests a storm-dominated prodelta. Note 5-cm-thick siltstone at 20 cm, which shows both normal and inverse color grading, interpreted as a hyperpycnite. No burrows are visible. Darkest gray is claystone. Legend is in Figure 11.

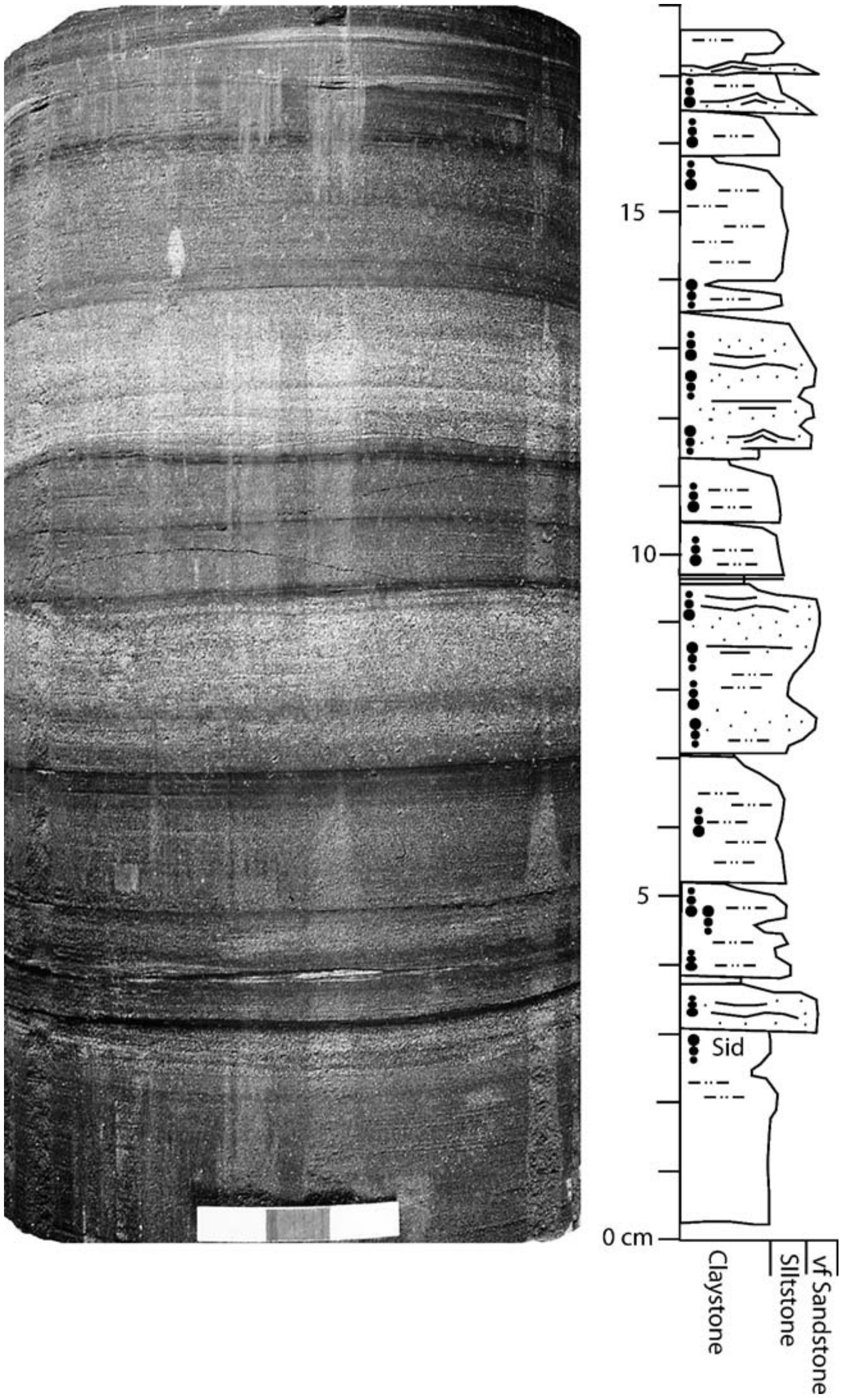

FIG. 13.—Close-up photo of diffusely bedded prodelta mudstones and siltstones, with no bioturbation. Note the inverse grading at 7, 8, and 12 cm. Scale is 3 cm. Core sample is from Dunvegan Formation, Allomember E, in Amoco Bigstone well 16-1-61-22W5, 1976 m.

sandstone beds (Figs. 11, 12, 13), virtually identical to those seen in some modern examples (Fig. 7). Thicker siltstone and sandstone beds locally show rhythmic stratification (e.g., thick bed at 20 cm in Fig. 12 and Fig. 13) similar to that described from Central Japan (Fig. 7B). Beds also locally show both inverse and normal grading, and internal scour surfaces, suggesting deposition during waxing as well as waning flows (Figs. 12, 13). Sandstones may show wave-formed cross lamination and, locally, hummocky cross stratification, suggesting a linkage with major storms (Fig. 12).

Prodelta mudstones show an abundance of small- to medium-scale, soft-sediment deformation features, as well as ball-and-pillow structures. In places, poorly connected, spindle-shaped, sand-filled mudcracks, interpreted as dewatering-related features, suggest high initial porosities (Fig. 14). These mudcracks commonly show ptygmatic folding, and restorations of the original crack depths suggest approximately 50% postdepositional compaction. Given the generally prodeltaic setting, a syneresis origin is considered likely, although this remains a topic of some controversy (Pratt 1998). Plint (2000) has documented numerous zones of probable shale-cored growth faulting associated with the lowermost Dunvegan Allomembers.

Distally, prodelta mudstones become distinctly more laminated (versus bedded), and display an increase in bioturbation intensities and burrowing uniformity. This suggests that sedimentation rates were lower, and that substrate stresses were less marked with increasing distance from

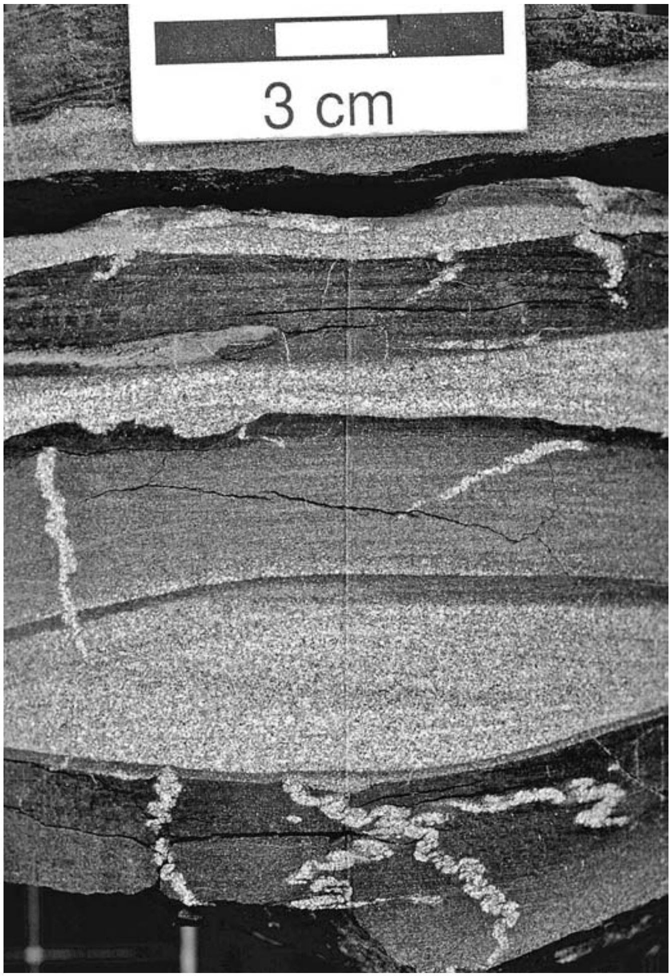

FIG. 14.—Dewatering cracks in prodelta mudstones with abundant centimeter-thick normally graded very fine-grained sandstone and siltstone beds (Dunvegan Formation, Allomember E, well 05-27-61-01W6; 2432.4 m).

the active river plumes. Comparable relationships are apparent in modern examples as well.

Prodelta Ichnofacies and Micropaleontology.—Gingras et al. (1998) and Coates and MacEachern (1999) summarized the ichnological parameters of the Dunvegan prodeltaic mudstones. The mudstones are largely devoid of burrowing, with a Bioturbation Index (BI) typically between 0 and 2 (Figs. 11–15). Burrowing is generally sporadically distributed and characterized by isolated ichnogenera. Deposit-feeding and rare grazing structures define an exceedingly low-abundance and low-diversity expression of the *Cruziana* Ichnofacies, characteristic of more strongly river-dominated deltaic successions (MacEachern et al. 2005). The most highly bioturbated intervals are typically dominated by *Phycosiphon* (Fig. 15C). Rarely, isolated "Terebellina" (*Schaubcylindrichnus freyi* sensu stricto), *Chondrites*, *Lockeia*, *Teichichnus*, fugichnia, *Cylindrichnus*, and *Planolites* are present (Fig. 15B, C, D). Some units show "mantle-and-swirl" structures (Lobza and Schieber 1999), characteristic of sediment-swimming organisms that disrupt sediments having high interstitial fluid contents, such as fluid muds (Fig. 15A, D, 16). Local pause planes, commonly at bedset or distal parasequence boundaries, locally show thin zones of more extensively burrowed facies (Coates and MacEachern 2007). Suites such as these may include small numbers of *Asterosoma*, *Zoophycos*, *Rhizocorallium* and *Siphonichnus*, in addition to the ichnogenera mentioned above (Fig. 16A, C, D). Such suites are attributable to slightly stressed expressions of the *Cruziana* Ichnofacies.

