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Lateral Variability of Sedimentological and Ichnological Characteristics of the Falher "D" Member, West-Central Alberta, Canada

by

Trevor Andrew Hoffman

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

Department of Earth and Atmospheric Sciences

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Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled LATERAL VARIABILITY OF SEDIMENTOLOGICAL AND ICHNOLOGICAL CHARACTERISTICS OF THE FALHER “D” MEMBER, WEST-CENTRAL ALBERTA, CANADA submitted by **Trevor Andrew Hoffman** in partial fulfillment of the requirements for the degree of **Master of Science**

Abstract

The lower Cretaceous Falher Member within west-central Alberta consists of five stacked successions of coarsening-upward storm-dominated sandstones and conglomerates. Using detailed core descriptions the Falher "D" member is subdivided into five facies associations: lower shoreface and distal delta-front (FA1), upper shoreface and foreshore (FA2), proximal delta-front (FA3), lower delta-plain (FA4), and non-marine coastal plain (FA5).

A detailed investigation of the Falher "D" reveals a number of along-strike trends. Typical strandplain deposits (FA2) are present in the western portion of the study area, while wave-dominated deltaic deposits (FA3) dominate the central region and lagoonal lower delta-plain deposits (FA4) dominate the eastern region. This distribution of depositional environments is interpreted to represent an asymmetrical wave-dominated delta. Additional evidence includes the presence of stacked fluvial deposits, depressed ichnological intensities and diversities, and the distribution of conglomerate within the upper shoreface and foreshore. Comparisons with modern asymmetrical wave-dominated deltas support this interpretation.

Acknowledgements

I wish to thank my supervisors, Dr. Murray Gingras and Dr. George Pemberton, for both their guidance during the course of this project and for introducing me to concepts that have broadened my focus and contributed to my development as a geologist. They were the best supervisors anyone could ever hope for. This project would not have been possible without their excellent supervision. I would also like to thank my thesis defense committee, Dr. Murray Gingras, Dr. George Pemberton, Dr. Ben Rostron, and Dr. Doug Craig for their advice.

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Chapter 1 – Introduction

(1.1) Introduction

The focus of this study is the Lower Cretaceous (Albian-age) Falher "D" Member, Spirit River Formation, Fort St. John Group of west-central Alberta. Subsurface data, including core and petrophysical log analyses, will be used to improve our understanding of coarse clastic shoreline successions containing considerable along-strike variation. The Falher "D" is one of several major northward prograding shoreline successions present within the Falher Member (Fig. 1.1). Each Falher cycle, A through E, is defined by marine and marginal-marine deposits of one cycle overlying coastal plain coals and mudstones from another cycle throughout most of the region. These cycles represent a series of transgressive-regressive sequences, with each succession overall regressive in nature separated by transgressions. In addition, a number of parasequences and allostratigraphic units have been defined within individual Falher cycles (e.g. Arnott, 1993; Casas and Walker, 1997; Rouble and Walker, 1997; Armitage et al., 2002; Caddel, 2002). These shoreline successions trend east west and are laterally continuous, extending 240km eastward of the foothills (Leckie, 1986). The cycles more or less stack vertically one top of one another from Township 65 to Township 75 and consist of storm-dominated shoreline deposits, truncated by wave-reworked deltaic deposits along the coastline. In the Elmworth/Wapiti field area, the Falher cycles are generally composed of coastal plain deposits in the south, wave-dominated shoreline and deltaic complexes in the center, and offshore deposits in the north.

The purpose of this study is to integrate the sedimentology, ichnology and stratigraphy of the Falher "D" in order to describe and interpret the facies succession and paleogeographic evolution of the study area. Detailed examination of cored intervals of the Falher "D" will provide the ichnological-sedimentological data necessary to describe and model depositional environments present within the succession. The along-strike variability and inter-relationship of these depositional environments will be the focus of this study. Subsequent understanding of the paleogeography and lateral variability of the

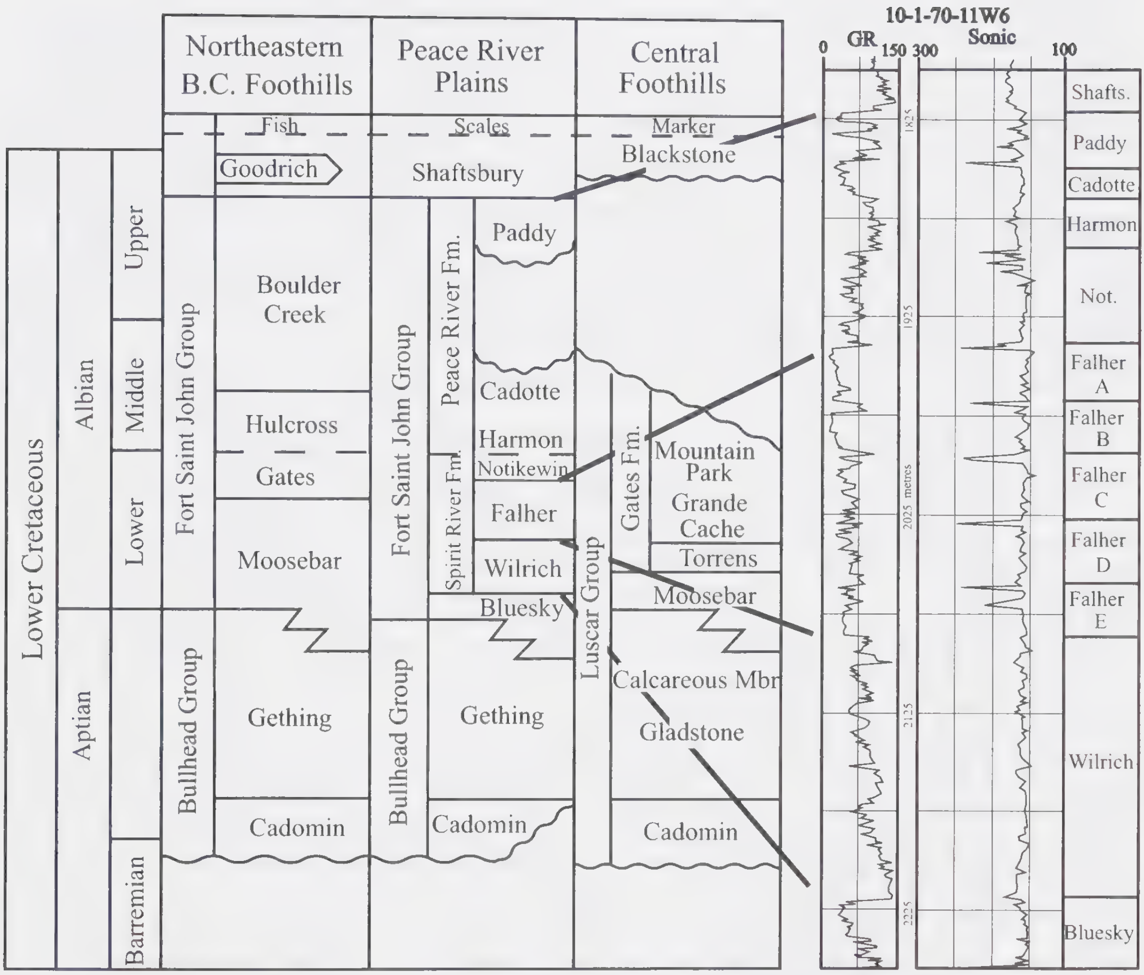


Fig. 1.1 - Lower Cretaceous stratigraphic nomenclature of Alberta and British Columbia. Gamma-ray (GR) and sonic log responses to the right from well 10-1-70-11W6, Elmworth field, Deep Basin. (modified from Armitage et al., 2004 and Smith et al., 1984)

Falher "D" will not only enhance future exploration and production strategies in the Falher Member, but also in similar clastic shoreline successions worldwide.

(1.2) Study Area

The area selected for this study is located in northwestern Alberta, just southwest of the city Grande Prairie, Alberta (Fig. 1.2). This area encompasses Townships 67-69 and Ranges 8W6–13W6 within Alberta. Within this region, roughly 1,000 wells penetrate the Falher Member and approximately 35 of those contain cored intervals relevant to this investigation (Fig. 1.2, Table 1.1). The greatest well/core control is concentrated within Township 68 hence this will be the focus of this study. Gamma ray and sonic log profiles will be used to depth correct core control and construct cross-sections. However, the best data is in the form of the cored intervals that presents essential sedimentological and ichnological information and allows the calibration of the geophysical well log data.

Trending east-west, the study encompasses most of the Wapiti field and the southern most portion of the Elmworth field (Fig. 1.3). These fields have been attractive exploration targets since their discovery in 1976 with over 2000 producing wells developed from 10 principal reservoir units (Stockmal et al., 2001). Most production from the Falher "D" occurs from the Falher "D1" pool located in the western half of the study area (Arnott, 1994). However, there are also a number of other smaller pools located throughout the study area. This portion of the Western Canadian Sedimentary Basin (WCSB), referred to as the Deep Basin, contains substantial hydrocarbon exploration and production from a number of stratigraphic intervals. The Deep Basin includes the Mesozoic section of the WCSB that thickens dramatically along the Cordillera (Masters, 1979). Increased accommodation space resulting from rapid tectonic subsidence during the Mesozoic produced sedimentary fill in excess of 4,000 m (Masters, 1979; Wright et al., 1994; Monger and Price, 2002). Current gas reserves within the Deep Basin are around 77 Trillion Cubic Feet (TCF) with another 25 TCF expected to be recovered with future exploration (Stockmal et al., 2001). However, Masters (1979) originally calculated ultimate resources of up to 400 TCF. It is apparent that the region contains vast quantities of gas and will continue to be an important exploration target for years to come.

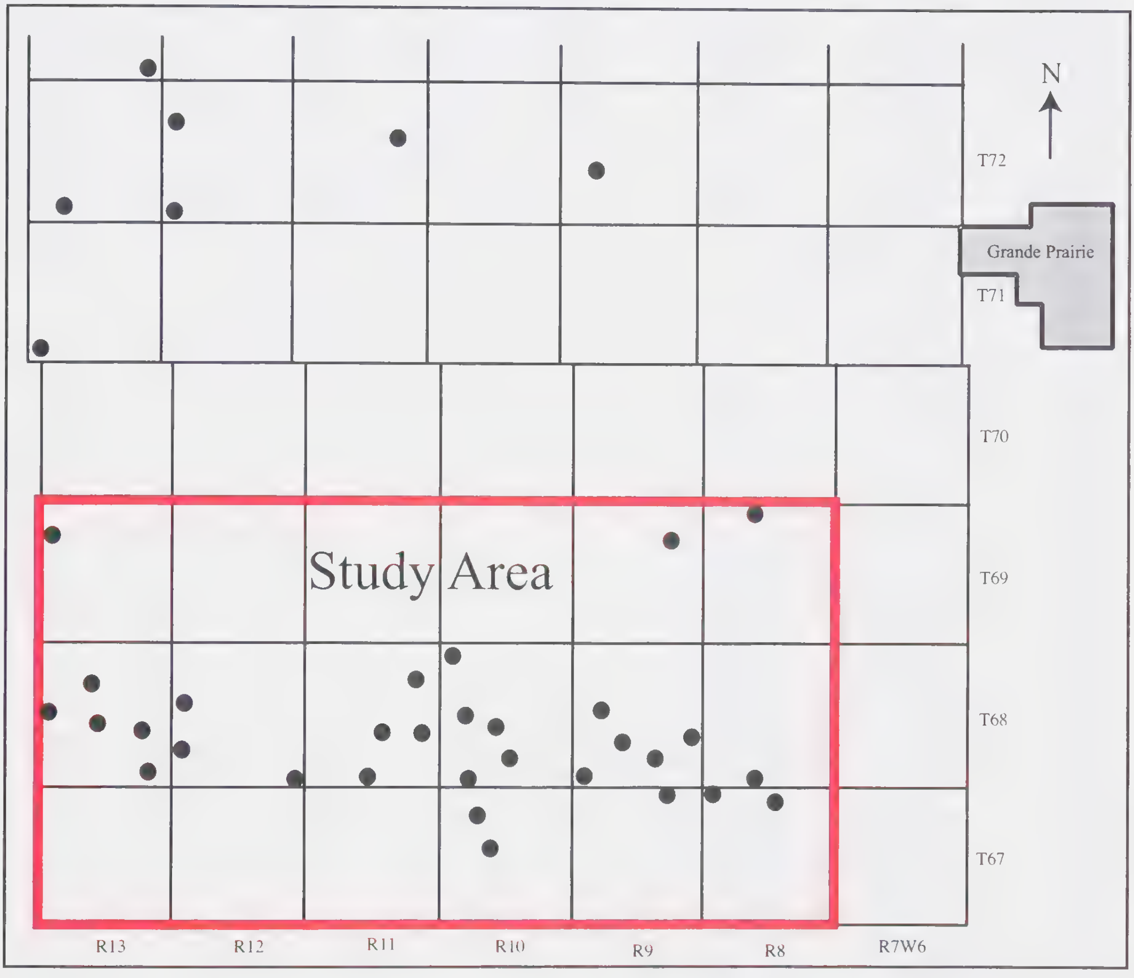


Fig. 1.2 - Location of study area within west-central Alberta. Cores logged are represent by round black dots. Table 1 contains the location, interval described, and length of each core.

Well Location				Core Interval		
l.s.d.	Section	Township	Range (W6)	Top (m)	Bottom (m)	Length (m)
10	1	73	13	1851.5	1870.0	18.5
16	5	72	13	2027.5	2046.5	19.0
6	30		12	1865.6	1884	18.4
6	6			1982.4	2000.2	17.8
10	23		11	1758.1	1797.3	39.2
6	17		9	1709.5	1730.5	21.0
11	6	71	13	2210.3	2227.8	17.5
6	30	69	13	2365.4	2391.6	26.2
7	26		9	1870.0	1901.9	31.9
10	32		8	1857.8	1863.0	5.2
6	28	68	13	2546.6	2565.5	18.9
6	19			2674.3	2682.8	8.5
15	16			Irregular		10.0
7	14			2501.2	2516.5	15.3
9	2			2572.3	2590.9	18.6
6	19		12	2433.6	2454.6	21.0
11	7			2490.5	2515.4	24.9
7	1			2427.0	2444.0	17.0
6	25		11	2205.4	2224.8	19.4
6	15			2317.3	2332.0	14.7
6	13			2264.6	2286.0	21.4
7	4			2400.7	2413.5	12.8
10	31		10	2153.7	2176.0	22.3
13	17			2203.0	2223.2	20.2
9	16			2198.0	2216.5	18.5
6	10			2240.3	2258.9	18.6
4	5			2301.0	2311.0	10.0
6	20		9	2156.2	2173.6	17.4
15	12			2196.3	2207.5	11.2
1	10			2239.1	2249.2	10.1
14	9			2263.6	2284.2	20.6
6	6			2221.6	2231.2	9.6
15	21		8	2043.2	2061.8	18.6
5	4			2201.6	2210.9	9.3
10	29	67	10	2385.5	2407.0	21.5
6	21			2453.1	2470.3	17.2
13	35		9	2235.3	2240.7	5.4
4	34		8	2202.1	2211.5	9.4
14	31			2310.6	2319.6	9.0

Table 1.1 - Table showing the location of cores logged during this study. The length and interval logged is also shown. All cored intervals contain detailed descriptions and are presented in Appendix A.