Extensive processing of core samples for microfossils showed extremely rare arenaceous benthic foraminifera (J.H. Wall, personal communication, Bhattacharya 1989). This paucity of recovery is attributed to high sedimentation rates, resulting in extremely diluted microfossil concentrations (in contrast to the high abundances found in overlying, more thoroughly bioturbated, condensed-section mudstones). The presence of arenaceous foraminifera, rather than calcareous planktonic elements, is also attributed to a slight brackish-water stress; such conditions favor benthic as opposed to calcareous planktonic foraminifera, which generally do better in fully marine salinities. This has led some to suggest that, at times, the proximal shelves of the seaway were largely brackish (e.g., West et al. 1998), which is also significant in facilitating hyperpycnal flows.

Abundant, early-formed siderite lenses, nodules, and beds (e.g., Fig. 12) are also interpreted to support brackish-water conditions, suggesting that estuarine mixing associated with river discharge at the delta also occurred (Bhattacharya and Walker 1991a, 1991b). Abundant allochthonous plant material also suggests derivation from a terrestrial source.

Delta-Front Deposits.—These prodelta mudstones pass vertically, and are correlated laterally, into the associated sandy delta-front and linked fluvial feeder systems, described extensively by Bhattacharya and Walker (1991a, 1991b) and Bhattacharya (1991). The delta-front sandstones show beds of structureless to climbing current-rippled sandstones, suggesting waning-flow Bouma cycles. In some parasequences, abundant hummocky cross-stratified sandstone beds and climbing-oscillation-rippled sandstones are intercalated with otherwise unbioturbated mudstones, which also contain centimeter-thick graded siltstone beds (Fig. 16B). This suggests a linkage between storm events and river floods in the generation of hyperpycnal conditions (Wheatcroft 2000).

The ichnology of delta-front units has also been described extensively by Gingras et al. (1998) and Coates and MacEachern (1999, 2007). Trace-fossil suites associated with delta-front sandstones and sand-dominated heterolithic intervals are sporadically distributed, characterized by exceedingly low bioturbation intensities (BI 0–2), and show reduced diversities of strongly facies-crossing ichnogenera attributable to deposit-feeding and dwelling behaviors. Indeed, numerous beds are entirely

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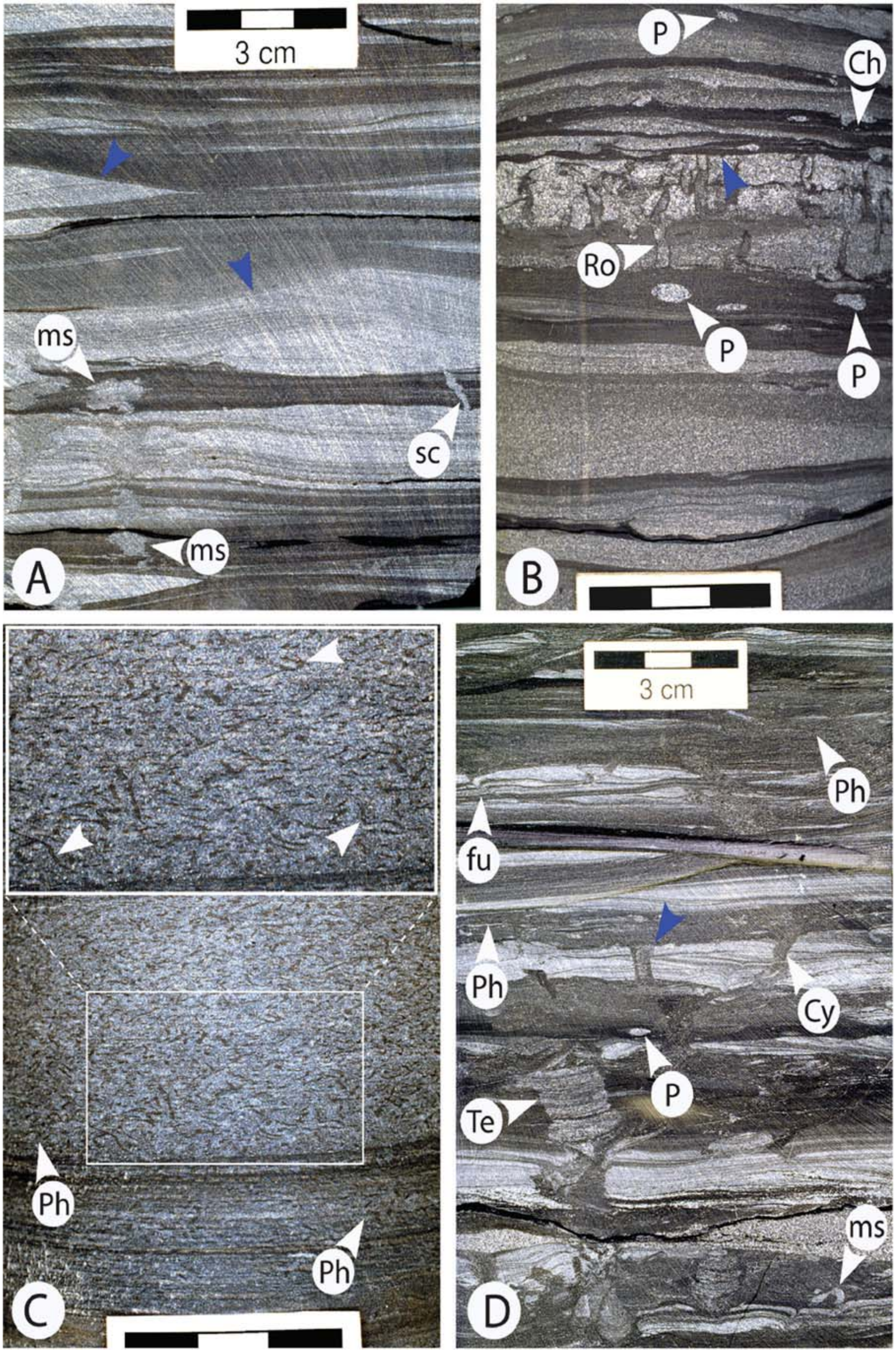
FIG. 15.—Heterolithic composite bedsets of the river-dominated proximal prodelta to distal delta front, Allomember E, Dunvegan Formation. **A)** Oscillation-rippled sandstones draped by claystones of fluid-mud origin, showing BI 0–1. Sandstones are locally scoured by mudstone layers (blue arrows), consistent with hyperpycnal emplacement. A subaqueous shrinkage crack (sc) is also present. Rapid sediment accumulation is supported by "mantle and swirl" structures (ms); Well 05-27-61-01W6; 2425.2 m. **B)** Graded sandstone and siltstone layers draped by dark claystones of fluid mud origin show BI 0–2. The trace-fossil suite includes *Planolites* (P) and *Chondrites*. The sandstone layer and *Rosselia* (Ro) (preserved as remnant dwelling tubes) are truncated (blue arrow) by a fluid-mud layer of hyperpycnal origin, Well 05-27-61-01W6; 2434.2 m. **C)** Pervasively bioturbated (BI 4–5) silty to sandy mudstone of probable hypopycnal plume origin, showing abundant *Phycosiphon* (Ph and arrows) and rare *Chondrites*. The central area is expanded and shown at the top of the photo; Well 16-01-61-22W5; 1899.7 m. **D)** Parallel-laminated sandstones with current- and oscillation-rippled layers showing normal grading and BI 1–2. The trace-fossil suite includes *Phycosiphon* (Ph), *Teichichnus* (Te), *Planolites* (P), *Cylindrichnus* (Cy), fugichnia (fu), and "mantle and swirl" structures (ms). The blue arrow shows an erosional contact with mudstone truncating a burrow shaft. Well 14-16-60-21W5; 1979.5 m.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devoid of bioturbation. Uncommon but persistent ichnogenera include *Rosselia*, *Ophiomorpha*, *Thalassinoides*, *Palaeophycus*, *Teichichnus*, *Cylindrichnus*, and *Macaronichnus*. Fugichnia are commonly associated with event beds.

The delta-front systems show, through the integration of ichnology and sedimentology, that sedimentation rates were high and that deposition was episodic, leading to a highly stressed benthic regime (e.g., MacEachern et al. 2005). Turbid water columns above otherwise sandy substrates likely operated to preclude filter-feeding and suspension-feeding organisms, leading to a paucity of *Skolithos* Ichnofacies elements (e.g., Moslow and Pemberton 1988; Gingras et al. 1998; Coates and MacEachern 1999, 2007).

Ferron–Tununk Facies

The delta-front sandstones of the Ferron Member overlie thick, age-equivalent prodelta shales of the Tununk Member (Fig. 17). Cores and outcrops through the river- to wave- and storm-dominated parasequences of the Ferron–Tununk show meters-thick units of weakly and sporadically bioturbated (BI 0–2) silty mudstones, particularly in the basal, fluvially dominated units (Figs. 18, 19). These mudstones are characterized by abundant, centimeter-thick, normally graded siltstone to claystone couplets (Figs. 19, 20). Inversely graded sandstone and siltstone beds are observed locally (Fig. 21). Sandstone beds within the prodelta also contain aggradational current-ripple and oscillation-ripple lamination, as well as distal or low-density Bouma sequences (e.g., T_{bce} and T_{ce} beds) (Fig. 22). Allochthonous plant material is ubiquitous.

These mudstones locally display abundant soft-sediment deformation features at a variety of scales, particularly in the more river-dominated parasequences (Fig. 23). These are typified by convolute bedding and loading structures, and are overlain by small-scale growth faults, which are particularly common in the lower Ferron parasequences. Accommodation of the growth strata is created by deformation of the underlying prodelta muds, which are inferred to have had high initial porosities, and thus were easily mobilized (Bhattacharya and Davies 2001, 2004). This, again, suggests a setting prone to high sediment accumulation rates and highly stressed substrate conditions, interpreted to be indicative of hyperpycnal conditions.

Prodelta Ichnofacies.—The prodeltaic units show low bioturbation intensities (BI 0–2) with ichnogenera that are sporadically distributed (MacEachern et al. 2007b; Pemberton et al. 2007). Many intervals are devoid of bioturbation (Figs. 19, 20). Trace fossils occur in low numbers and consist mainly of diminutive and isolated *Planolites*, *Palaeophycus*, *Thalassinoides*, *Chondrites*, and fugichnia, with small amounts of *Phycosiphon* (Fig. 21). Trace fossil suites are broadly similar to, though more impoverished than, those observed in the Dunvegan Formation. The low diversity and reduced abundance of trace fossils are thought to indicate strong fluvial domination of the delta lobe and more persistently stressed conditions. The predominance of strongly facies-crossing ichnogenera, their diminutive sizes, and the concomitant abundance of siderite nodules within the prodeltaic intervals suggest that brackish-water conditions may have been a major source of environmental stress, in addition to high sedimentation rates. Along strike, these brackish-water indicators decrease, and trace-fossil diversities increase (e.g., Kf-1-Iv[a] Parasequence of Anderson et al. 2004 and Parasequence 1F of Garrison and van den Bergh 2004, in the Ivie Creek #11 core, MacEachern et al. 2007b).

Delta-Front Deposits.—The prodelta deposits pass into delta-front turbidites, interpreted to be related to river floods (Bhattacharya and Davies 2004). The presence of steeply inclined (up to 15°) delta-front strata within the Ferron Member (such as in the Kf-1-Iv Parasequence of Anderson et al. 2004; their fig. 11 and Parasequence 1F of Garrison and van den Bergh 2004, Fig. 5) also indicates rapid deposition, probably during river flood events. These steep slopes should have been capable of generating initially autosuspending (ignitive?) hyperpycnal flows, although wave and tidal forcing is likely required for the associated sediments to migrate along the significantly lower-gradient shelf.

Sandstone beds showing hummocky cross-stratification and oscillation ripples are also intercalated with the otherwise rather more fluvially dominated delta-front units (characterized by low bioturbation intensities and a predominance of graded beds) as described above for the Dunvegan delta-front deposits. This also supports a linkage between river floods and major storms (Wheatcroft 2000). Indeed, the abundant decimeter-thick sets of nearly vertically climbing aggradational oscillation-ripple-laminated sandstones suggests that storm waves reworked the delta front simultaneously with rapid deposition (Fig. 24), although post-flood reworking by storm waves may also have occurred.

Delta-front sandstones show BI 0–2, with isolated, predominantly facies-crossing elements such as *Palaeophycus*, *Ophiomorpha*, *Thalassinoides*, and *Teichichnus* (Fig. 21), as well as uncommon *Diplocraterion* and *Skolithos*. Interlaminae of mudstone and siltstone are common, and locally contain *Planolites*, as well as very rare *Chondrites* and *Phycosiphon*.

The reduced bioturbation intensities support high deposition rates. The paucity of dwelling structures of inferred suspension-feeding organisms in otherwise sandy depositional media is consistent with heightened water turbidity (Moslow and Pemberton 1988; Gingras et al. 1998; Coates and MacEachern 1999, 2007; MacEachern et al. 2005); such conditions tend to be maximized in strongly river-dominated deltaic lobes. The diminutive nature of most of the ichnogenera and the strongly facies-crossing character of the trace-fossil suite also supports generally reduced-salinity conditions.

GENERAL INTERPRETATION AND COMPARISON OF MODERN AND ANCIENT MUDDY HYPERPYCNITES

The prodelta mudstones associated with the Dunvegan Formation and Ferron Member, as described above, show a number of features identical to those reported from modern settings (Fig. 7), including both the

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FIG. 16.—Heterolithic composite bedsets of the wave/storm-dominated proximal prodelta to distal delta front, Allomember D, Dunvegan Formation. **A)** Wave-rippled to parallel-laminated sandstone, locally with normal grading, interstratified with weakly burrowed, fissile claystone and mudstone layers. The facies shows BI 1–2. The trace-fossil suite includes *Teichichnus* (Te), *Rhizocorallium* (Rh), *Siphonichnus* (Si), *Thalassinoides* (Th), *Planolites* (P), *Chondrites* (Ch), and *Phycosiphon* (Ph). "Mantle and swirl" structures (ms) are present, and record sediment-swimming behaviors; Well 10-33-60-05W6; 2835.9 m. **B)** Aggradational oscillation-rippled fine-grained sandstone of likely storm generation, truncated (blue arrow) by fissile mudstone of probable hyperpycnal fluid mud origin. The unit shows low bioturbation intensities (BI 0–1), with *Planolites* (P), and "mantle and swirl" structures (ms) confined to the top of the interval; Well 6-29-63-2W6, 2057.2 m. **C)** Oscillation-rippled sandstones, intercalated with dark mudstone locally containing siltstone and sandstone interlaminae. The unit shows BI 0–2, with *Planolites* (P), *Teichichnus* (Te), fugichnia (fu), and "mantle and swirl" structures (ms); Well 11-16-63-24W5; 1706.8 m. **D)** Sharp-based, parallel-laminated sandstones and oscillation-rippled silty sandstones are intercalated with normally graded siltstones and claystones. The unit shows BI 0–2, although mainly BI 0–1. Subaqueous shrinkage crack (sc) is interpreted as a syneresis crack, suggesting freshet conditions during sediment emplacement. A probable "mantle and swirl" structure (ms) occurs near the base of the unit. The facies shows weakly burrowed to nonbioturbated, stressed mudstones juxtaposed against layers containing a low-diversity but more normal marine trace-fossil suite containing *Zoophycos* (Z), *Phycosiphon* (Ph), *Palaeophycus* (Ph), and *Planolites* (P); Well 07-10-63-01W6; 1980.4 m.

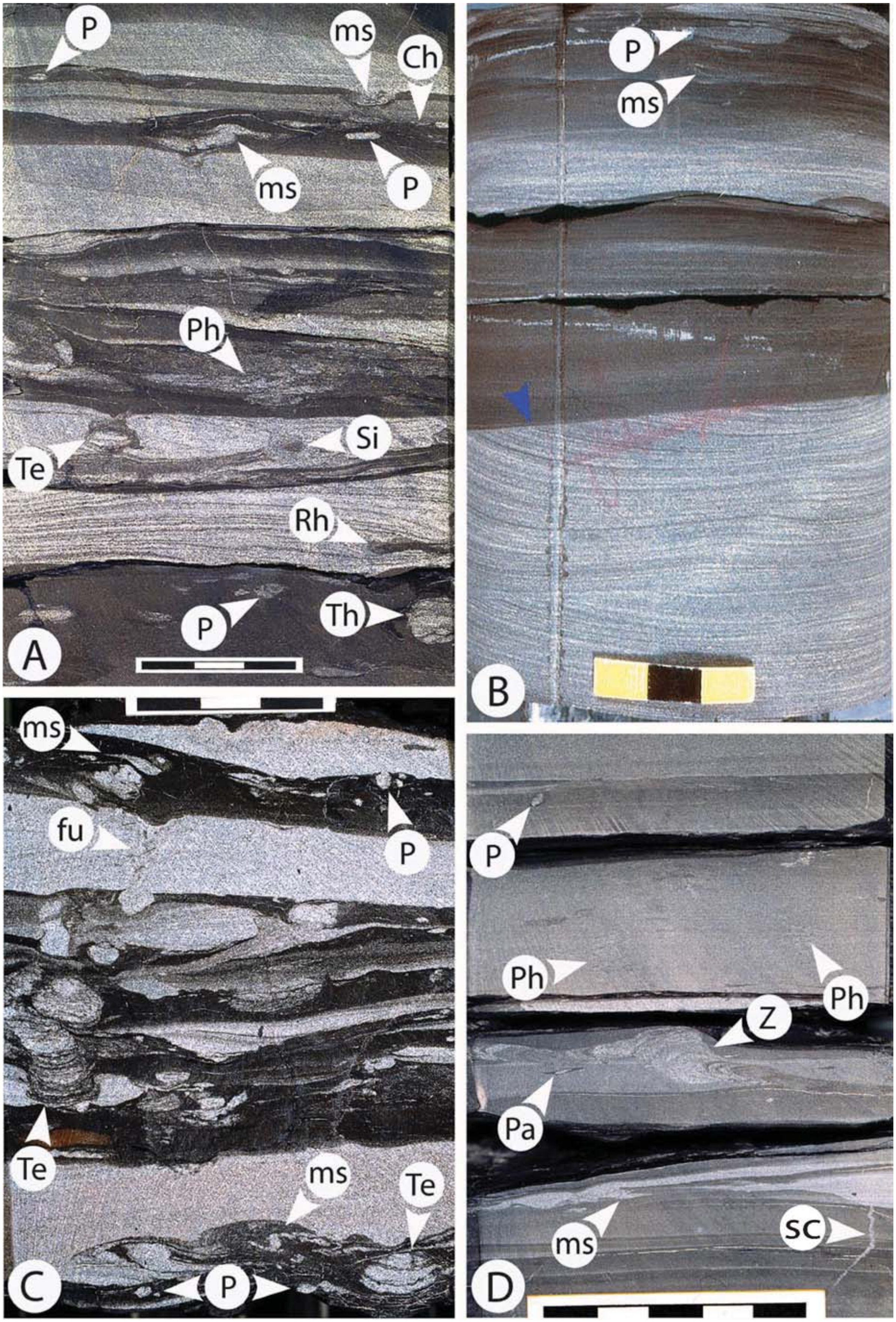
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FIG. 17.—Photo of the Ferron delta-front sandstones overlying thick, prodeltaic mudstones of the Tununk Shale Member, Last Chance Delta Complex. View from Bear Gulch looking east across the Miller Canyon Road (located in Fig. 5B).