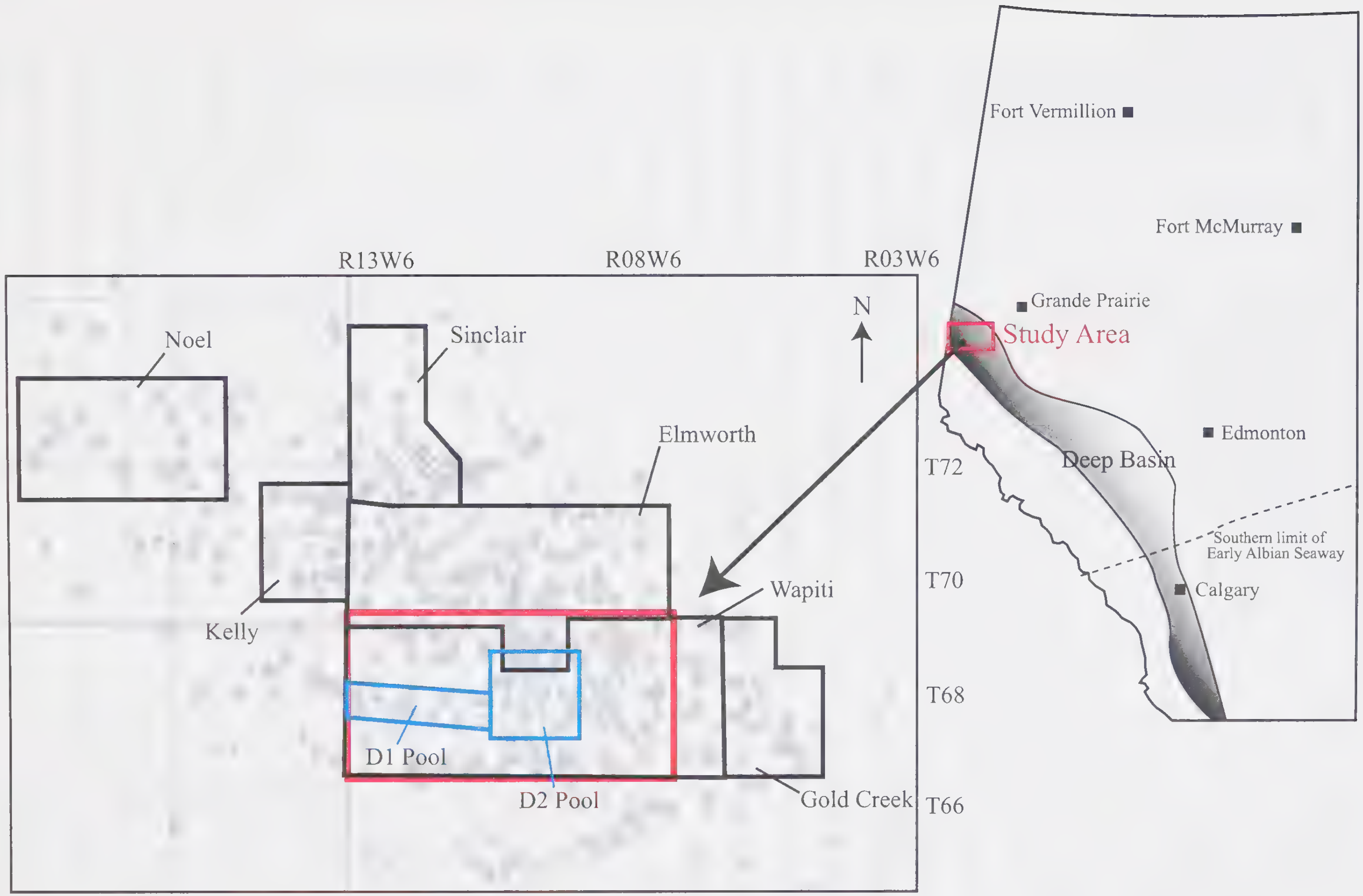


Fig. 1.3 - Location of study area (red) within west-central Alberta. Wells penetrating the Falher "D" are represent by round dots. Gas fields (black) and pools (blue) of interest are shown. The position of the study area, Deep Basin, and southern limit of the early Albian seaway are shown on the province of Alberta (modified from Cant, 1988).

(1.3) Objectives and Methodology

The main objective of this study is to describe and interpret the lateral viability of the Falher "D" succession within northwestern Alberta. This will be accomplished through a series of chapters including the description of cored intervals, grouping of related facies into environmentally significant units, and detailed mapping of these units. The overall aim is to increase our knowledge of the Falher Member and therefore enhance potential exploration and recovery strategies within the Deep Basin. An introduction to the Falher "D", including the structural setting, regional paleogeography, and previous work, is necessary in-order to provide a framework or regional perspective for understanding the study of the Falher "D" within a relatively small study area.

Chapter Two contains detailed descriptions of the 35 cored wells, by grouping rocks with similar lithological, sedimentological, and ichnological characteristics into facies. In this study 15 facies were identified and each will contain a description of the physical and biogenic sedimentary structures as well as an overall interpretation. Trace fossil abundances will be shown in the following form: rare (r), common (c), moderate (m), and abundant (a). Grain sizes are shown as: very fine-grained lower (vfL), very fine-grained upper (vfU), fine-grained lower (fL), fine-grained upper (fU), medium-grained lower (mL), medium-grained upper (mU), coarse-grained lower (cL), coarse-grained upper (cU), very coarse-grained lower (vcL), very coarse-grained upper (vcU). These facies will then be grouped, in Chapter Three, into genetically related packages referred to as facies associations. Each of the five facies associations identified in this study will include a description and a discussion on their environmental significance. Facies associations will include multiple facies and represent a particular depositional environment present with the Falher "D". Using these environmental interpretations, a depositional model is described. This model identifies and interprets the substantial along-strike variability of depositional environments present within the Falher "D".

The spatial distribution of the five facies associations is the focus of Chapter Four. This will be accomplished through cross-sections and isopach, lithological, ichnological, and paleogeographical maps. Both core descriptions and petrophysical log are used to generate the various maps and cross-sections. As well, key stratigraphic surfaces present within the Falher Member will be identified and described. Using these surfaces the

Falher "D" will be subdivided into two parasequences. Each parasequence is described and correlated using a series of strike- and dip-oriented cross-sections. Lastly, this information is incorporated with the depositional model from Chapter Three to produce a series a paleogeographical maps illustrating the evolution of the Falher "D" within the study area. Through these means, it is hoped that a greater understanding of the Falher "D" succession, and wave-dominated clastic shorelines in general, can be accomplished.

(1.4) Structural Setting

The Western Canada Sedimentary Basin is the result of the accretion of allochthonous terrains onto the western margin of North America in the late Early Jurassic (Monger and Price, 2002). The consequences of these events were the transition of the formally passive margin to an active one. Tectonic uplift commenced and created the present day Rocky Mountains. As a result of this uplift, an associated foreland basin formed to the east. The immense loading of the North American Craton triggered the depression and flexure of the craton and formed the foreland basin (Wright et al., 1994). The WCSB is characterized by eastward-moving deformation as uplift continued and lies between the Cordilleran Belt and the Precambrian Shield. Erosion of the newly uplifted source occurred and westerly-derived clastics were deposited into the subsiding basin (Monger and Price, 2002).

The foreland basin sequences form a thick (up to 4000m) elongated band of sediment parallel to the orogeny. The thickest sedimentary fill occurs nearest the western margin, where it was closest to the tectonic loading. It is continuous with the Western Interior Basin in the United States. In Canada, the basin in divided by two large basement structures, the Peace River Arch and the Sweetgrass Arch, both of which originated in the Paleozoic. These basement features have moved upward and downward through time and thus affect sedimentation in the Cretaceous.

The orogenic event that created the foreland basin began in the middle Jurassic while the accretion of much smaller terrains occurred as early as the Carboniferous (Cant, 1989; Monger and Price, 2002). Significant amounts of clastic material were not deposited into the basin until the middle to late Jurassic. The sediment filling the basin is largely terrigenous and contains primarily three grain sizes: shale, fine- to medium-

grained sandstone, and granule to fine-pebble conglomerate (Cant, 1989). Most of the sandstones in the Mesozoic section of the basin are lithic and have source areas from the Main Ranges and western Front Ranges (Price and Mountjoy, 1970; Price, 1994). However, sediment derived from Proterozoic strata in the Canadian Shield is responsible for quartzose sandstones in the eastern part of the basin.

The major stratigraphic packages/wedges of the Foreland basin include the Upper Jurassic, Lower Cretaceous, Upper Cretaceous, and Tertiary clastic wedges. The lower most sediment of the WCSB is grouped into the Upper Jurassic clastic wedge, which is only preserved in the western part of the basin. Unconformably (sub-Cretaceous unconformity) overlying this is the Lower Cretaceous clastic wedge, which is known in the subsurface as the Mannville Group and the Blairmore Group in outcrop. The sub-Cretaceous unconformity formed during the Early Cretaceous as a result of minimal subsidence combined with a lack of sediment input, that lead to erosion across the interior. The unconformity is angular in nature, however the angular discordance between the Cretaceous and underlying strata is very gentle.

Most of the Mannville Group strata are sandstones and shales with minor amounts of conglomerate and limestone. The sediments of the lower Mannville Group that in-fill topography on the sub-Cretaceous unconformity are referred to as the Cadomin and Gething formations, from bottom to top, in northwestern Alberta. Sediments deposited in the middle Mannville are referred to as the Bluesky Formation and represent a marine transgression. The upper Mannville Group (Fig. 1.4) represents the subsequent regression following the middle Mannville transgression. The Spirit River Formation is part of the Fort St. John Group, which is equivalent to the Upper Mannville. A more detailed description of the paleogeography of the Lower Cretaceous is found below. After the deposition of the Mannville Group, dramatic changes in sedimentation occurred within the Alberta and Colorado groups, which were dominantly shale with minor sandstones (Cant, 1989; Monger and Price, 2002). The Upper Cretaceous and Tertiary clastic wedges will not be discussed here but interested readers are referred to Leckie (1989).

The provenance of the Gates Formation (Falher equivalent) sediment is the subject of a study by Leckie (1985) using detailed petrographic descriptions of the Gates

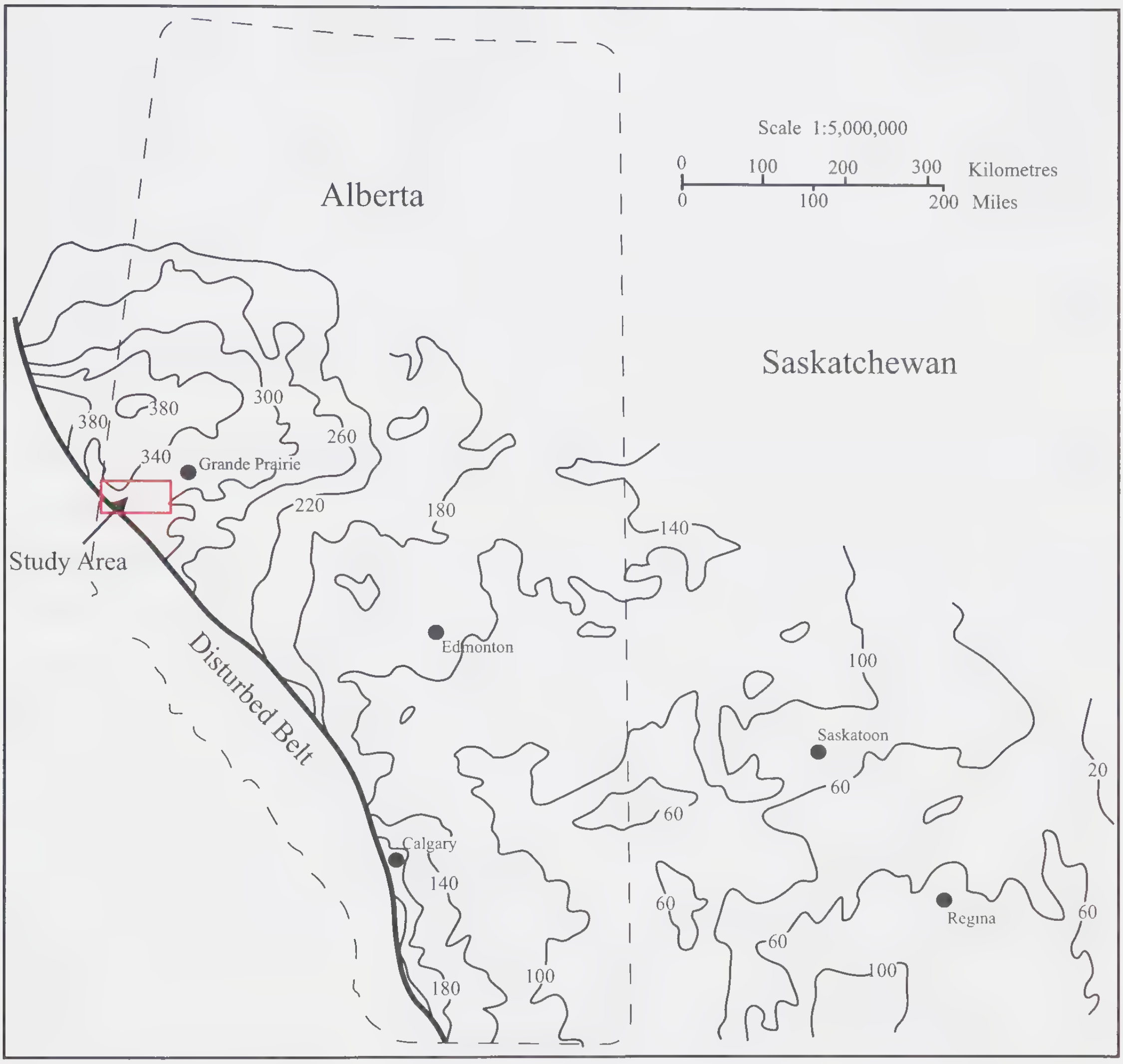


Fig. 1.4 - Isopach map of the Upper Mannville of Alberta and Saskatchewan. The Upper Mannville includes the Bluesky, Wilrich, Falher, Notikewin, Harmon, Cadotte, and Paddy members. Strata thickens toward the foredeep and the Peace River arch regions, where subsidence is the greatest (modified from Hayes et al., 1994).

sandstones. He found that Moosebar-Gates sandstones are predominantly litharenites with some feldspathic litharenites with a mixed source of clastic and carbonate sedimentary rocks, acidic to intermediate plutonic and volcanic igneous rocks, and metamorphic rocks (Leckie, 1985). The regionally extensive source area extended well into the Omineca Crystalline Belt and eastern margins of the Intermontane Belt (Fig. 1.5). Using sole markings on sediment gravity-flow deposits, he extrapolated the paleoflow direction to be 332 degrees. Therefore, the regional paleoslope dipped toward the north-northwest. At the time of Moosebar-Gates deposition, the Tenakihi Group of the Omineca Crystalline Belt was to the south of the Gates shorelines and could have provided sediment. Further information on the petrology and tectonics of the Gates Formation are referred to Leckie (1985).