deeper-water hyperpycnites (e.g., Nakajima 2006) as well as shallow-water examples from the Atchafalaya (Neill and Allison 2005) and Eel rivers (Bentley and Nittrouer 2003). They also show many similarities to the hyperpycnite facies model of Mulder et al. (2003) (Fig. 2). The abundance of diffusely bedded, centimeter- to decimeter-thick intervals of massive to stratified siltstones and very fine-grained sandstones, especially coupled with occurrences displaying both inverse and normal grading, suggest deposition by waxing and waning hyperpycnal flows. The general paucity of burrowing and abundant soft-sediment deformation are consistent with rapid sediment emplacement, possibly as high as tens of centimeters per year. The recurrence of strongly facies-crossing diminutive ichnogenera reflects opportunistic organisms inhabiting a highly stressed and at least periodically brackish-water setting. Such conditions are compatible with inundation of fresh- to brackish-water hyperpycnal plumes at the seafloor. The predominance of simple facies-crossing structures also suggests an endobenthos dominated by trophic generalists (cf. Beynon et al. 1988; Pemberton and Wightman 1992), in which short-lived species flourish intermittently between seasonal river flood events. Some hyperpycnal layers occur closely stacked and are associated with possible syneresis cracks, suggesting that these may be freshet-driven flood event beds. These conditions may have led to short-lived periods of salinity reduction near the bed, followed by a return to fully marine deposition (e.g., Dunvegan Allomember E and Allomember D). Alternatively, an embayed portion of the coast may see persistent salinity reduction in that portion of the basin, and prolonged periods of brackish-water deposition; such a scenario appears likely for the river-dominated lower cycle of the Ferron Sandstone (Bhattacharya and Davies 2004). In either event, seasonal river discharge probably served to facilitate hyperpycnal plumes. Early flood events may have reduced the salinity of the embayment, making it easier for successive floods to achieve hyperpycnal conditions. Such ''prepping'' may explain the occurrence of numerous hyperpycnites stacked one upon another.

The common observation of wave ripples and hummocky cross stratification suggests that many of these hyperpycnites were linked to large storms, thought to have been very common in the Cretaceous Seaway. Given the generally small scale of the Ferron and Dunvegan drainage basins (100 to 200 km in length), large hurricanes and tropical storms, modern examples of which average between 160 to 1000 km in diameter, would have routinely affected both drainage basin and nearshore shelf at the same time. The rivers would have experienced major flooding and would have deposited this sediment across a simultaneously very stormy shelf.

Distinguishing Anoxic Laminites from Graded Hyperpycnites

Apparently unburrowed laminated black mudstones are a common feature of the Cretaceous interior, and are commonly associated with oceanic anoxic events (Laurin and Sageman 2007). As a consequence, a paucity of burrowing and the presence of laminated mudstones are not sufficient evidence of ancient hyperpycnites (Table 3).

Reductions in bioturbation intensities or the absence of burrowing within mudstones certainly may result from dysaerobic or anoxic conditions (e.g., Rhoads and Morse 1971; Bromley and Ekdale 1984; Savrda and Bottjer 1987; Wignall 1991; Savrda 1992, 1995; Wignall and Pickering 1993; Martin 2004). Anoxic laminites generally display an abundance of pelagic constituents, such as authigenic organic matter and calcareous microfossils, thanatocoenoses composed of nektonic and pelagic organisms, and a general absence of benthic fauna, suggesting far lower sedimentation rates than are inferred for the hyperpycnal units (Table 3). In the Cretaceous, such organic-rich mudstone laminites contain abundant fecal pellets and fossiliferous debris (Sethi and Leithold 1994), including fish remains as well as calcareous microfossils. Pyrite and other minerals indicative of reducing conditions are also common. The White Speckled Shale in the Alberta Basin, the Mowry Shale in the US Western Interior, and, of course, the Fish Scale Zone described above are examples.

The abundance of graded beds, siltstone and sandstone interlaminae, heterolithic composite bedsets, and low organic contents suggest that reduced oxygenation was not a significant stress in the prodeltaic mudstones of the Dunvegan Formation and the Ferron Member described above. Emplacement of such clastic layers within the mudstones would have occurred under conditions of traction transport or wave agitation. Storm waves, sediment-gravity flows, and tidal currents would have operated to introduce oxygenated water to the substrate. The ''mantle and swirl'' structures record the activity of sediment-swimming organisms (particularly polychaete worms) that swim through fluid mud (Lobza and Schieber 1999; Schieber 2003). Barrett and Schieber (1999) showed that it can take from days to weeks for a fluid mud to self-compact to such a degree that it effectively precludes sediment swimming. However, these subtle ''mantle and swirl'' structures (e.g., Figs. 15A, D, 16) preclude the interpretation of anoxic conditions at the bed (Schieber 2003).

Most of the organic debris within the prodelta mudstones of the Dunvegan Formation and Ferron Member delta systems consist of allochthonous terrestrial plant debris rather than marine algal organic material commonly found in anoxic laminites. Micropaleontological

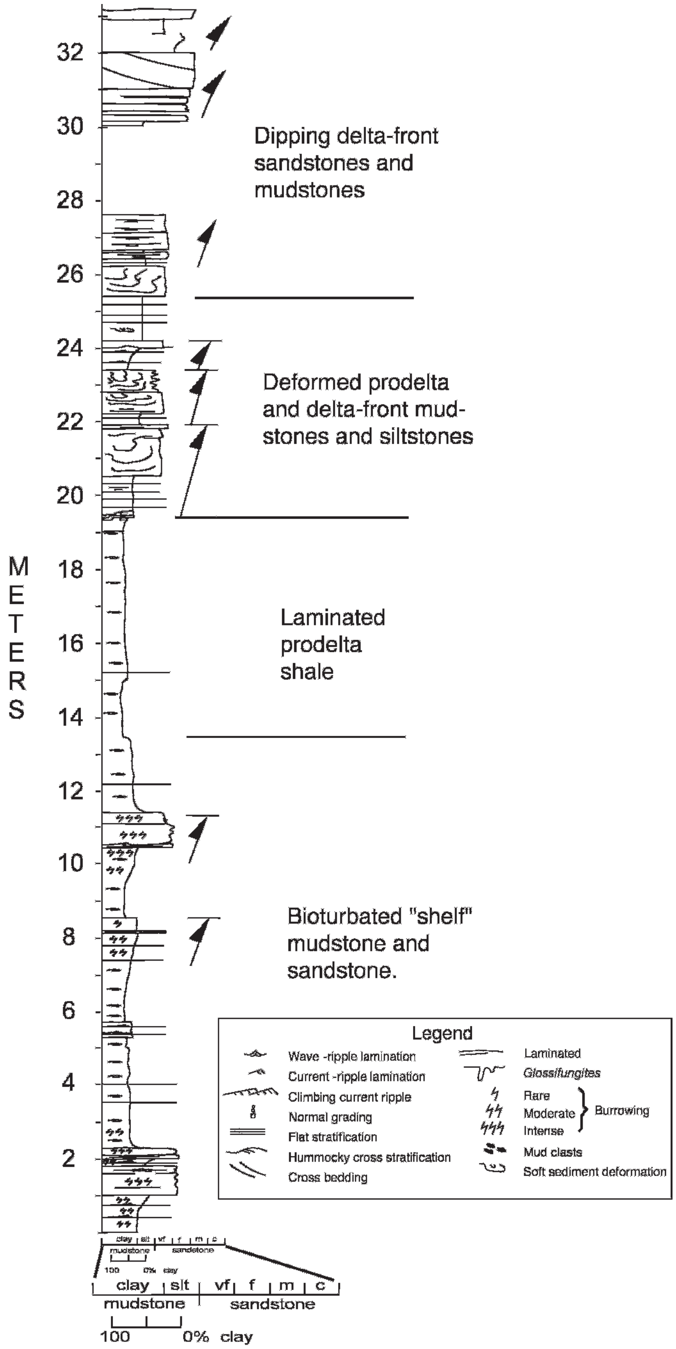

FIG. 18.— Ferron Sandstone measured along Muddy Creek, through Parasequence 2c in Figure 5 (see Bhattacharya and Davies 2004 for more details). Prograding prodelta mudstones downlap onto bioturbated shelf deposits at about 13.5 m in the section.