(1.5) Regional Stratigraphy and Paleogeography of the Lower Cretaceous in northwestern Alberta

Subsidence of the Foreland basin in the early Albian allowed the intrusion of marine waters into the interior of North America (Fig. 1.6). This formed a shallow epicratonic sea, which collected sediment during the various periods of uplift/erosion of the cordillera. The first such event in the Cretaceous resulted in the formation of an alluvial and braid plain along the western edge of the basin, which are represented by the Cadomin Formation. These alluvial fans expanded from their source and eventually formed a single widespread alluvial plain covering much of western Alberta. The alluvial-plain deposits are comprised of poorly sorted, sandy chert conglomerates (Stott, 1984). The Fox Creek Escarpment, a gentle range of hills, marks the Cadomin Formation's eastern limit. This paleographic high is identified in the subsurface by an absence of the Cadomin, overlain by a thin Gething Formation. Continued subsidence and accumulation of sediments formed fluvial and delta-plain deposits of the Gething Formation. In the Peace River area, the Gething Formation forms extensive delta-plain deposits, which grade northward into marine sandstones, siltstones, and mudstones (Stott, 1984). South of the Peace River, the Gething gives way to alluvial and floodplain deposits. In middle Gething Formation time, the Fox Creek Escarpment became buried as the fluvial deposits expanded eastward. With no local constraints, the drainage plain

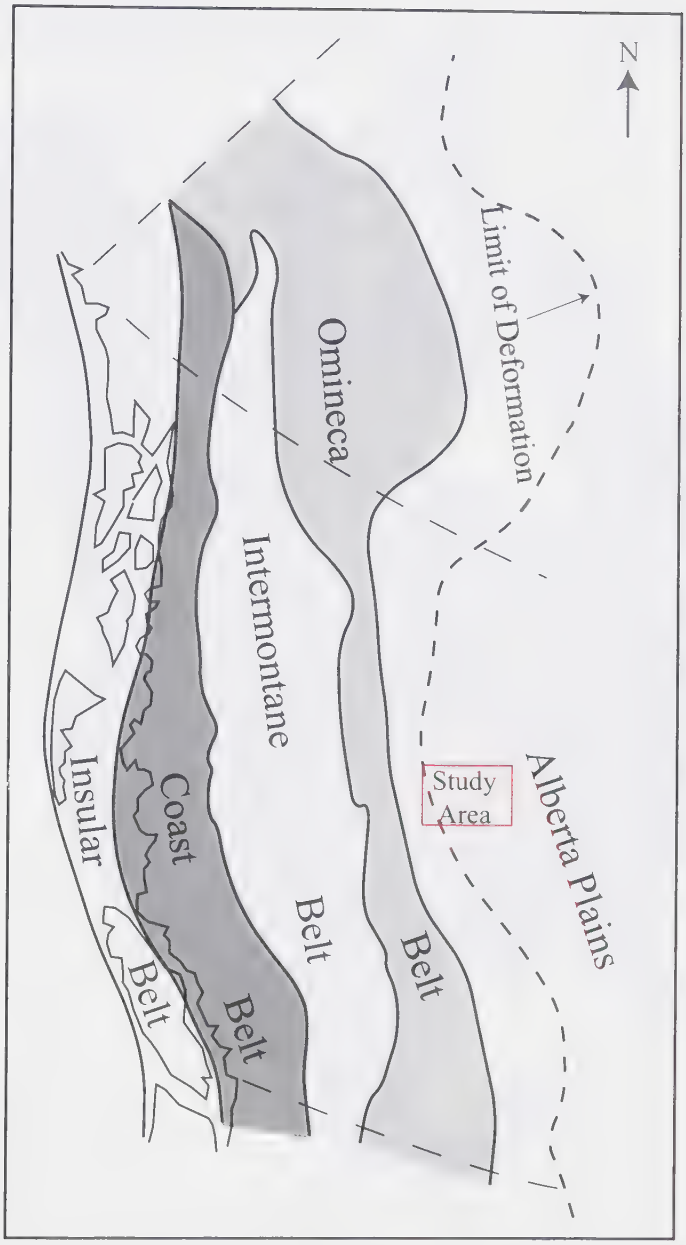


Fig. 1.5 - Distribution of the morphogeological belts of the Cordilleran (Modified from Monger and Hutchison, 1971).

Fig. 1.6 - Map of North America illustrating the extent of the the Boreal and Gulfian Seaways during the Falher Member time (early Albian) (modified from Williams and Skelck, 1975; Jackson, 1984). Study area location shown in red.

expanded randomly forming a low-lying, swampy plain with numerous lakes and became heavily forested (Smith et al., 1984).

During the early Aptian the Boreal Sea intruded into the continent, drowning the Gething fluvial deposits and depositing coastal and shallow-marine sandstones of the Bluesky Formation. The overall transgressive Bluesky Formation contains numerous coarsening-upward regressive cycles due to an essentially continuous sediment supply. Most of the regressive cycles consist of barrier bar sequences that prograded northward capped by lagoonal and bay sediments. As the Clearwater Sea continued to transgress southward along the Mackenzie River Basin (Stelck, 1975), the shallow marine deposits of the Bluesky Formation are overlain by the marine shales of the Wilrich Member (Moosebar Member equivalent) were deposited. The Clearwater Sea flooded most of Alberta and may in fact have reached into Montana (Stelck, 1975).

Late-early Albian time signals a definitive change in the system, with increased tectonism of the Cordillera (continued Columbian Orogeny). This resulted in sedimentation rates exceeding relative sea-level rise, as it did during the Cadomin and Gething time. Under these conditions, a series of northward prograding clastic wedges formed. The Spirit River Formation represents the regressive infilling of the seaway after the transgression of the Boreal Sea (Smith et al., 1984). The overall regressive Falher Member is subdivided into five cycles, Falher A through Falher E Members, each separated by rapid transgressions. Marine sediments overlying coastal-plain coal deposits signal the transgression in core. The Falher Member is age equivalent to the following stratigraphic units; lower Gates Formation is the central foothills, Grand Rapids B Member in northeastern Alberta, Beaver Mines Formation in the southern foothills, and Clearwater Formation in northern Alberta. The Falher Member within Townships 64 to 78 consists of thick sequences of shoreface marginal marine deposits. North of this area the Falher Member consists of dominantly marine deposition with non-marine deposition dominant in the south (Fig. 1.7). Fluvial channels punctuate the shoreline deposits along the length of each Falher coastline (Cant, 1983). The Falher Member's shorelines are strongly wave-dominated, resulting in a linear east west trending coastline with deltaic lobes reworked. The Notikewin Member is another regressive cycle, which overlies the Falher "A" Member. Similar to the Falher Member,

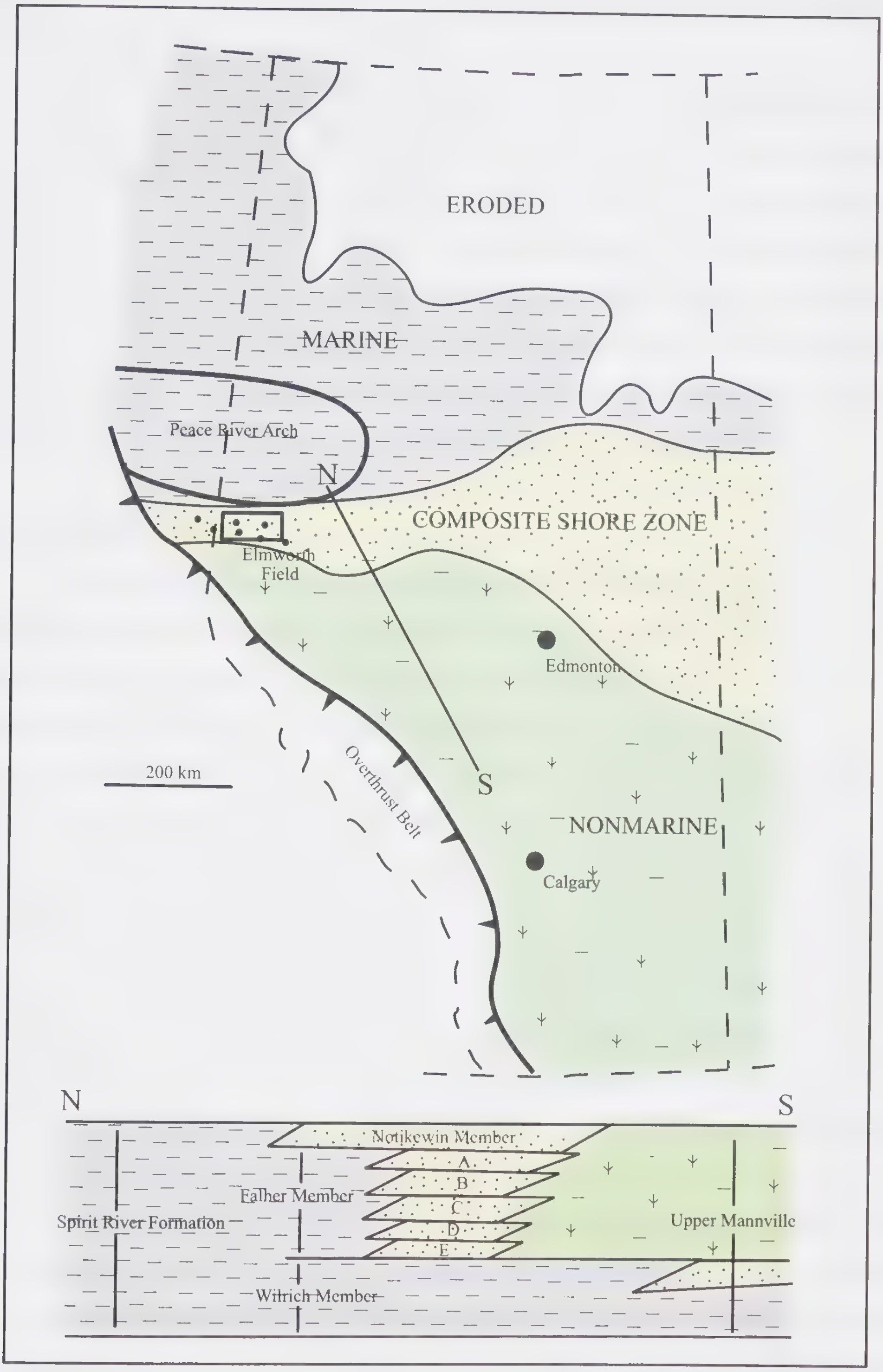


Fig. 1.7 - Generalized facies of the Falher Member. (Modified from Cant, 1995 and Casas & Walker, 1997)

the Notikewin contains prograding shoreline deposits in Townships 65 to 80 trending east west and offshore deposits to the north.

A second major transgression followed with the Boreal Sea again intruding into the continent. This time the Boreal Sea advanced farther southward and eventually connected with the Gulfian Sea to produce a continuous intercontinental sea (Cant, 1989). The marine shales of the Hulcross/Harmon/Joli Fou (northern Alberta, northern B.C, and southern Alberta/Saskatchewan respectively) Members represent this. This transgression lasted until the end of the Albian time and was the result of a major global rise in sea level (Cant, 1989). Within this overall transgressive period, the regressive Paddy and Cadotte members were deposited as a result of continued sediment input.

(1.6) Previous Work

The Spirit River Formation, especially the Falher Member, has been the subject of many geological studies in recent years due to its large hydrocarbon reserves. However, Lower Cretaceous aged rocks have been studied as early as the late 1800's. In 1877, Alfred Selwyn published "a Report on Exploration in British Columbia" in which he described shales outcropping along the Peace River. Dawson (1881) later named these shale outcroppings as the Fort St. John Shales, due to their proximity to the town of Fort St. John, British Columbia. He also recognized that the sediments making up the Cretaceous shorelines in that region most likely originated west of the Rocky Mountains. McLearn (1918, 1923) also described exposures in northeastern British Columbia, where he identified the sandstones of the Gates Formation and the underlying shales of the Moosebar Formation. In 1950, McLearn & Kindle summarized previously collected data on the Lower Cretaceous and produced early paleogeographic maps. Their work was incomplete due to a lack of subsurface data at that time.

The Alberta Study Group (1954) extended, with the use of newly acquired subsurface data, the correlation of Lower Cretaceous strata eastward from the previously established stratigraphic framework of the foothills in northeastern British Columbia. At the same time, Badgley (1952) was also involved in the correlation of these rock units into the subsurface and was the first to formally study the Falher Member. In the Peace River plains regions, the Fort St. John Group was subdivided into the Spirit River

Formation, the Peace River Formation, and the Shaftesbury Formation. The Alberta Study Group (1954) further subdivided the Spirit River Formation into the Wilrich Member, Falher Member, and Notikewin Member. Stott (1968, 1982) discussed the regional geology of the Fort St. John Group in northeastern British Columbia and northwestern Alberta as well. He interpreted the Gates Formation (Falher Member equivalent) as deltaic and flood plain deposits, also suggesting a southwestern source of sediment and a north-south transition from coastal plain to shallow marine environments.

With the discovery of the Deep Basin Elmworth gas field in 1976, geological studies of the highly gas-charged Spirit River Formation were of the utmost importance. In particular, the sedimentology and stratigraphy of coarse-grained reservoir units within the Deep Basin were of interest. Outcrop of equivalent units in the foothills of northeastern British Columbia provided an excellent database to compare to subsurface data from the Deep Basin. Leckie & Walker (1982) produced a depositional model of the Gates Formation based on this outcrop. In doing so, they differentiated between fluvial and beach conglomerates and added that the model could be used to predict their reservoir distribution in the adjacent Deep Basin. McLean (1979) dealt with the relationship between conglomeratic units of the foothills to those of the Deep Basin. He examined tectonic influences and the reservoir composition of the Falher Member. In 1979, Masters described the Deep Basin's reservoir characteristics, including their low porosity and low permeability nature.

In recent years, many excellent sedimentological and stratigraphic studies of the various Falher Members have been completed due to the wealth of subsurface data that is now available. Cant (1984) identified eight major transgressive-regressive cycles within the Spirit River Formation. With the use of core, Cant (1984) describes the sedimentology of the Falher and Wilrich Members. He observed coarsening-upward sequences within the Spirit River Formation, which he correlated in a 140 km long north-south cross-section. Leckie (1985, 1986) through a series of studies in the foothills of northeastern British Columbia discussed the stratigraphy of the Moosebar and Gates Formations (Wilrich and Falher equivalents respectively). In these studies, he identifies seven major transgressive-regressive cycles and suggested that the lateral extent of the cycles may be related to the Peace River arch. Jackson (1984) and Smith et al. (1984)

briefly discussed the paleogeography of the Lower Cretaceous Mannville Group of the Elmworth field area in northwestern Alberta and northeastern British Columbia.

Several studies have used the petrographic analysis of cored intervals to reveal important information on the porosity and permeability of the Falher Members (Cant 1983, Cant & Ethier 1984, Rahmani 1984). Most of the studies listed above focus on the Elmworth field area due to the large gas resources. The Spirit River Formation has undergone significance diagenesis to alter the reservoir potential of any deposits in the Deep Basin. Tilley's (1988) thesis and Tilley & Longstaffe (1989) studied the diagenesis and porewater evolution of the Cretaceous of Alberta. Tilley & Longstaffe (1989) identified four stages of diagenesis and porewater evolution including: deposition and burial, maximum burial and relief, uplift and erosion, and maximum generation of methane from interbedded coals.

Rouble & Walker (1997) produced a detailed facies analysis and allostratigraphic framework for Falher Members A and B. In this study, the authors divided the Falher Members A and B into four allomembers, A1, A2, B1, and B2. In a similar study Casas & Walker (1997) produced a detailed facies analysis and depositional history of the Falher Members C and D. They subdivided the Falher "C" Member into six sub-members, C1 to C6, and the Falher "D" Member into five sub-members, D1 to D5. Their interpretations differed greatly from those of Arnott (1993) who studied the sedimentology and sequence stratigraphy of the Falher "D" pool. He subdivided the Falher "D" Member into four sub-members, D1 to D4. His study also discussed the importance of changes in relative sea level in relation to the distribution of reservoir units. Caddel (2000) and Caddel & Moslow (2004) studied the sedimentology and stratigraphy of the Falher "C" Member from outcrop in the Bullmoose Mountain area of the foothills of British Columbia. They described the facies distribution in terms of reservoir quality and reservoir potential. Using their stratigraphic framework created from the foothills outcrop data, they extended their model into the subsurface toward the east. Wadsworth et al. (2003) detailed the stratigraphy of coal and non-marine strata of the Falher (Gates equivalent) Formation. This study extended the body of knowledge to the continental areas of the Falher Formation. Wadsworth et al. (2003) used coal

compositional characteristics to provide information involving their stratigraphic position and the stratigraphic behavior of surrounding strata.

More recently, Armitage (2002) completed a thesis studying the sedimentology, ichnology, and allostratigraphy of the Falher "C" Member. He sub-divided the Falher C Member into four units, C1 to C4, through the recognition of key allostratigraphic surfaces. Facies associations FA2 and FA3, wave-dominated upper shoreface and foreshore and tidal inlet deposits respectively, were shown to contain facies successions of the greatest reservoir potential. Armitage et al. (2004) considered the facies distribution, stratigraphic occurrence, and paleogeographic extend of conglomeratic shorelines of the Falher "C" Member. The reservoir quality coarse-grained sandstones and conglomerates, contained within their parasequences C2, were deposited along shorelines during a relative lowstand and a period of increased sediment supply coeval with a forced regression. Hobbs (2004) presents a studied on the along-strike variations of ichnological, sedimentological, and sequence stratigraphic characteristics of the upper Falher and the Notikewin Members. The influence of basement faulting and reef-induced topography on the formation of the Falher "F" conglomerate trend was address by Nodwell (2004) and Nodwell and Hart (2004, 2006). These authors hypothesized that the longshore extent, geographical location, and lithologic composition of the Falher "F" conglomerate trend is controlled by syn-depositional accommodation development and paleobathymetry. An enhanced shore-normal sorting processes influenced by a paleobathymetric feature resulting from differential compaction of the northern edge of the underlying Devonian Gold Creek reef trend was established in order to explain the Falher "E" conglomeratic trend.

Chapter 2: Facies Descriptions and Interpretations

Detailed sedimentological and ichnological descriptions of 42 cores within the study area (Fig. 1.2) permits the subdivision of the Falher "D" into 15 facies. These facies are determined based upon recurring lithologies, physical and biogenic sedimentary structures, and ichnological characteristics. The facies are described in order of increasing (inferred) energy and/or grain size. Individual facies can be present within more than one depositional environment due to internal variability. These descriptions and interpretations provide the basis for recurring facies associations that are used for depositional modeling and mapping.

(2.1) Facies 1a - Bioturbated Silt-rich Mudstone

Physical Sedimentary Structures - Facies 1a contains siltstone, silty mudstone, and rare very fine-grained sandstone forming a wide variety of sedimentary structures. The most abundant structures include pin-striped planar parallel laminated to oscillation-rippled (i.e. combined flow ripples) siltstone beds generally not exceeding 5cm in thickness. Combined flow ripples and climbing current-ripples are also common and may show minor rhythmic bedding. Some strongly current rippled siltstones and sandstones have erosional bases. Other prominent sedimentary structures include wavy through lenticular bedding, which generally contains abundant syneresis cracks and minor mudcracks (Fig. 2.1b/c). Convolute laminations are locally abundant and deformation occurs in localized zones less than 10 cm in thickness (Fig. 2.1a). Organic-rich laminae and siderized intervals are common but not abundant. Rooted and coal-rich horizons are present locally and can be relatively abundant.

Biogenic Sedimentary Structures - Facies 1a contains common bioturbation throughout and localized intervals that are completely reworked. Typical trace fossils within Facies 1a include *Teichichnus* (c-a), *Planolites* (c-m), *Chondrites* (c), *Thalassinoides* (r), *Diplocraterion* (r-c), and *Skolithos* (r). Of these trace fossils *Teichichnus, Planolites*, and *Chondrites* burrows are the most common and are frequently found together. *Teichichnus* burrows appear in cross-section as a vertical series of concave-up crescentric

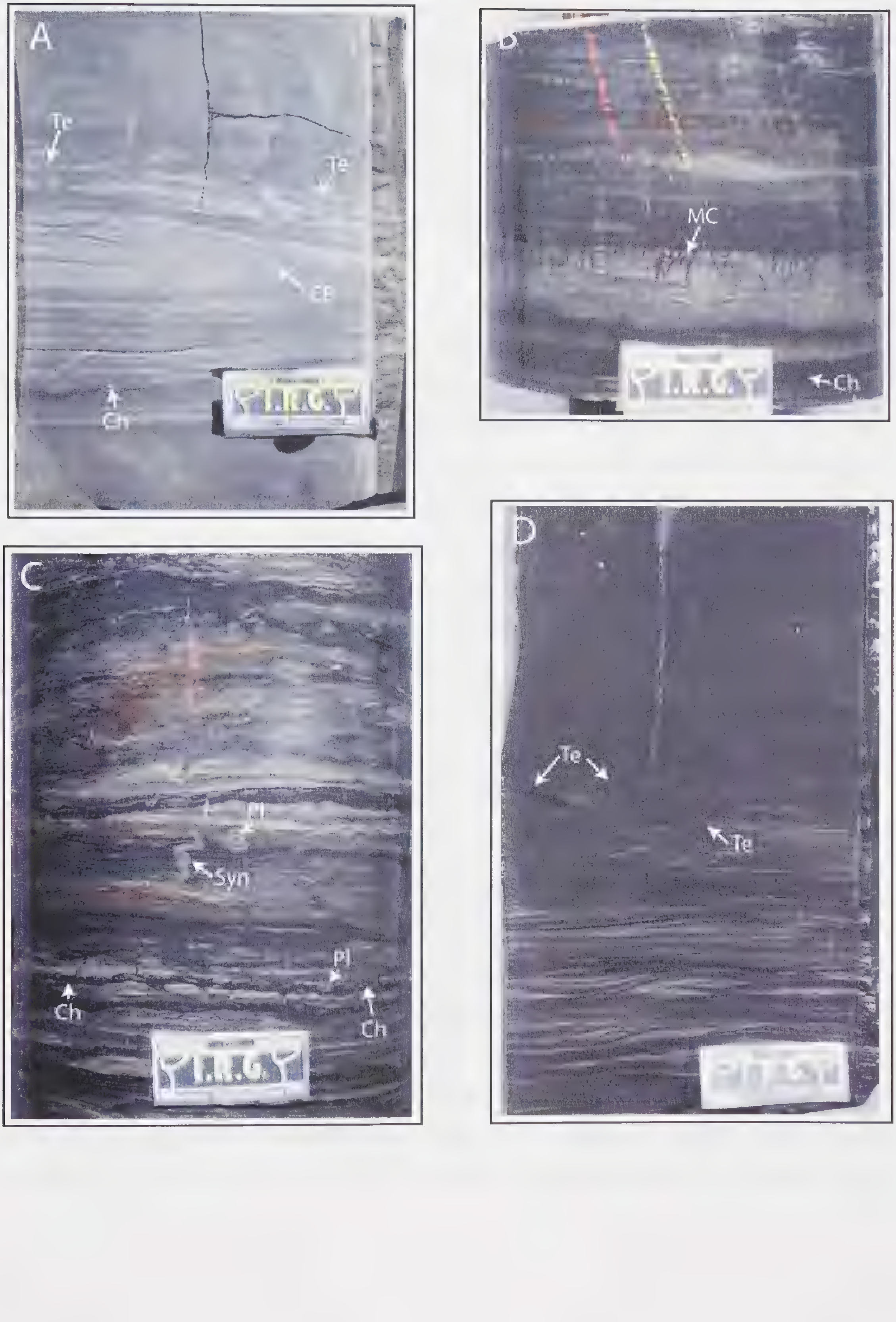
Facies	Lithology	Physical Structures	Biogenic Structures	Depositional Environment
1a	Bioturbated Silt-Rich Mudstone	Planar to wavy lenticular siltstone laminae, current-rippled	Pl(c), Te(c), Ch(c), Di(r), Th(r)	Lagoon, Interdistributary Bay
1b	Unburrowed Silty Mudstone and Massive Shale	Planar to wavy lenticular siltstone laminae, syneresis cracks, deformation, pyrite nodules	Pl(r),Th(r), Bivalve Shells(r)	Lagoon, Interdistributary Bay, Delta-Plain, Floodplain, Bay-Fill
2	Sandy Siltstone	Massive, convolute laminations, large angular mudstone rip-up clasts	None	Fluvial Overbank
3a	Bioturbated Interbedded Mudstone and Very Fine-Grained Sandstone	Planar/sub-planar sandstone laminations, bioturbated mudstone	Th(c), Ch(m), Pl,(m), Ch(c), Hm(r), Te(c), Pa(c), Op(r), Di(r), Rh(r), Sch(r), fu(c)	Upper Offshore to Distal Lower Shoreface, Lagoon
3b	Non-bioturbated Interbedded Mudstone and Fine-Grained Sandstone	Wavy to current-rippled lenticular laminae, planar to massive mudstone, rare bioturbation	Pl(r), Te(r)	Prodelta to Distal Delta-Front, Lagoonal, Delta-Plain
4a	Very Fine-Grained Hummocky Cross-Stratified Sandstone (HCS/SCS)	Planar parallel to sub-planar (HCS) VWS sandstone, rare organic laminae, rare thin Cgl beds	Pa(c),Paramac(c), Op(r), Co(r), Sch(r), Di(r), Te(r), Th(r), As(r), Cryptic (a)	Distal to Proximal Lower Shoreface, Distal Delta-Front
4b	Sporadically Bioturbated Very Fine- to Fine-Grained Trough Cross-Bedded Sandstone	Trough cross-bedded, MS-WS, common pebble stringers, common thin PS Cgl beds	Pa(m), Di(r), Op(r), Sk(r), Co(r), Ra(r), fu(r), Sch(r), Th(r), Ma(r)	Distal to Proximal Upper Shoreface, Proximal Delta-Front

Table 2.1 – Facies summary from Chapter Two.