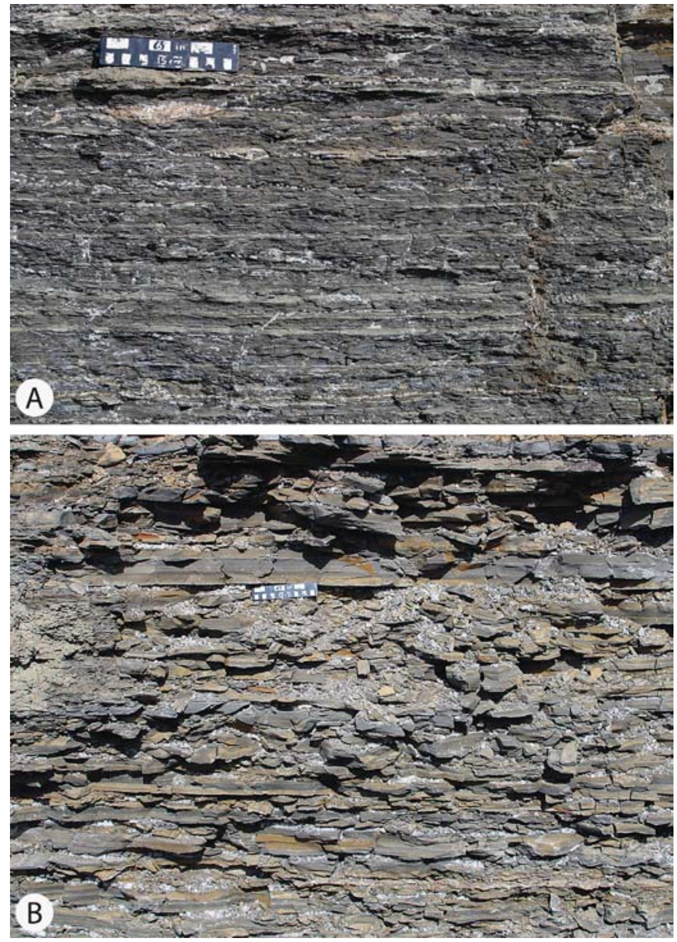

FIG. 19.—**A)** Laminated to **B)** thin-bedded prodelta mudstones of the Tununk Shale. These shales comprise the prodeltaic equivalents of the Ferron Sandstone Member. Note the pristine physical sedimentary structures, bedded character, and paucity of bioturbation.

collections of prodeltaic and muddy shelf deposits likewise consist of mainly arenaceous benthic foraminifera and an absence of pelagic elements, which also suggests an oxygenated substrate (e.g., MacEachern et al. 1999; Stelck et al. 2000).

MacEachern et al. (1999) also argued that some apparently unburrowed dark mudstones may reflect a taphonomic bias, imparted by a predominance of surface grazing fecal trails and mud-filled burrows that lack lithologic contrast with the host sediment, making them challenging to discern. Using photo-enhancement, SEM work, and large-format thin sections, Schieber (2003) showed that many laminated and apparently black shales thought to record anoxic conditions actually display evidence of persistent, millimeter-scale bioturbation forming a "burrow-laminated fabric." Casual inspection of dark mudstones, such as is typically done in routine core description, typically overlooks such subtle evidence of bioturbation.

From a taphonomic perspective, the prodeltaic mudstones of the Dunvegan and Ferron systems described above display well-developed normal and inverse graded beds, delicate siltstone and sandstone laminae and thin beds, and locally high interstitial silt contents. Such facies show far too much lithologic variability to obscure significant proportions of the ichnological suite. Disruptions of interlaminae and burrowed tops to beds are readily apparent where they occur, and the similar beds that appear unburrowed almost certainly never were.

Salinity Stresses and Comparison with Hypopycnal Deltas and Normal Marine Shelves

Although we have generally interpreted the deltas of the Ferron Member and Dunvegan Formation to reflect hyperpycnal conditions, the prodelta mudstones in both units include ichnogenera attributed to organisms regarded to be generally intolerant of salinity reductions, particularly *Phycosiphon*, *Helminthopsis*, *Zoophycos*, *Chondrites*, *Asterosoma*, *Scolicia*, and *Rhizocorallium* (e.g., Coates and MacEachern 1999,

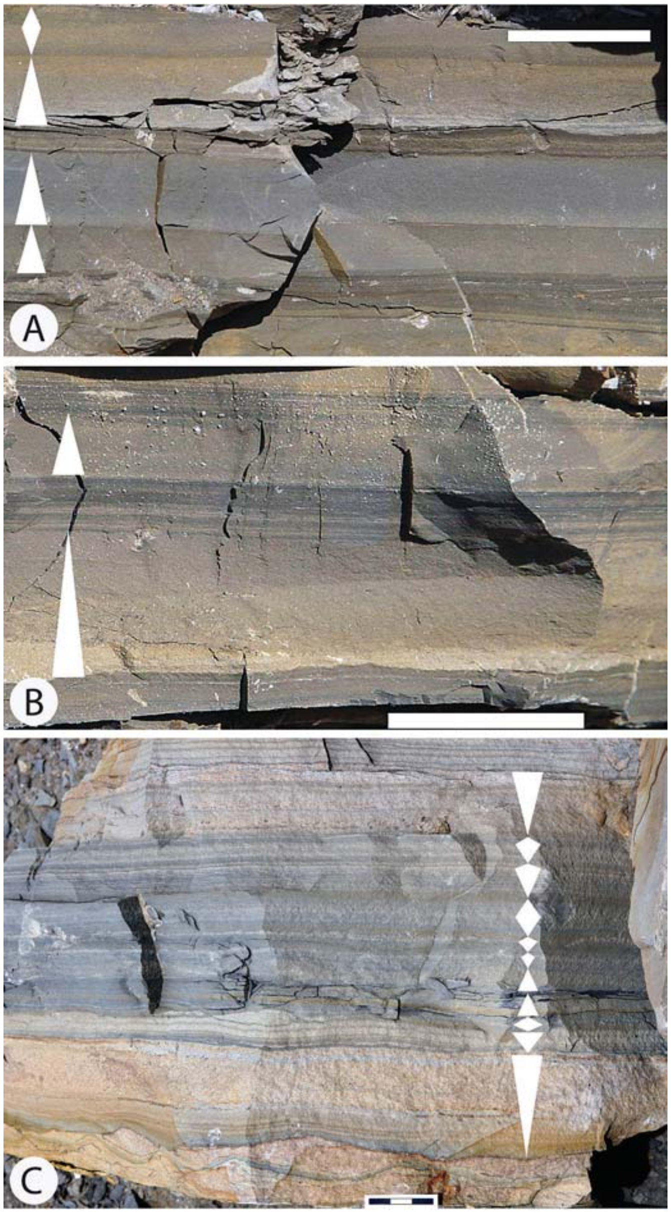

FIG. 20.—Close-up photos of prodelta mudstones of the Tununk Shale Member and lower Ferron Sandstone Member. **A)** Close-up photo of centimeter-scale, normally graded siltstone to claystone beds. Inverse grading can be seen in uppermost beds. The bed immediately below the inversely graded bed shows lamination and scour. Triangles indicate normal grading, inverted triangles indicate inverse grading, diamonds indicate beds that show inverse grading at the base with normally graded tops. Ferron Notom delta, near Hanksville, Utah. **B)** Close-up photo of normal grading. Lower bed shows erosional scour and faint internal lamination. Also note the complete lack of burrowing. Ferron Notom delta, near Hanksville. **C)** Complex heterolithic unit showing inverse and normal grading (triangles and diamonds) overlying rippled sandstones. Photo of Parasequence 2c, entrance to Muddy Creek. Note the lack of bioturbation in all examples. All scales are 3 cm.

2007; Bann et al. 2004; MacEachern et al. 2005, 2007a; MacEachern et al. 2007b), although these are sporadically distributed and commonly occur at parasequence boundaries and bed tops that represent pauses in deposition. This suggests that there were marked salinity fluctuations and probable alternations between normal marine and brackish-water conditions.