Facies	Lithology	Description	Biogenic Structures	Depositional Environment
4c	Very Fine-Grained Planar Laminated Sandstone	VWS-MS, massive to planar, rare pebbles, upper portions rooted	None	Upper Shoreface Foreshore, Fluvial, Backshore
5	Fine- to Coarse-Grained Trough Cross-bedded and Planar Laminated Sandstone	PS-WS, massive to cross-bedded, large angular mst rip-up clasts, coal lenses, fining-upward trend	None	Fluvial Channel Fill
6	Very Coarse-Grained Sandstone	VWS, cL-vcU planar to sub-planar sandstone, rare cross-beds	None	Reworked Delta-Front, Foreshore, Upper Shoreface
7	Interbedded Sandstone and Conglomerate	vfL-fU trough cross-bedded sandstone, pebble stringers, VPS-WS, matrix-rich Cgl	Pa(r)	Upper Shoreface, Proximal Delta-Front, Delta-Plain, Fluvial
8a	Unimodal Chert Granule Conglomerate	VWS, no matrix, granule - small pebble, mostly massive, rare imbrication	None	Reworked Delta-Front/ Delta-Plain, Foreshore
8b	Bimodal Chert Conglomerate	Bimodal, ~30% vfL-fU matrix, 1-2cm well rounded pebbles, massive to cross-bedded imbrication	None	Upper Shoreface, Foreshore
8c	Polymodal Chert Conglomerate	VPS-MS, ~35% vfU matrix, well rounded, massive to cross-bedded imbrication	None	Proximal Delta-Front, Delta-Plain, Fluvial
9	Organic-rich Shale with Interbedded Coal	Thin planar siltstone laminae, rooted, coal lenses, pyrite nodules, deformed	Pedogenic Alteration	Coastal Plain, Floodplain, Swamp

Table 2.1 – Facies summary from Chapter Two continued.

Fig. 2.1 - Selected examples from Facies 1a – Bioturbated Silt-rich Mudstone: (A) Convoluted silt-rich mudstone with *Teichichnus* (Te) and *Chondrites* (Ch) burrows (06-10-68-10W6, 2241.5m); **(B)** 2.5 cm thick siltstone bed with abundant desiccation cracks (MC) encased in a silt-rich mudstone containing common siderite-rich bands and *Chondrites* (Ch) burrows (07-14-68-13W6, 2506.7m); **(C)** Finely interlaminated siltstone and mudstone with common syneresis cracks (Syn) and *Planolites* (Pl) and *Chondrites* (Ch) burrows (07-01-68-12W6, 2430.7m); **(D)** Wavy current-rippled silt-rich mudstone with abundant *Teichichnus* (Te) burrows. This monospecific *Teichichnus* assemblage has completely reworked the upper 6 cm of this unit (06-10-68-10W6, 2247.7m).


A
Te
Te
Cp
Ch
B
MC
Ch
C
Pl
Syn
Pl
Ch
Ch
D
Te
Te

laminae cross-cutting interbedded sand and shale beds (Pemberton et al., 2007). The burrow diameter tends to be less than 1 cm and the length is generally less than 10 cm in length. *Planolites* and *Chondrites* burrows are circular to elliptical in cross-section and are less than 1 cm and 1 mm in diameter respectively. Both vertical and horizontal burrows are common throughout. Ichnogenera are relatively small in size and generally have very low diversities. Intervals of abundant reworking by only one ichnofossil (e.g. *Teichichnus*) are abundant and represent the most common form of bioturbation. Therefore, even though trace fossil diversities tend to be very low, bioturbation intensities can be locally very high.

Interpretation – The overall fine-grained nature of this facies indicates low-energy conditions (Pemberton and Wightman, 1992). Thin rippled siltstones and sandstones represent intermittent periods of weak wave and current activity in a generally quiet environment. These sedimentary structures indicate both common uni- and multi-directional flow. Uni-direction flow can occurs as a result of increased fluvial input, tidal activity, and storm surges. Multi-directional flow indicates weak wave influence within the quiet water sheltered conditions. Rare, however locally common, rhythmically bedded combined flow rippled siltstone units, indicates a weak tidal influence. The presence of syneresis cracks indicates frequent fluctuating salinity conditions, most likely resulting from large influxes of freshwater (Burst, 1965; Plummer and Gostin, 1981). Syneresis cracks are normally associated with siltstone and/or sandstone beds, and therefore and interpreted to be associated with the deposition of slightly coarser sediment (Pemberton and Wightman, 1992). The trace fossil assemblage is a low diversity mixed *Skolithos-Cruziana* ichnofacies (MacEachern and Pemberton, 1992). The presence of thoroughly reworked intervals by one ichnogenera indicates a stressful environment (Pemberton and Wightman, 1992). This assemblage likely indicates a shallow, subtidal environment and the relatively low ichnological diversity implies the environment was restricted (Ekdale et al, 1984; Beynon et al., 1988). This trace fossil suite represents an impoverished marine suite with no non-marine traces identified. Environment stresses, such as salinity, temperature, oxygen content, and turbidity, are a result of fluctuating environment conditions associated from variations in the amount of freshwater input

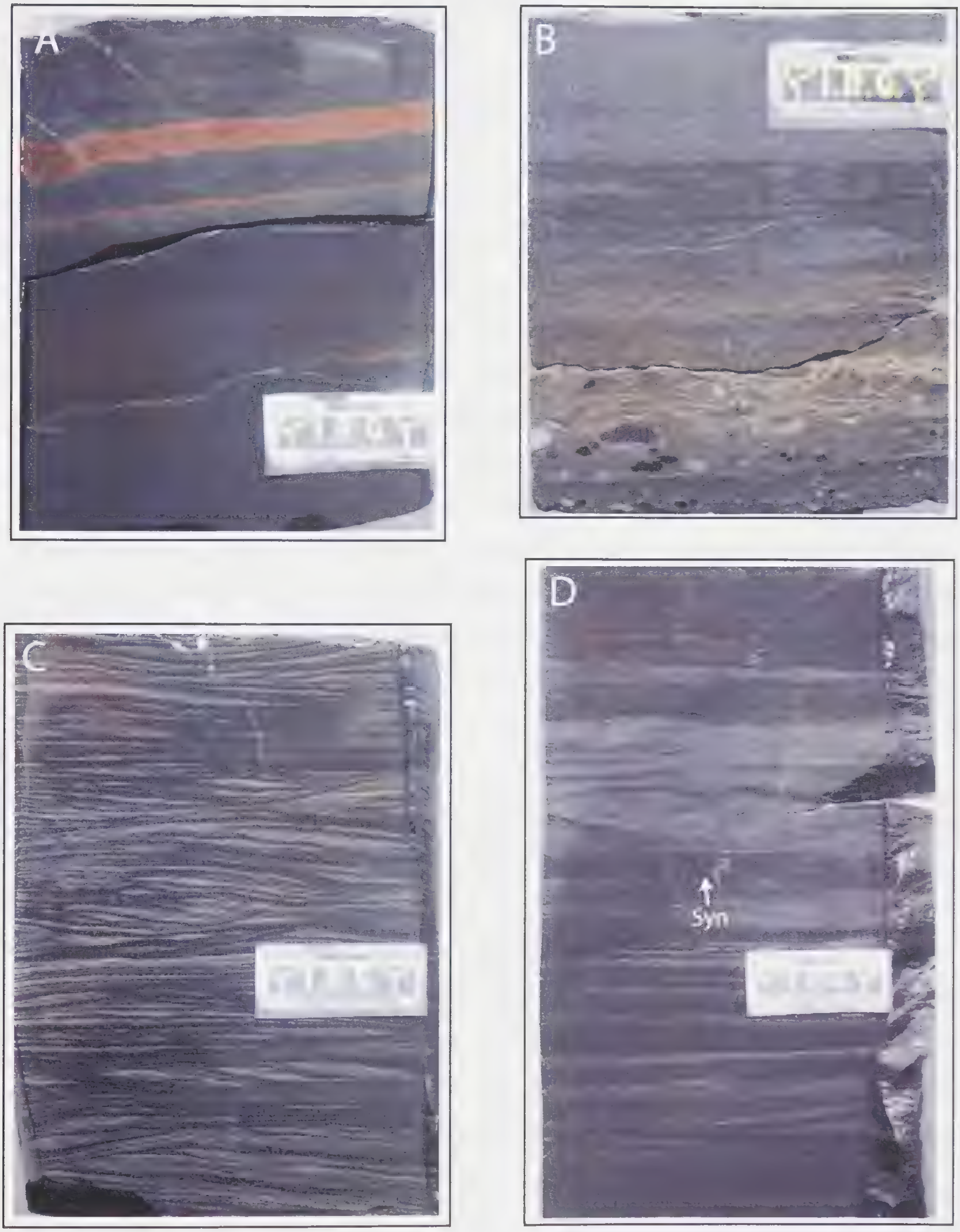
from rivers and run-off from land, rainfall, evaporation, tidal range and salinity of ocean, morphology of coastal areas, and differences in wind direction and velocity (Pemberton and Wightman, 1992). This ichnological suite is dominated by opportunistic (r-selected behavior) trophic generalists (Pemberton and Wightman, 1992) typical of an organism in a stressful environment. These characteristics are consistent with previously described brackish-water ichnological assemblages (e.g. Wightman et al., 1987; Beynon et al., 1988; Beynon and Pemberton, 1992; Pemberton and Wightman, 1992; MacEachern, 2000; Pemberton et al., 2001). Considering the sedimentological and ichnological information present above, Facies 1a is interpreted to represent localized backshore and interdistributary bay deposits including lagoonal, tidal flat, marsh, and protected bay environments (e.g. Pemberton and Wightman, 1992; Pemberton et al., 2001). Therefore, this facies potentially represents a wide variety of brackish-water depositional environment within the marginal marine realm.

(2.2) Facies 1b - Unburrowed Silt-rich Mudstones

Physical Sedimentary Structures - Facies 1b contains physical sedimentary structures very similar to Facies 1a, but is rarely burrowed. This facies also contains a higher proportion of massive mudstone and very rare oscillation-rippled siltstone (Fig. 2.2a). Wavy lenticular bedding is common in Facies 1b. Abundant syneresis cracks are commonly observed (Fig. 2.2d). Combined flow ripples and climbing current-rippled siltstones are very common within Facies 1b and also contain common micro faults Fig. 2.2c). Rhythmic bedding is more common than with Facies 1a but still only rarely present. Soft sediment deformation is localized into 5-15 cm intervals. Intervals with massive mudstone contain pyrite-rich nodules and laminae, and siderite. Organic detritus is commonly associated with locally abundant rooted and coaly intervals.

Biogenic Sedimentary Structures - This facies contains very little bioturbation, with only very rare *Planolites* and *Thalassinoides* present. Rare bivalve shells are also present within the muddiest intervals and are associated with the presence of pyrite nodules.

Fig. 2.2 - Selected examples from Facies 1b – Unburrowed Silt-rich Mudstone: (A) Nearly massive mudstone with siderite-rich laminations ranging in thickness from pin-striped to 1.5 cm (06-10-68-10W6, 2257.9m); **(B)** Planar laminated silt-rich mudstone with abundant pyrite-rich laminae and small pebbles (13-17-68-10W6, 2210.5m); **(C)** Combined flow ripples and climbing-ripples in a silt-rich mudstone. Current ripples appear bi-directional and regularly spaced indicating a tidal environment (06-10-68-10W6, 2249.5m); **(D)** Planar laminated and oscillation rippled silt-rich mudstone with abundant syneresis cracks (Syn) (06-10-68-10W6, 2240.7m).


A
B
C
D
Syn

Interpretation – As with Facies 1a, the overall fine-grained nature of the facies indicates low-energy conditions. The presence of uni-directional sedimentary structures, such as current-ripples and combined flow-ripples, indicate periodic current activity and the presence of rare oscillation ripples implies relatively weak wave activity. Climbing current ripples and soft sediment deformation indicate episodic increases in the rate of deposition (Bhattacharya and Walker, 1992). The restricted ichnological expression of Facies 1b indicates a relatively more stressful environment than Facies 1a (Pemberton and Wightman, 1992). This is likely due to extreme environmental stresses tied directly to salinity fluctuations as a result of increased fluvial input (Pemberton et al., 2001). Increased fluvial input would lead to an overall freshening of the water column with more numerous and greater salinity variations. Due to the sedimentological similarities with Facies 1a, this facies is interpreted to represent similar marginal-marine brackish-water environments. However, the reduced diversity and abundant of trace fossils indicates a highly stressful environment (Pemberton and Wightman, 1992; MacEachern, 2000; Pemberton et al., 2001; MacEachern et al., in press). Facies 1b is interpreted to represent primarily interdistributary bay-fills located within the delta plain, central bay-fill within sheltered lagoonal environments, and to a lesser extent floodplain depositional environment (Pemberton and Wightman, 1992; Reinson, 1992).

(2.3) Facies 2 - Sandy Siltstone

Physical Sedimentary Structures - Facies 2 is defined by massive siltstone and more rarely very fine lower to fine lower sandstone with interbedded organic-rich wavy to deformed mudstone beds (Fig. 2.3). Large angular mudstone clasts, 0.3 cm - 10 cm in size, are locally abundant and common within facies 2 (Fig. 2.3b/d). These mudstone clasts are generally massive, organic-rich, and deformed themselves. Soft sediment deformation is locally common and tends to be associated with intervals of pedogenic alteration (rooting). Siltstone and sandstone beds that are not massive or deformed generally include planar parallel to current-rippled laminations. Sandstone/siltstone dykes and coal lenses are rare to locally abundant.

Fig. 2.3 - Selected examples from Facies 2 – Sandy Siltstone: (A) Planar laminated to oscillation rippled muddy siltstone with minor soft sediment deformation and possible sandstone dyke (SD) (13-17-68-10W6, 2222.1m); **(B)** Massive sandy siltstone containing large organic-rich mudstone clast (13-17-68-10W6, 2218.8m); **(C)** Convoluted muddy siltstone with common coal lenses (06-21-67-10W6, 2461.6m); **(D)** Massive sandy siltstone with abundant angular mudstone clasts ranging in size from 0.5cm to greater than 6 cm in diameter. This is interpreted to represent bank collapse associated with fluvial channels (13-17-68-10W6, 2220.6m).


A
Coal
D

Biogenic Sedimentary Structures - Facies 2 is not bioturbated but does contain abundant rooting, which leads to pervasive pedogenic alteration.

Interpretation - This facies is interpreted to represent proximal fluvial overbank deposits within the upper delta plain and coastal plain (Bhattacharya and Walker, 1991; MacEachern, 2000). This interpretation is supported by the lack of bioturbation, which indicates freshwater conditions, and by its close association with sandy fluvial channel-fill deposits (Facies 5). The massive siltstone beds with abundant large angular mudstone clasts are interpreted to be the result of bank collapse within the channel margins. Penecontemporaneous soft sediment deformation is common and forms as a result of pedogenic alteration (Wadsworth et al., 2003). Although not volumetrically significant, this facies generally indicates the presences of large fluvial channels in the vicinity.