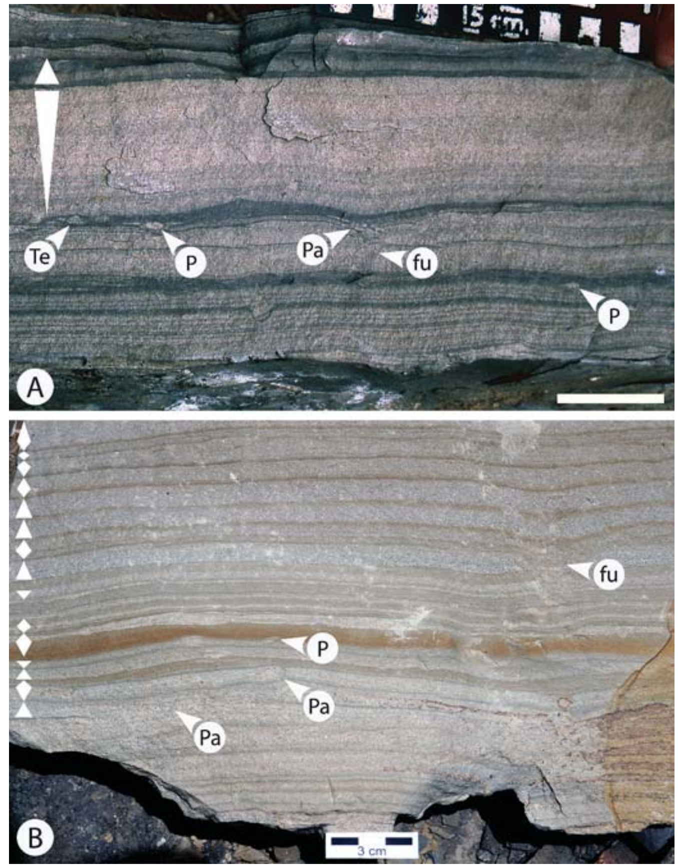

FIG. 21.— Graded bedding in prodelta to distal delta-front units of Parasequence 1f of the Ferron Sandstone Member. **A)** Inverse and normally graded sandstone lamina-sets interbedded with prodelta mudstones. Note sporadically distributed *Planolites* (P), *Palaeophycus* (Pa), *Teichichnus* (Te), and fugichnia (fu). Scale is 3 cm. Photo taken along the I-70 Ivie Creek road-cut. **B)** Parasequence 2c, entrance to Muddy Creek Canyon. Stacked normally graded sandstones, inversely graded sandstones, and normal to inversely graded sandstones of hyperpycnal origin, with a sideritized mudstone interbed from the distal delta front. Trace fossils include *Palaeophycus* (Pa), *Planolites* (P), and fugichnia (fu). Note that the escape structure transects at least three graded layers, attesting to their rapid, possibly concomitant emplacement. Such high-frequency deposition is consistent with flood-induced hyperpycnal discharge.

Markedly reduced salinities induce depauperate ichnological suites with a predominance of diminutive, strongly facies-crossing ichnogenera (e.g., Milne 1940; Levinton 1970; Remane and Schlieper 1971; Perkins 1974; Dörjes and Howard 1975; Howard and Frey 1975; Pemberton and Wightman 1992; Sethi and Leithold 1994; Gingras et al. 1999). MacEachern and Gingras (2008) have summarized a range of brackish-water inshore settings, wherein strongly reduced salinities show low bioturbation intensities and monospecific ichnological suites. Salinities must approach $< 5‰$ before wholesale depopulation occurs (cf. Gingras et al. 1999), and such conditions are unlikely to occur in a marine basin, even where hyperpycnal flows occur. Indeed, many brackish-water facies actually show very high bioturbation intensities, albeit characterized by very low diversities (e.g., Beynon et al. 1988; Pemberton and Wightman 1992; Gingras et al. 1999; MacEachern and Gingras 2008). Brackish-water suites tend to show specific combinations of ichnogenera. Facies-crossing elements such as *Planolites*, *Teichichnus*, *Thalassinoides*, *Cylindrichnus*, *Rosselia*, *Ophiomorpha*, "Terebellina," and *Palaeophycus* are common to both the prodeltaic and inshore brackish-water settings. Persistently brackish-water regimes, however, commonly have *Gyrolithes*, *Skolithos*, *Arenicolites*, *Gastrochaenolites*, *Lingulichnus*, and *Lockeia* as

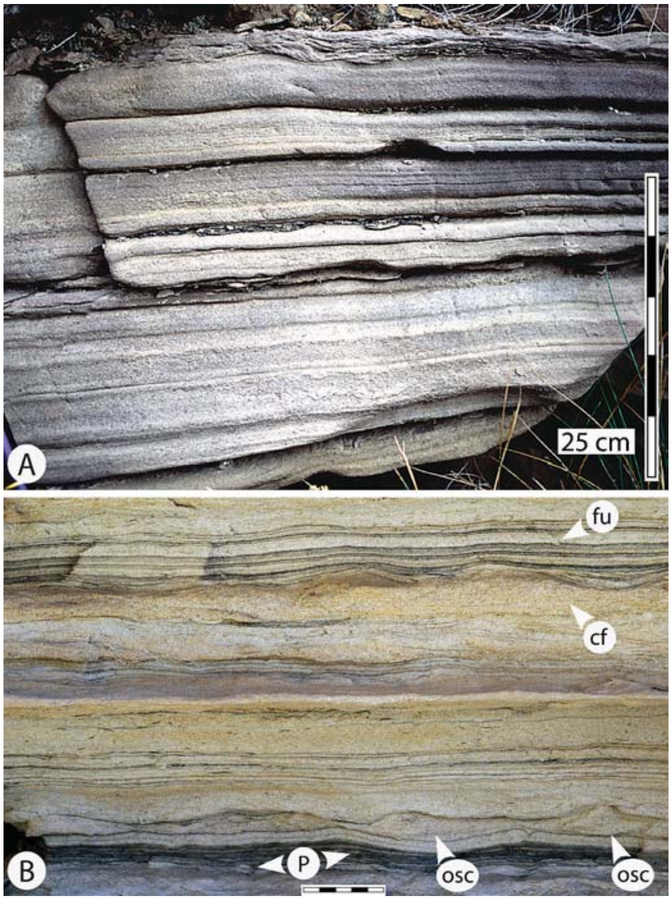

FIG. 22.—Sandy turbidites in Parasequence 2c, of the Last Chance delta of the Ferron Sandstone Member, Muddy Creek. **A)** Bouma T_{BC} units in distal delta-front sandstones. Event beds are unburrowed. **B)** Sandy T_{BC} and T_{BCE} turbidites of the proximal prodelta, intercalated with combined-flow (cf) and oscillation ripples (osc). Note the abundance of dark carbonaceous detritus in the parallel-laminated zones. The unit shows little burrowing, with isolated fugichnia (fu) and *Planolites* (P) confined to the muddy interbeds. Possible rhythmic carbonaceous claystone drapes occur in the sandstones, supporting some tidal influence. Scale is 5 cm.

associated ichnogenera (e.g., MacEachern and Gingras 2008). Such indicators of persistently brackish-water conditions are largely absent in the facies described in this study, suggesting that the deltas consistently alternated between normal and brackish-water (i.e., probably hyperpycnal) conditions.

The combination of sedimentological and ichnological characteristics observed in the prodelta mudstones associated with the Dunvegan and Ferron deltas indicate that these facies were emplaced episodically and rapidly. High depositional rates lead to general reductions in bioturbation intensities. Where sedimentation rates exceed recolonization rates associated with larval recruitment, thick intervals may be largely devoid of endobenthic communities. The micropaleontological analyses independently support this as a principal cause of faunal impoverishment, as indicated by the small numbers of exclusively arenaceous benthic foraminifera, faunal expressions consistent with rapid deposition. Rapid deposition, coupled with associated (though subordinate) stresses operating in the prodelta setting lead to ichnological characteristics distinctive of deltaic regimes (MacEachern et al. 2005; MacEachern et al. 2007a). These stresses include short-lived salinity fluctuations related to freshet conditions and/or river flood stages, episodic heightened water turbidity due to hyperpycnal and/or hypopycnal river plumes, and periodic oxygenation reductions associated with breakdown of terrestrially derived phytodetritus.

Mudstones associated with hypopycnal conditions may show significantly higher abundances and diversities of ichnofauna (MacEachern et al. 2005). In such settings, mud flocculation from buoyant mud plumes creates a regime wherein mudstone deposition rates are more uniform (less episodic) and generally slower than in their hyperpycnal counterparts. Such mudstones may be more thoroughly burrowed, show shallow-tier (e.g., *Phycosiphon*, *Planolites*, and *Teichichnus*) as well as deep-tier structures (e.g., *Rosselia*, *Cylindrichnus*, *Ophiomorpha*, *Thalassinoides*, *Chondrites*, and *Zoophycos*), and display wider ranges of organism ethology, though dominated by structures indicative of deposit-feeding and grazing behaviors. Sediment-swimming organisms are probably less abundant in hypopycnal-dominated systems, although they may be present where thicker fluid-mud beds are emplaced due to rapid mixing of storm/flood-related buoyant mud plumes with basinal waters, which heightens the rate of clay flocculation. In contrast to the nondeltaic offshore zones, however, even these suites remain impoverished, dominated by facies-crossing ichnological elements, and a paucity of suspension- and filter-feeding structures due to greater than optimal water turbidity (e.g., Moslow and Pemberton 1988; Gingras et al. 1998; Coates and MacEachern 1999, 2007; Bann and Fielding 2004; MacEachern et al. 2005; MacEachern et al. 2007a).