(2.4) Facies 3a - Bioturbated Interbedded Mudstone and Fine-grained Sandstone

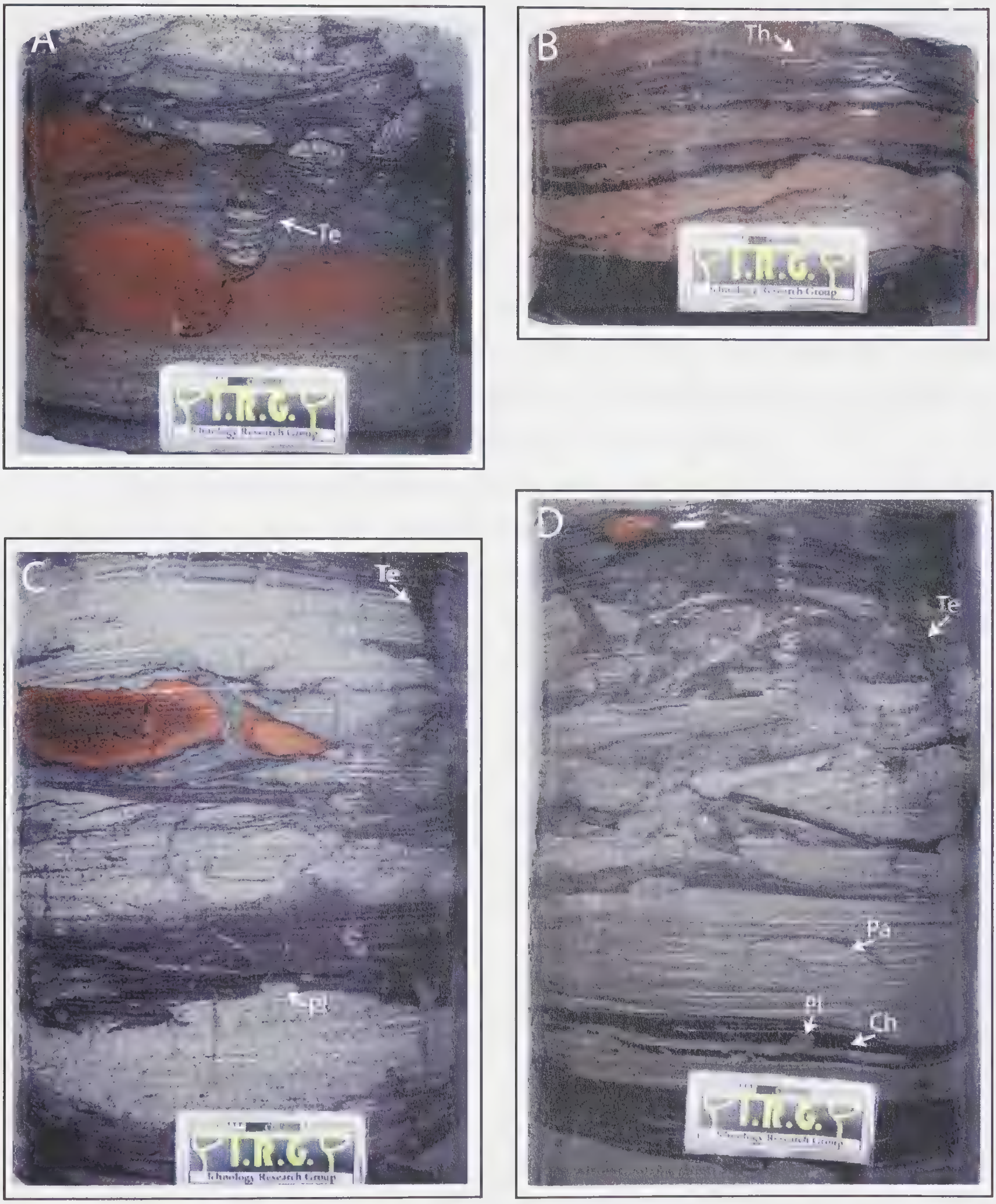
Physical Sedimentary Structures - Facies3a consists of interbedded very fine-grained sandstone and silty mudstone (Fig. 2.4a). This facies is present within two very distinct depositional environments and therefore contains very different sedimentary structures. The most distal expression of facies 3a consists of sharp erosionally based sub-planar to planar parallel laminated sandstones. These sandstone beds generally increase in thickness upward from roughly 3 cm until there are no intervening mudstone beds, thereby grading into facies 4a. These structures are interpreted as hummocky cross-stratification (HCS) formed during storm deposition (Harms et al., 1975; Walker et al., 1983; Arnott and Southard, 1990). Rare mudstone rip-up clasts and organic-rich laminations are locally abundant. The mudstones contain thin planar to wavy, and rare lenticular, sandstone laminae. Siderite is locally common and forms 1-3 cm bands as well as large clasts (Fig. 2.5). Sedimentary structures are generally difficult to observe within the muddier intervals due to the high degree of biogenic reworking.

The proximal expression of facies 3a comprises of a sandy version of facies 1a and shares many of the same characteristics (Fig. 2.4d). Combined flow ripples and planar laminations are common in the sandstone beds. The interbedded silt-rich mudstones are generally planar laminated however combined flow ripples as also

Fig. 2.4 - Selected examples from Facies 3a – Bioturbated Interbedded Mudstone and Fine-grained Sandstone (non-deltaic): (A) Planar laminated muddy sandstone containing *Teichichnus* and *Cylindrichnus* burrows interpreted to be present within the distal lower shoreface (10-31-68-10W6, 2166.0m); **(B)** Plan view of bedding surface containing greater than 20 vertical sand-filled *Diplocraterion* burrows (06-25-68-11W6, 2209.8m); **(C)** *Diplocraterion, Planolites,* and *Chondrites* burrows in a moderately bioturbated interbedded mudstone and sandstone (06-19-68-12W6, 2433.6m); **(D)** Finely interlaminated mudstone and sandstone with common soft sediment deformation and rare *Chondrites* burrows (07-26-69-09W6, 1879.9m); **(B-D)** Interpreted to have formed within a lagoonal brackish-water environment.


A
Cy
Te
Dl
D
CB

Fig. 2.5 - Selected examples from Facies 3a – Bioturbated Interbedded Mudstone and Fine-grained Sandstone (deltaic influenced): (A) Planar laminated and oscillation rippled muddy sandstone with *Teichichnus* burrows and siderite-rich beds (07-26-69-09W6, 1888.5m); **(B)** Oscillation-rippled interbedded mudstone and sandstone with rare *Thalassinoides* burrows (07-26-69-09W6, 1899.8m); **(C)** Interbedded mudstone and sandstone with minor siderite clasts and bioturbation including *Teichichnus*, *Planolites,* and unidentified vertical mud filled burrows (07-26-69-09W6, 1886.3m); **(D)** Interbedded oscillation rippled mudstone and sandstone containing soft sediment deformation and minor bioturbation including *Teichichnus, Planolites, Palaeophycus*, and *Chondrites* (07-26-69-09W6, 1894.7m); **(A-D)** Interpreted to have formed within the distal delta front due to the increased amount of mud and silt, presence of convolute bedding, and overall stressed ichnological suite.


A
Te
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common. They contain common syneresis cracks as well as locally abundant rooting and micro faulting. Soft sediment deformation is also present however not abundant.

Biogenic Sedimentary Structures - There are two distinct ichnological assemblages present within facies 3a that correspond to the two distinct depositional environments present within this facies. The first assemblage is present within the HCS sandstones and intervening mudstones and includes *Planolites* (m), *Chondrites* (c), *Helminthopsis* (c), *Thalassinoides* (r), *Palaeophycus* (c), *Schaubcylindrichnus* (r), *Diplocraterion* (r), *Teichichnus* (r), *Ophiomorpha* (r), and fugichnia (c). Muddy sandstones are typically intensely burrowed with the greatest diversity of trace fossils. Thicker laminated sandstones tend to be unburrowed or weakly burrowed. However, bioturbation intensity and diversity can be highly variable. Overall, this suite represents the fully marine proximal *Cruziana* ichnofacies (MacEachern and Pemberton, 1992).

The second assemblage observed within facies 3a consists of *Planolites* (c), *Chondrites* (c), *Thalassinoides* (r), *Teichichnus* (m), and *Diplocraterion* (r). Ichnogenera tend to be relatively small in size and generally have very low diversities (Fig. 2.4c). Ichnological suites tend to be dominated by single form as illustrated by monospecific *Teichichnus* and *Diplocraterion* assemblages (Fig. 2.4b). This suite represents a low-diversity stressed *Cruziana* ichnofacies similar to that of Facies 1a (Pemberton and Wightman, 1992).

Interpretation – Interbedded HCS sandstones and thoroughly bioturbated mudstones are typical of the distal lower shoreface (MacEachern and Pemberton, 1992). This interpretation is supported by the presence of a relatively diverse proximal *Cruziana* assemblage (MacEachern and Pemberton, 1992; Pemberton et al., 1992e; Pemberton et al., 2001). The distal lower shoreface lies just above fair-weather wave base. The presence of thick storm amalgamated HCS sandstones indicates a strongly storm-dominated environment (Harms et al., 1975; Walker et al., 1983; MacEachern and Pemberton, 1992; Walker and Plint, 1992; Saunders et al., 1994). Within this environment two very different sets of depositional processes are at work at any given time. The first is high-energy storm deposition. High-energy storms, such as hurricanes,

result in the basinward movement of large quantities of sand and mud (Reading, 1989; Walker and Plint, 1992). These storms also typically result in the erosion of previously deposited fair-weather sediments. Thick sharp-based HCS sandstone beds are the recognized product of such storm deposition (Leckie and Walker, 1982; Walker et al., 1983; Walker and Plint, 1992). Post-storm biological reworking occurs as opportunistic organisms exploit the newly deposited sand and mud (MacEachern and Pemberton, 1992). In shallower water, a greater number of storms, which are more powerful, result in the amalgamation of storm beds leaving no preserved record of fair-weather conditions (Facies 4a). The second set of sedimentary processes are coupled to fair-weather or inter-storm sedimentation. This consists of mostly mud deposition from post-storm suspension fall-out and under oscillatory wave action (fair-weather waves) (MacEachern and Pemberton, 1992). Under these conditions bioturbation tends to be intense due to the replacement of opportunistic communities by deposit-feeding organisms from an equilibrium community better suited to the ambient environmental conditions (Pemberton et al., 1992c; Pemberton and MacEachern, 1997; MacEachern et al., 2005). The interbedding of the fair-weather bioturbated mudstones ("scram") and the generally non-bioturbated HCS sandstones ("lam") is referred to as "lam-scram" (Pemberton et al., 1992c). In the case of the Falher D Member, pervasively bioturbated mudstones are not generally visible due to the fact that most cored intervals contain no deposits interpreted to have accumulated below storm wave base.

This facies contains a second ichnological assemblage consisting of relatively smaller traces with a low-diversity stressed *Cruziana* suite (Pemberton and Wightman, 1992). Sedimentary structures associated with this trace fossil assemblage include syneresis cracks, combined flow ripples, soft sediment deformation, and rare rooting. The ichnology and sedimentary structures are consistent with the brackish-water environment described in Facies 1a (Pemberton and Wightman, 1992). The brackish-water deposits of Facies 3a are a sandier version of Facies 1a and share a number of characteristics. Hence they will not be described again.

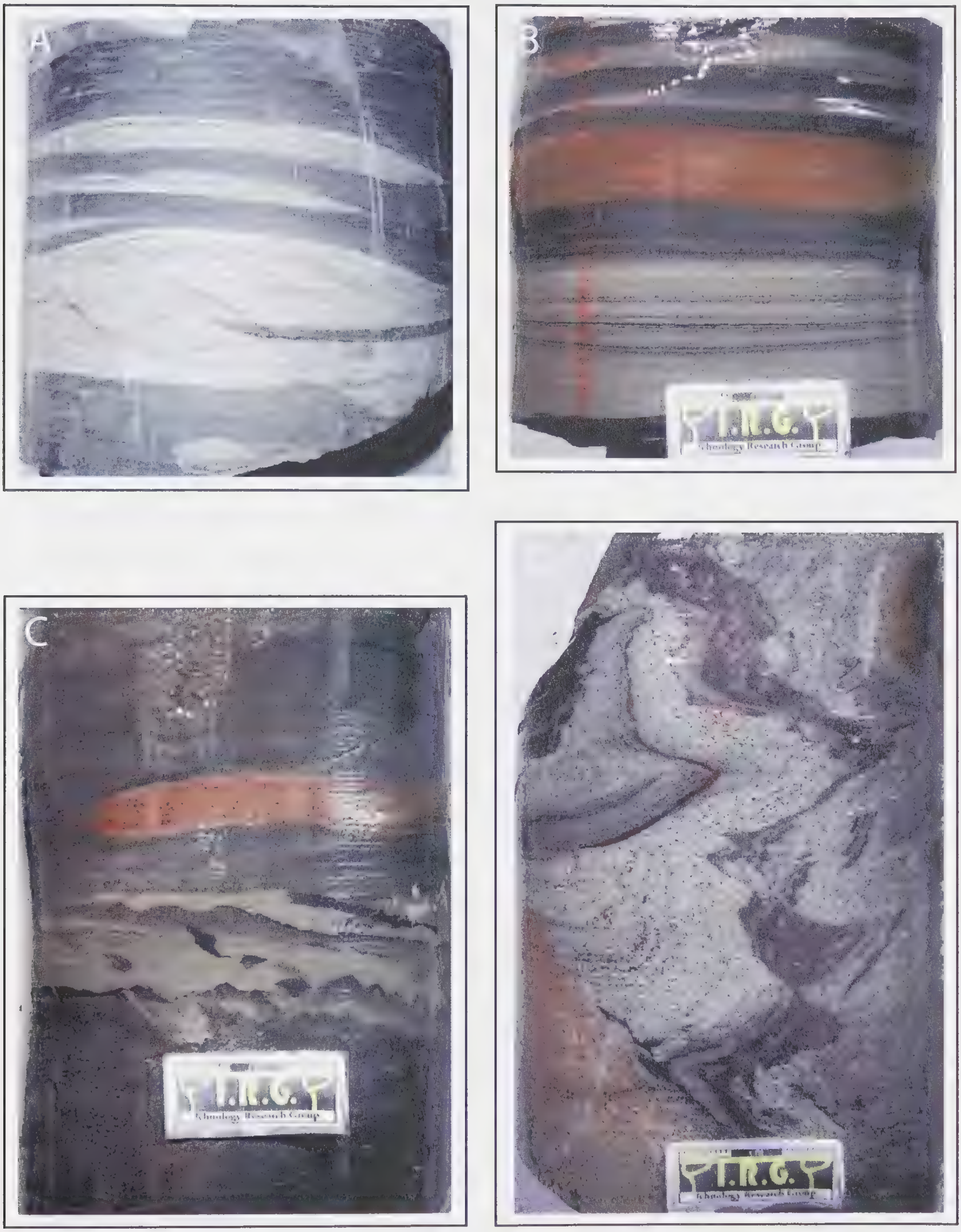
(2.5) Facies 3b - Non-bioturbated Interbedded Mudstone and Fine-grained Sandstone

Physical Sedimentary Structures - Facies 3b consists of interbedded very fine-grained sandstone and non-bioturbated silt-rich mudstone. This facies contains a number of characteristics similar to those of Facies 3a. Facies 3b is different from Facies 3a only in the amount and type of bioturbation, which will be described below, and the relative proportion of mudstone. The most common sedimentary structures include current-rippled and planar parallel laminations with lesser amounts of lenticular bedding and oscillation-ripples (Fig. 2.6b-d). Deformation is also very common, affecting 2 cm to 20 cm thick intervals (Fig. 2.6d). The very fine-grained sandstones also contain common organic-rich laminae as well as rare mudstone rip-up clasts. Oscillation-rippled to planar laminated mudstone comprise a much greater proportion of Facies 3b than Facies 3a. These mudstone beds also contain common siderite-rich intervals 1-4 cm in thickness.