On the shelf, deltaic overprint (acting as the principal source of sediment) is readily apparent. Shelf settings that experience *neither* hypopycnal nor hyperpycnal processes are characterized by heightened carbonate production and an increase in nektonic and planktonic calcareous microfauna. Bioturbation intensities tend to be high, with unstressed, fully marine ichnological suites showing a complex overprint of successive tiers. By contrast, shale-dominated "shelf" mudstones displaying a strong prodeltaic overprint are characterized by impoverished microfauna limited mainly to arenaceous benthic foraminifera, show sediment-swimming structures, sporadically distributed burrowing, generally reduced bioturbation intensities, and lower trace-fossil diversities that nonetheless comprise both facies-crossing elements and ichnogenera characteristic of normal marine conditions.

IMPORTANCE OF PRODELTA HYPERPYCNITES

Hyperpycnal processes are suggested to be significant in deposition of many of the shale units in the Cretaceous Seaway. Such hyperpycnal turbidites may be directly fed by rivers, producing hyperpycnites similar to those shown in the models of Mulder et al. (2003), but they may also evolve from collapsing hypopycnal plumes forming associated mud belts, especially where aided by storms, waves, tides, and other marine currents.

Other examples of river-fed ancient muddy prodelta hyperpycnites include the Cretaceous Lewis shale in Wyoming (Soyinka and Slatt 2008), the Lower Kenilworth, and the Storrs and Aberdeen members of the Blackhawk Formation in the Book Cliffs of central Utah (Pattison 2005; Pattison et al. 2007), which also form part of the upper Mancos Shale Formation. Although river-fed hyperpycnal processes were not invoked, a recent study by Varban and Plint (2008) of the Kaskapau shales, which lie directly above the Dunvegan, suggests that they represent a long-lived prodelta-shallow shelf mudbelt, in which mud was transported as much as 250 km offshore across a shallow gradient shelf ramp. The transport mechanisms invoked are very similar to those suggested by Bentley (2003), in which storm waves resuspended shelf mud, forming a sea-floor nepheloid, fluid-mud layer that was subsequently dispersed by wind-driven currents (Fig. 1B). Mutti et al. (2003) has also summarized the importance of river-generated hyperpycnal processes in combination with major storms in the deposition of sediment within delta-front and prodelta deposits of the European foreland basins. Mutti et al. (2003) also suggest a linkage between the generation of thick, storm-generated HCS

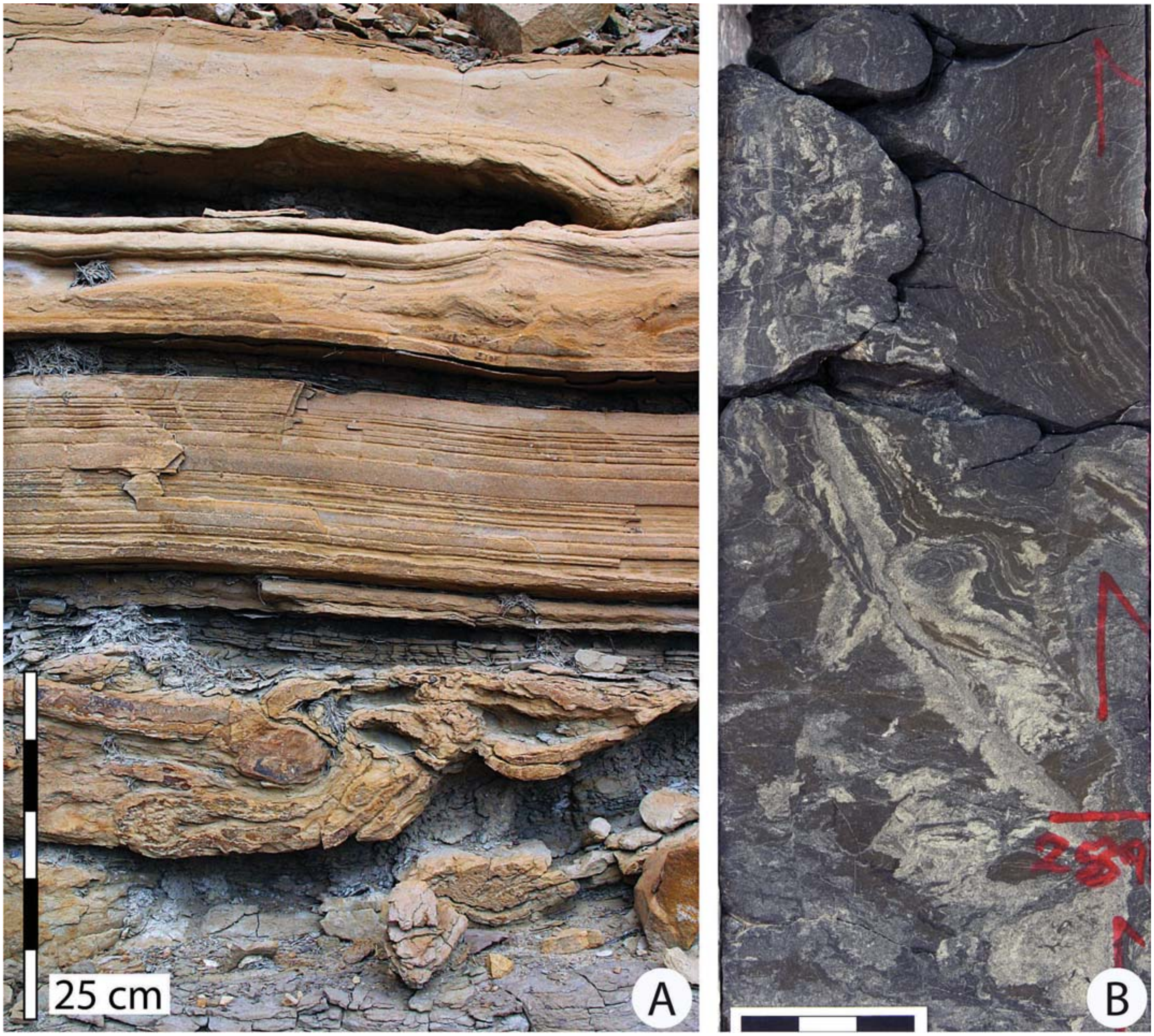

FIG. 23.—Soft-sediment deformation of delta-front units of the Ferron Sandstone Member. **A)** Soft-sediment deformation associated with parallel-laminated to ripple-cross-laminated sandstones and interbedded mudstones of distal delta-front deposits of Parasequence 2c, at Bear Flat. **B)** Deformed prodeltaic mudstones from the Ferron Muddy Creek Well #5, (MC-5 in Fig. 5) NNE Section 23, T. 22, R6E, 289 ft (88.1 m), Parasequence 2e. Scale is 3 cm.

beds and river-flood-generated turbidites, and surmise that these may be important linked processes in deltas deposited within tectonically active basins.

There may also be a linkage between formation of growth faults and prodelta hyperpycnites. Small-scale growth faults in the Ferron Sandstone Member (Bhattacharya and Davies 2001, 2004) as well as the Permo-Triassic river-dominated deltas of the Ivishak Formation in the supergiant Prudhoe Bay oil field of Alaska (Tye et al. 1999), show that growth faults start as a consequence of loading of delta-front sands on underlying mobile prodelta muds. Plint (2000) has also interpreted several growth faults in delta-front sands of the Dunvegan Formation. These prodelta mudstones have all been described and

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FIG. 24.—Aggradational oscillation ripples in the Ferron delta front sandstones. **A)** Alternating hummocky cross-stratified to aggrading wave-rippled sandstone, taken along Utah State Road 803, Dry Wash, Utah. **B)** Strongly aggradational oscillation ripple, with vertical accretion of ripple crest in the delta front; USGS Ivie Creek Well # 3 (IC-3 in Fig. 5), NWNW Sec. 16, T. 23, R6E, 306.25 ft (93.3 m), Parasequence 2b. **C)** Lower bed shows vertical and lateral shift of oscillation ripple crest (arrows), passing into vertically accreted oscillation ripples in the distal delta front. Unit shows isolated *Planolites* (P). BP Muddy Creek Well #5 (MC-5 in Fig. 5), NNE Section 23, T. 22, R6E, 364 ft (110.9 m), Parasequence 2d. **D)** Aggradational oscillation ripples with abundant carbonaceous detritus, and isolated rare *Ophiomorpha* (O) in the delta front, USGS Ivie Creek Well #3 (IC-3 in Fig. 5), NWNW Sec. 16, T. 23, R6E, 322 ft (98.1 m), Parasequence 2a. Scale is 3 cm.