Biogenic Sedimentary Structures - This facies contains very little bioturbation, with only very rare *Planolites*, *Thalassinoides,* and *Teichichnus* burrows present. Biogenic reworking is generally confined to the muddier intervals. However, most mudstone beds tend to be non-bioturbated. The thicker sandstone beds may contain rare cryptic bioturbation.

Interpretation – The increased concentration of organic-rich laminae, mudstone rip-up clasts, siderite, syneresis cracks, presence of locally common soft sediment deformation, and reduced diversity and intensity of bioturbation indicate a deltaic setting (Reading, 1989; Bhattacharya and Walker, 1991; Bhattacharya and Walker, 1992; MacEachern and Pemberton, 1992; Gingras et al., 1998, Coates and MacEachern, 1999; Coates and MacEachern, in press). Silty convoluted mudstones tend to be nearly unique to deltaic successions and are related to high sedimentation rates (e.g. Bhattacharya and Walker, 1992; Coates and MacEachern, in press). Organic-rich laminae may represent "phytodetrital pluses" associated with increased river discharge accompanying storm events (Raychaudhuri and Pemberton, 1992; MacEachern 1994; Saunders et al., 1994). Syneresis cracks represent salinity fluctuations most likely related to fresh-water input

Fig. 2.6 - Selected examples from Facies 3b – Non-bioturbated Interbedded Mudstone and Fine-grained Sandstone: (A) Current and oscillation rippled mudstone and sandstone interpreted to have formed in a lagoonal brackish-water environment (15-21-68-08W6, 2052.3m); **(B)** Planar laminated and oscillation rippled mudstone and sandstone with common siderite-rich beds (07-26-69-09W6, 1894.0m); **(C)** Massive to planar laminated muddy sandstone with siderite-rich beds, minor soft sediment deformation, and small angular mudstone rip-up clasts (07-26-69-09W6, 1895.3m); **(D)** Strongly convoluted sandstone and mudstone unit (07-26-69-09W6, 1891.4m); **(B-D)** Interpreted to have formed within the distal delta front due to the increased mud content as well as the lack of bioturbation.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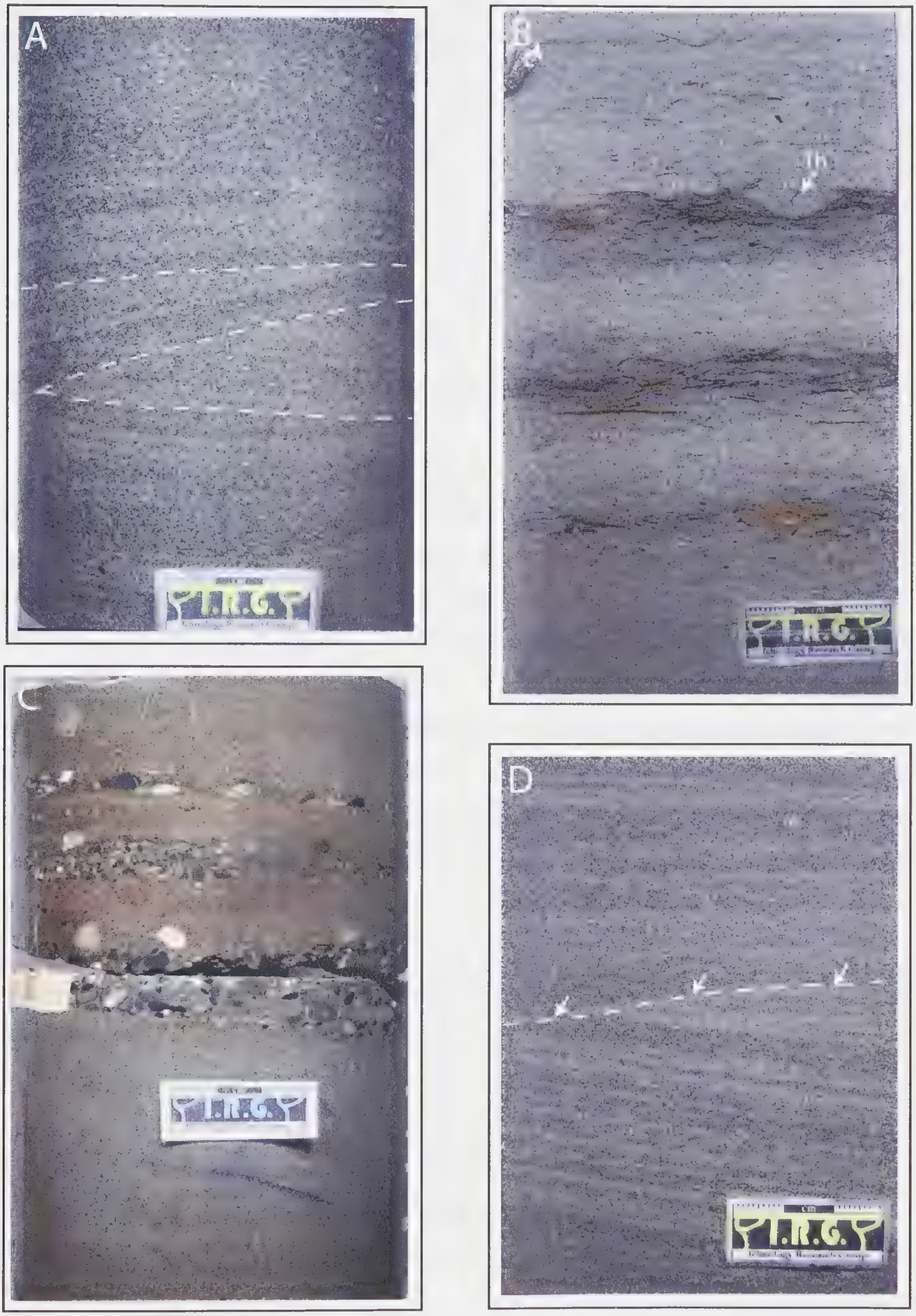
from river discharge (Pemberton and Wightman, 1992). The extreme reduction of the intensity and diversity of bioturbation is likely due to extreme environmental stresses, tied directly to salinity fluctuations as a result of freshwater input (MacEachern et al., 2005; Coates and MacEachern, in press). This will produce thin non-bioturbated mudstone beds, which would in a normal shoreface environment, be moderately to extensively bioturbated. The complete lack of suspension-feeding structures in the sandier intervals is also marked departure from non-deltaic successions. This is especially true for the distal and proximal delta front environments. This is a result of high-suspended loads in the water column near the bed associated with high water turbidity (Gingras et al., 1998; Coates and MacEachern, in press). Fluvial point sources will also supply large quantities of sand and mud to the system. Therefore thicker sand and mud accumulations can be tentively associated with deltaic systems. In general, most sedimentological and ichnological differences between Facies 3a (non-deltaic) and Facies 3b (deltaic) are tied directly to fluvial influence. A proximal prodelta to very distal delta front environment is selected for Facies 3b. This is roughly equivalent along-strike to the distal lower shoreface deposits of Facies 3a. Therefore, Facies 3b is interpreted to be the deltaic equivalent of Facies 3a.

This facies is also formed within proximal brackish-water lagoonal and delta plain environments. This would correspond to a sandier version of Facies 1b. Since these environments are described in detail within other facies descriptions (i.e. Facies 1a and 1b), they are not discussed again.

(2.6) Facies 4a - Very fine-grained Hummocky Cross Stratified Sandstone (HCS/SCS)

Physical Sedimentary Structures - Facies 4a is defined by planar to sub-planar (less than 10 degrees) parallel laminated very fine-grained sandstone (Fig. 2.7). This stratification forms low angle, convex up and down curvilinear laminations in 10 cm - 50 cm thick beds, which tend to have basal erosional surfaces. This is interpreted to represent hummocky cross stratification (HCS) and in the case of only convex downward laminations swaley cross-stratification (SCS) (Harms et al., 1975; Leckie and Walker, 1982; Walker and Plint, 1992). In most cases these structures are only visible as sub-

Fig. 2.7 - Selected examples of physical sedimentary structures from Facies 4a – Very fine-grained Hummocky Cross Stratified Sandstone (HCS/SCS): (A) Cryptically bioturbated hummocky cross-stratified very fine-grained sandstone. Surfaces illustrating truncation are shown with a dashed line (09-16-68-10W6, 2207.0m); **(B)** Organic detritus concentrated along 1-3 cm bands within a massive to weakly sub-planar laminated sandstone. *Thalassinoides* burrow and possible cryptic bioturbation also present (06-15-68-11W6, 2327.1m); **(C)** Thin 0.5-3 cm thick poorly sorted conglomerate beds sharply overlying sub-planar laminated (HCS) sandstone (10-31-68-10W6, 2171.8m); **(D)** Cryptically bioturbated swaley cross-stratified sandstone. Surfaces illustrating truncation are shown with a dashed line and arrows (14-09-68-09W6, 2278.9m).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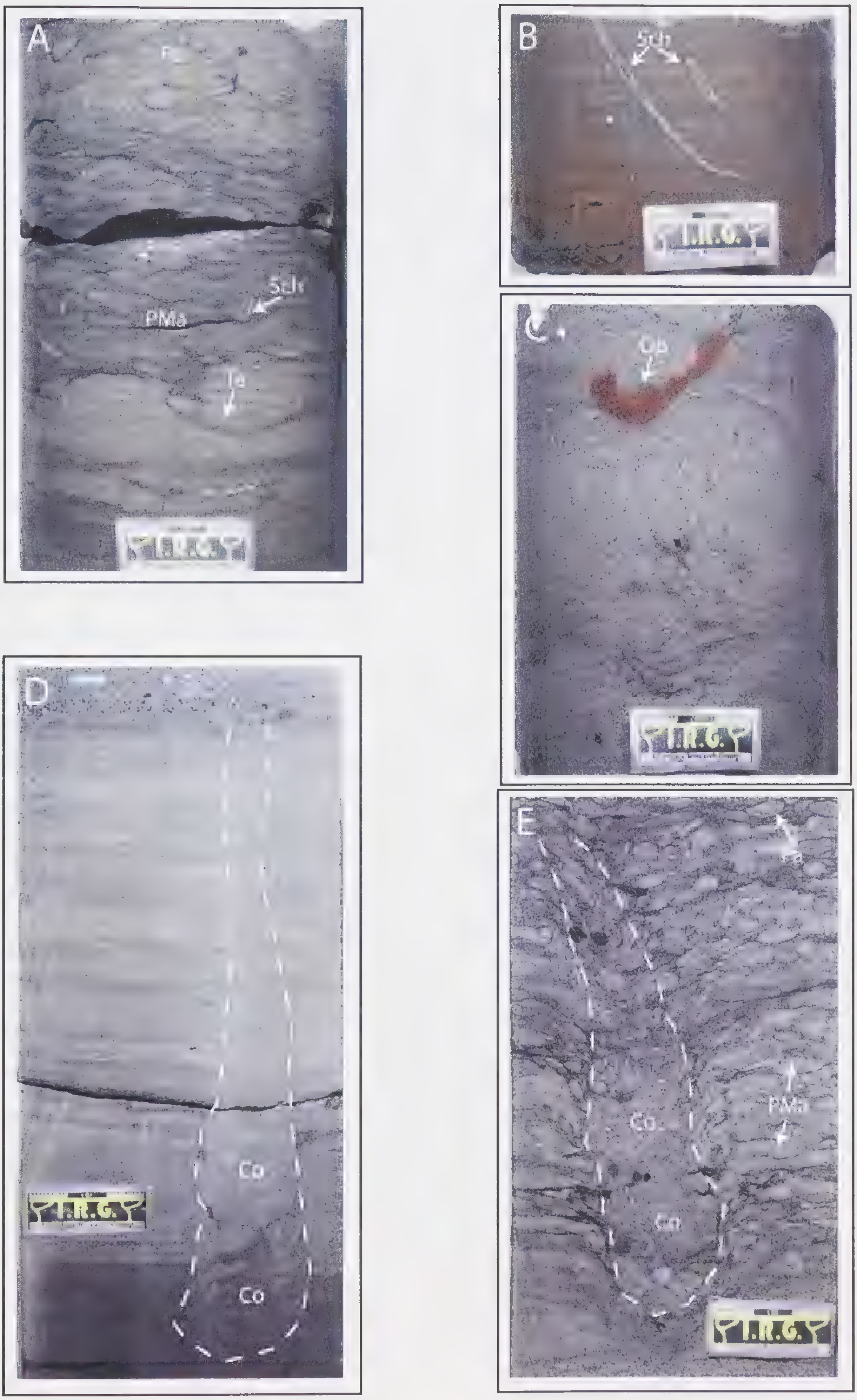
planar laminations that change angle abruptly. These sandstones tend to be very well sorted with only very rare randomly dispersed pebbles. Cross-bedded sandstones are rarely interbedded with erosionally based thin poorly sorted conglomerate beds. Thin mudstone and organic-rich laminae, mudstone rip-up clasts, and wood fragments are uncommon but locally abundant (Fig. 2.7c). Other less common sedimentary structures include oscillation ripples, massive bedding, combined flow-ripples, and planar parallel laminations (not interpreted as HCS/SCS). This facies contains very little mudstone and any that is present occurs near the base of this facies where overlying Facies 3a/3b. Overall facies 4a forms a coarsening upward succession with increasing conglomerate and pebbles upward as well as increasing storm amalgamation.