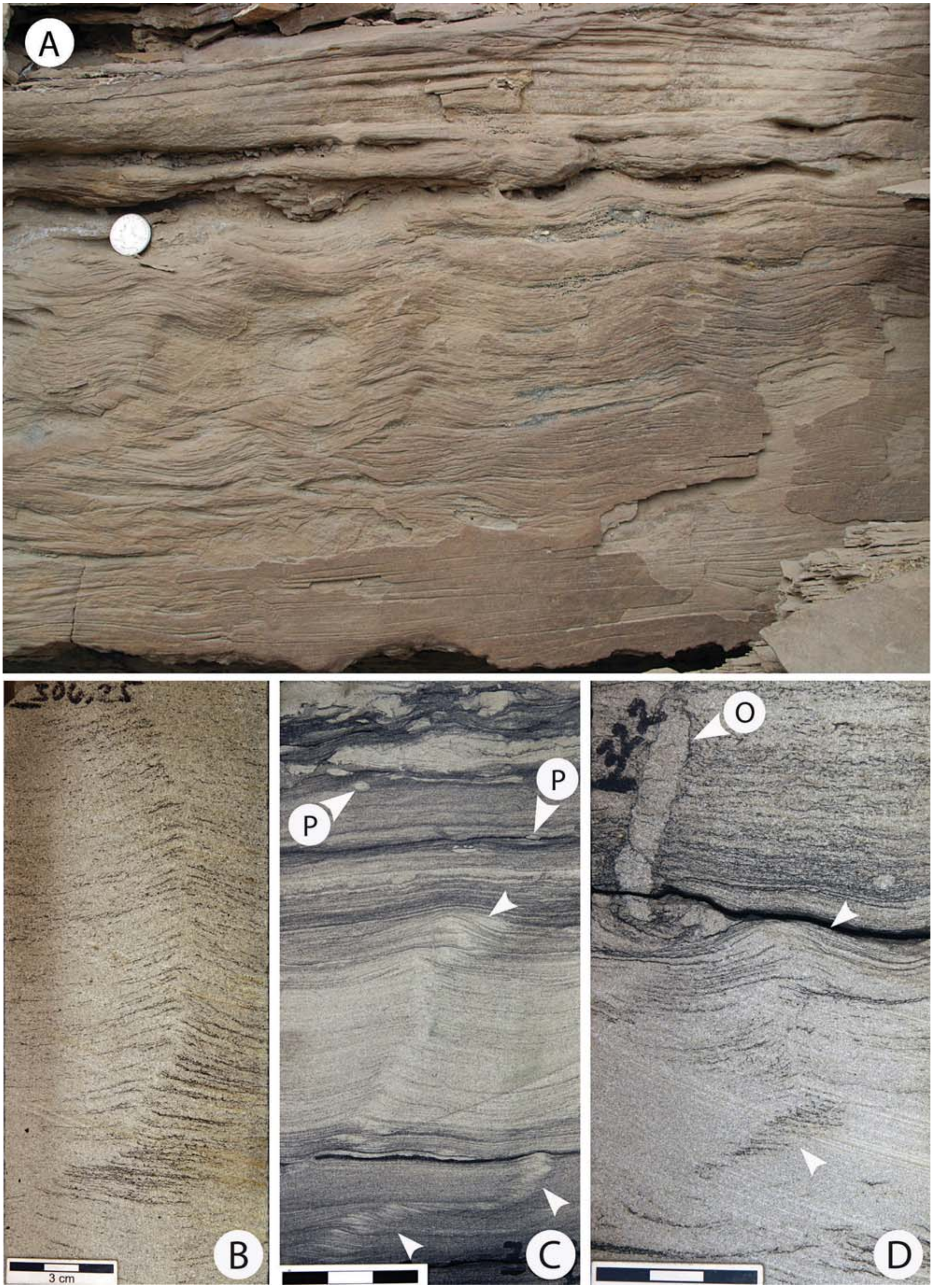
A
306,25
3 cm
B
P
P
C
O
D

TABLE 3.—*Hyperpycnites, hypopycnal deposits, and anoxic laminites.*

Parameter	Hyperpycnites	Hypopycnal Deposits	Anoxic Laminites
Lithology	Sand, silt, and clay	Silt and clay	Clay, silt, limestone, and organics
Bedding	Laminated to medium bedded	Laminated to bedded	Laminae to very thin beds
Sedimentary structures	Normal and inverse grading, traction structures (Bouma sequences; massive units, plane bed, current ripples), storm-associated hyperpycnites may show aggrading wave ripples and HCS	Normal grading, wave ripples, HCS	Lamination
Bioturbation Index	0–1	0–5	0–3
Dominant substrate	Soupground (mantle and swirl common)	Softground, deep-tier	Softground, shallow-tier
Burrow diversity	Low, brackish-tolerant forms	Low to high, fully marine forms	low, dysaerobic-tolerant forms
Body fossils	Allochthonous, mostly terrestrial flora, benthic infauna.	Mixed terrestrial flora and marine fauna, benthic and nektonic	Marine. autochthonous, mostly nektonic, abundant fecal pellets, fish remains
Organic matter	Mostly terrestrial, Type III kerogen, could have high TOC, but gas prone	Mixed terrestrial and marine, Types I, II, and III kerogen, moderate to low TOC	Mostly marine, algal, Type I and II Kerogen, high TOC
Diagenetic constituents	Siderite		Pyrite, calcite, dolomite
Sedimentation rate	20 cm/year	1 cm/year	1 mm/year

interpreted as rapidly deposited and probably hyperpycnal in origin. Certainly, the extremely high sedimentation rates described in modern hyperpycnal prodelta muds would result in elevated initial porosities and the development of soupy substrates susceptible to remobilization. We thus hypothesize that prodelta hyperpycnites may be important in the development of mobile substrates, especially in river- and storm-dominated deltas.

In general, prodelta hyperpycnites likely may also form leaner, gas-prone source rocks (i.e., type III kerogen) that are prone to the generation of overpressure, versus more slowly deposited, organic-rich, anoxic laminites and condensed-section shales that typically contain Type I and II kerogens (Varban and Plint 2008).

CONCLUSIONS

- Delta systems deposited in the Ferron Sandstone Member of Utah and Dunvegan Formation in Alberta in the Cretaceous Western Interior Seaway of North America show evidence of abundant, prodeltaic muddy "hyperpycnites." These mudstones show diffusely bedded, centimeter-thick, normally to inversely graded siltstone and very fine-grained sandstone beds, with internal scours, suggesting deposition during waxing as well as waning hyperpycnal flows. Sandstones may show wave-formed cross lamination and, locally, hummocky cross stratification, suggesting a linkage with major storms. A depauperate fauna, and the presence of "mantle and swirl" sediment-swimming structures also suggest rapidly deposited fluid muds.
- Simple paleohydraulic calculations of the feeding rivers in the Dunvegan Formation and Ferron Member show that paleo-river discharges never exceeded the 6000 m^3/s theoretical threshold, above which rivers seldom generate hyperpycnal plumes. We thus believe that these rivers routinely generated hyperpycnal plumes. Hyperpycnal conditions are ameliorated by the fact that the rivers are relatively small and drained an active mountain belt, within humid temperate (Dunvegan Formation) to subtropical (Ferron Sandstone Member) "greenhouse" conditions. Local freshening and estuarine mixing in the shallow coastal areas would have enhanced further the ability of both river systems to achieve hyperpycnal states. Despite very low shelf gradients, which would mitigate long-traveled hyperpycnites, waves, resulting from the stormy nature of the Cretaceous Seaway, likely aided in significant along-shelf and across-shelf transport of fluid mud.
- Muddy hyperpycnites can be distinguished from anoxic laminites by their greater intensity of burrowing, higher ichnologic diversity, presence of wave ripples and HCS, abundance of very thin to thin, normal to inversely graded beds, versus the predominance of parallel lamination, as well as lower organic content, predominance of allochthonous fauna and flora, and paucity of pelagic microfossils.
- Prodelta systems associated with hypopycnal-dominated deltas may show zones of more normal marine burrowing, indicating that salinity reductions were not common stresses on the substrate, although river systems may alternate between hyperpycnal and hypopycnal conditions, resulting in alternation of more and less bioturbated zones; a situation observed in the Ferron and Dunvegan systems described above.
- A common association of hyperpycnal-prodelta mudstones with overlying growth faults suggests that such muds are important in the generation of growth strata as well as the development of overpressure in rapidly deposited deltaic continental margins.
- Prodeltaic hyperpycnites will typically form lean, gas-prone source rocks, compared to richer, oil-prone anoxic laminites or condensed-section shales.

ACKNOWLEDGMENTS

The authors would like to acknowledge Antonio Cattaneo and Simon Pattison for their thorough reviews, as well as the comments of guest Associate Editor Gary Hampson and of course JSR editor Paul McCarthy. Their comments helped us focus our still rather long manuscript. We would also like to thank Mark Barton, Mike Gardner, James Garrison, Gus Gustason and Tom Ryer, who enthusiastically shared their insights on the Ferron, especially in many field excursions, and who contributed to our understanding of this fascinating unit. This work was made possible by funding to Bhattacharya's Quantitative Sedimentology Consortium at the University of Houston by Anadarko, BP, Chevron, and Shell. MacEachern is funded with a Discovery Grant from the Natural Sciences and Engineering Research Council (NSERC).

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Received 19 April 2008; accepted 2 October 2008.