Biogenic Sedimentary Structures - Bioturbation within this facies is extremely variable in diversity and intensity (Fig. 2.8). A typical assemblage includes cryptic bioturbation (m-a), Para-*Macaronichnus* (c-m), *Macaronichnus segregatis* (c), *Palaeophycus* (c), *Macaronichnus simplicatus* (r), *Ophiomorpha* (r), *Conichnus* (r), *Schaubcylindrichnus* (r-c), *Teichichnus* (r), *Diplocraterion* (r), *Thalassinoides* (r), *Asterosoma* (r), and fugichnia (r). This trace fossil suite represents a mixed *Skolithos-Cruziana* ichnofacies, reflecting a mix of suspension-feeding and deposit-feeding structures (MacEachern and Pemberton, 1992). Trace fossils are commonly preserved along 3 cm - 15 cm intervals where subsequent storm event bed deposition has not resulted in complete erosion. This results in a sandy version of “lam-scram”, as discussed above, with very little “scram” (i.e. bioturbation) (Pemberton et al., 1992c).

Interpretation - Facies 4a is dominated by amalgamated HCS/SCS storm beds preserved within the lower and middle shoreface and equivalent distal to proximal delta front (MacEachern and Pemberton, 1992; Pemberton et al., 1992c; Walker and Plint, 1992). Frequent storm deposition has eroded most fair-weather or inter-storm deposits in this facies due to the shallow water depths and abundance of high-energy storms (Saunders et al., 1994). Under these conditions it is theorized that only deeply penetrating burrows would survive erosion. This may explain the lack of a typical shoreface assemblage. The

Fig. 2.8 - Selected examples of bioturbation from Facies 4a – Very fine-grained Hummocky Cross Stratified Sandstone (HCS/SCS): (A) *Paramacaronichnus, Palaeophycus, Teichichnus,* and *Schaubcylindrichnus* burrows (09-16-68-10W6, 2208.3m); **(B)** Large *Schaubcylindrichnus* burrows within a planar to sub-planar laminated sandstone with small mudstone rip-up clasts near the base (06-25-68-11W6, 2222.0m); **(C)** Siderized *Ophiomorpha* burrows within a massive to completely bioturbated sandstone. Possible *Palaeophycus* and *Paramacaronichnus* burrows are also present (06-25-68-11W6, 2221.6m); **(D)** Large 12-15 cm long *Conichnus* burrow is shown with the dashed line (06-15-68-11W6, 2331.7m); **(E)** Pervasively bioturbated sandstone including *Conichnus, Paramacaronichnus*, and *Palaeophycus* burrows. (?) *Macaronichnus* burrows are also present (14-31-67-08W6, 2315.5m).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abundance of Para-*Macaronichnus* may be due to an increased burrow depth or possibly do to preservation potential (i.e. presence of a "burrowed zone" as discussed below).

Storm influence becomes most prominent in the most proximal expressions of this facies where storm amalgamated SCS beds dominate (Leckie and Walker, 1982). This produces a conundrum due to the fact that the greatest inter-storm preservation occurs as thinly bioturbated intervals of Para-*Macaronichnus*, *Palaeophycus*, and *Macaronichnus segregatis* near the top of the storm amalgamated zone. One would expect this zone to contain a very low preservation potential, however this is not the case. This is consistent with the "burrowed zone" described by Saunders et al., 1994 with one notable discrepancy. The "burrowed zone" in the Falher D member contains no *Rosselia*. The authors gave two possible contributing factors to this zones preservation; (1) A flat shoreface gradient and the formation of several storm-built bars protected the "burrowed zone" from the erosion energy of storms; (2) Rapid accretion of landward adjacent bars buried the inter-storm beds before the next storm occurred (Saunders et al., 1994). This hypothesis is supported by the fact that the internal stratification of Facies 4a within the "burrowed zone" is either planar laminated or weakly oscillation-rippled and is not interpreted as HCS/SCS. The presence of *Macaronichnus* within the lower shoreface is most likely the result of an "oxygen window" that occurs as a post-storm phenomena (Saunders et al., 1989; Pemberton et al., 2001). Within the foreshore, where the presence of *Macaronichnus* is most recognized, oxygenated surface waters circulate several meters into the substrate, carrying with it considerable volumes of organic-matter (Pemberton et al., 2001). These conditions produce a stable environment with an abundant food supply, well below the zone of surface wave influence. This scenario may also be present with the lower shoreface of highly wave-dominated shorelines as well. Another possible explanation is that the trace-making organism may be exploiting a zone of nutrient convergence, with nutrients being supplied from both the landward and seaward sides (Saunders et al., 1994). What is clear is that *Macaronichnus* is present not only in the foreshore but the upper and proximal lower shoreface as well.

Discussion: Para-Macaronichnus

Para-*Macaronichnus* is the most common trace fossil present in Facies 4a and represents a trace that shares characteristics similar to that of *Palaeophycus* and *Macaronichnus segregatis* (Fig. 2.9). It should be noted that the trace fossil referred to as Para-*Macaronichnus* in this thesis has been referred to as *Macaronichnus simplicatus* is most publications. Saunders et al., 1994 described a form of *Macaronichnus,* similar to what I am referring to as Para-*Macaronichnus,* in the Cadotte Member as "commonly taking on unusually large (>1 cm) and heavily mantled proportions". Para-*Macaronichnus* forms 5 to 15 mm wide, 3 to 8 mm high circular shaped horizontal to sub-horizontal (less than 15 degrees) unlined burrows. Burrows display minor grain segregation, far less than typical *Macaronichnus segregatis* burrows, with a concentration of dark mafic grains around the burrow margin. Comparisons between burrowed and un-burrowed sediment show a slightly increased concentration of quartz within the burrow. Burrows generally tend to form in clusters of 2 to 5 individuals burrows with multiple burrows close or interpenetrating. When observed in plan view the burrows appear to be branching and commonly cross-cut older burrows. The clustered nature and close proximity of other burrows supports the proposed branching behavior. Para-*Macaronichnus* burrows are generally closely associated with *Macaronichnus segregatis.* These two trace fossils are commonly observed together. Within bioturbated intervals where both ichnogenera are present, *Macaronichnus segregatis* tends to decrease upwards with the highest concentrations occurring near the base, while Para-*Macaronichnus* burrows tend to increase upwards with the highest concentrations occurring near the top (Fig. 2.9c). In these cases, the lower 2 to 5 cm of a bed tend to have no Para-*Macaronichnus* burrows and the upper 5 to 10 cm tend to have greatly reduced to no *Macaronichnus segregatis* burrows.

As previously stated, Para-*Macaronichnus* shares a number of similarities with both *Palaeophycus* and *Macaronichnus segregatis* (Fig. 2.10). The branching behavior and size of the burrows are characteristic of *Palaeophycus* burrows (Pemberton et al., 2007). However, the large number of burrows present within a given interval, the lack of a mucus lining, and grain segregation are characteristics not present with typical *Palaeophycus* burrows (Pemberton et al., 2001). The grain segregation and mantling of

Fig. 2.9 - Selected examples of Para-*Macaronichnus* from Facies 4a and Facies 4b: **(A)** Plan view of bedding plane illustrating possible branching behavior (shown with black arrows) of Para-*Macaronichnus* burrows (06-13-68-11W6, 2280.5m); **(B)** *Macaronichnus* and Para-*Macaronichnus* burrows tend to be associated with the *Macaronichnus* burrows transitioning upwards into Para-*Macaronichnus* burrows (06-15-68-11W6, 2330.0m); **(C)** Abundant *Macaronichnus* burrows in the lower half of the photo with abundant Para-*Macaronichnus* and possible *Palaeophycus* burrows in the upper half. Some of the Para-*macaronichnus* burrows appear to be siderized (06-15-68-11W6, 2328.7m); **(D)** *Macaronichnus* burrows and cryptic bioturbation within the lower shoreface (14-31-67-08W6, 2317.8m).


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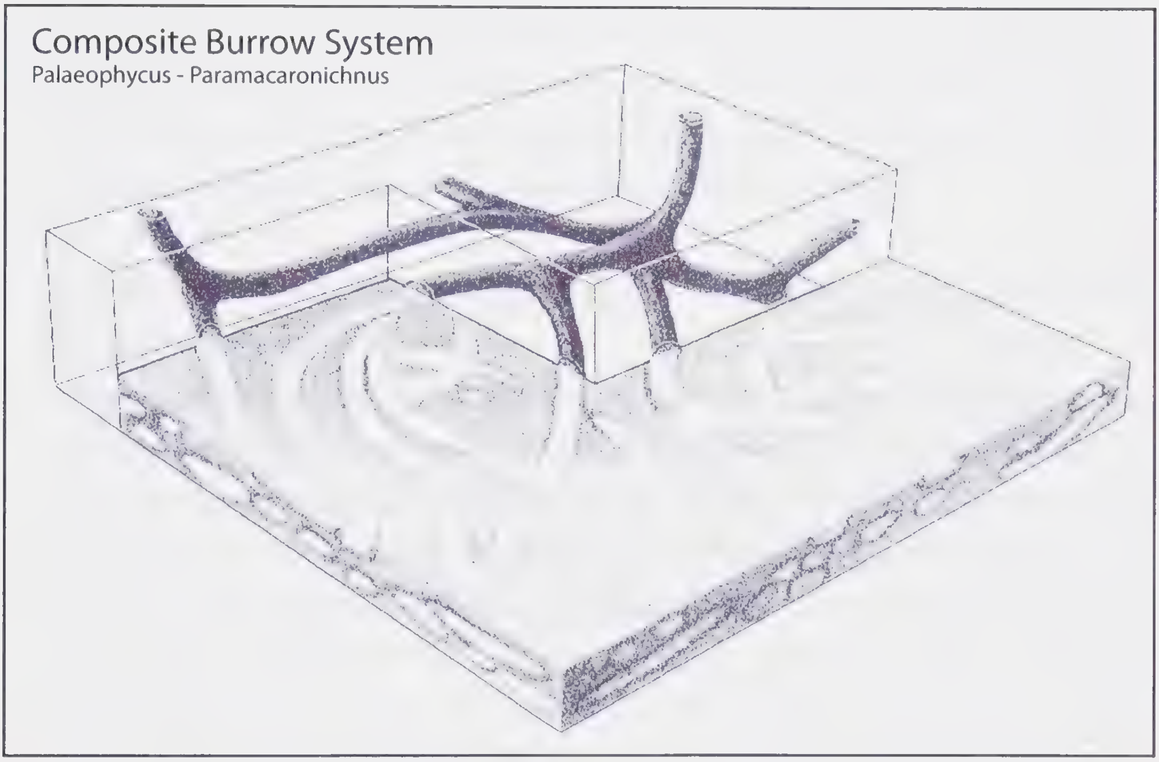

Fig. 2.10 - Idealized sketch of a *Palaeophycus* - Para-*Macaronichnus* burrow system (Drawn by Tom Saunders).

burrows with mafic grains as well as the large number of burrows present are characteristics shared by *Macaronichnus segregatis* (Clifton and Thompson, 1978; Saunders, 1989; Pemberton et al., 2001). However, *Macaronichnus* burrows do not display branching geometries and grain segregation is much lower than one would expect within a typical burrow network (Fig. 2.9a). It is theorized that both traces are produced by the same organism, most likely some form of polychaete. In this instance the *Macaronichnus segregatis* burrows would be produced by the juvenile forms of the species, while the adult forms would produce the much larger Para-*Macaronichnus* burrows (Personal communication Tom Saunders, 2007). This would explain the close association between the two ichnogenera as well as the size differences. The reduced grain segregation in Para-*Macaronichnus* burrows may be a function of increased efficiency with age (Personal communication Tom Saunders, 2007).

(2.7) Facies 4b – Sporadically Bioturbated Very fine- to fine-grained Trough Cross-bedded Sandstone

Physical Sedimentary Structures - Facies 4b contains very fine upper to fine lower trough cross-bedded sandstone with common to abundant dispersed pebbles (Fig. 2.11). The grain size and the occurrence of pebbles increase upwards. Trough cross-stratified beds, generally 3 cm - 10 cm thick, reflect migration of subaqueous 3-dimensional dunes. Most beds are sharp-based and display significant erosion. This results in the formation of erosionally amalgamated beds with cross-bedding oriented in multiple directions. Interbedded medium to coarse sand stringers and thin conglomerate beds are common and generally increase upward. Sorting of the sandstones generally varies from moderately to poorly sorted and most clasts are subrounded to rounded. Organic detritus, coal fragments, and wood fragments are all locally common and found along bedding planes. Oscillation-rippled sandstones are rare and decrease upwards. Intervals of planar to sub-planar parallel laminations are common and tend to be found near the top of the facies. Current-rippled sandstones are locally common.

Biogenic Sedimentary Structures - Bioturbation in facies 4b is sporadically distributed and contains low diversities of ichnogenera (Fig. 2.12). Typical biogenic sedimentary

Fig. 2.11 - Selected examples of physical sedimentary structures from Facies 4b – Sporadically Bioturbated Very fine- to fine-grained Trough Cross-bedded Sandstone: (A) Trough cross-bedded sandstone containing Para-*Macaronichnus* burrows overlain by a moderately sorted conglomerate (09-02-68-13W6, 2588.1m); **(B)** Pebbly trough cross-bedded sandstone with medium-grained sand to pebble sized stringers (01-10-68-09W6, 2242.8m); **(C)** Planar laminated to cross-bedded fine- to medium-grained sandstone (01-10-68-09W6, 2244.7m); **(D)** Fine-grained trough cross-bedded sandstone with large randomly dispersed pebbles and a 2 cm thick sharp-based normally graded conglomerate bed (11-07-68-12W6, 2505.5m).

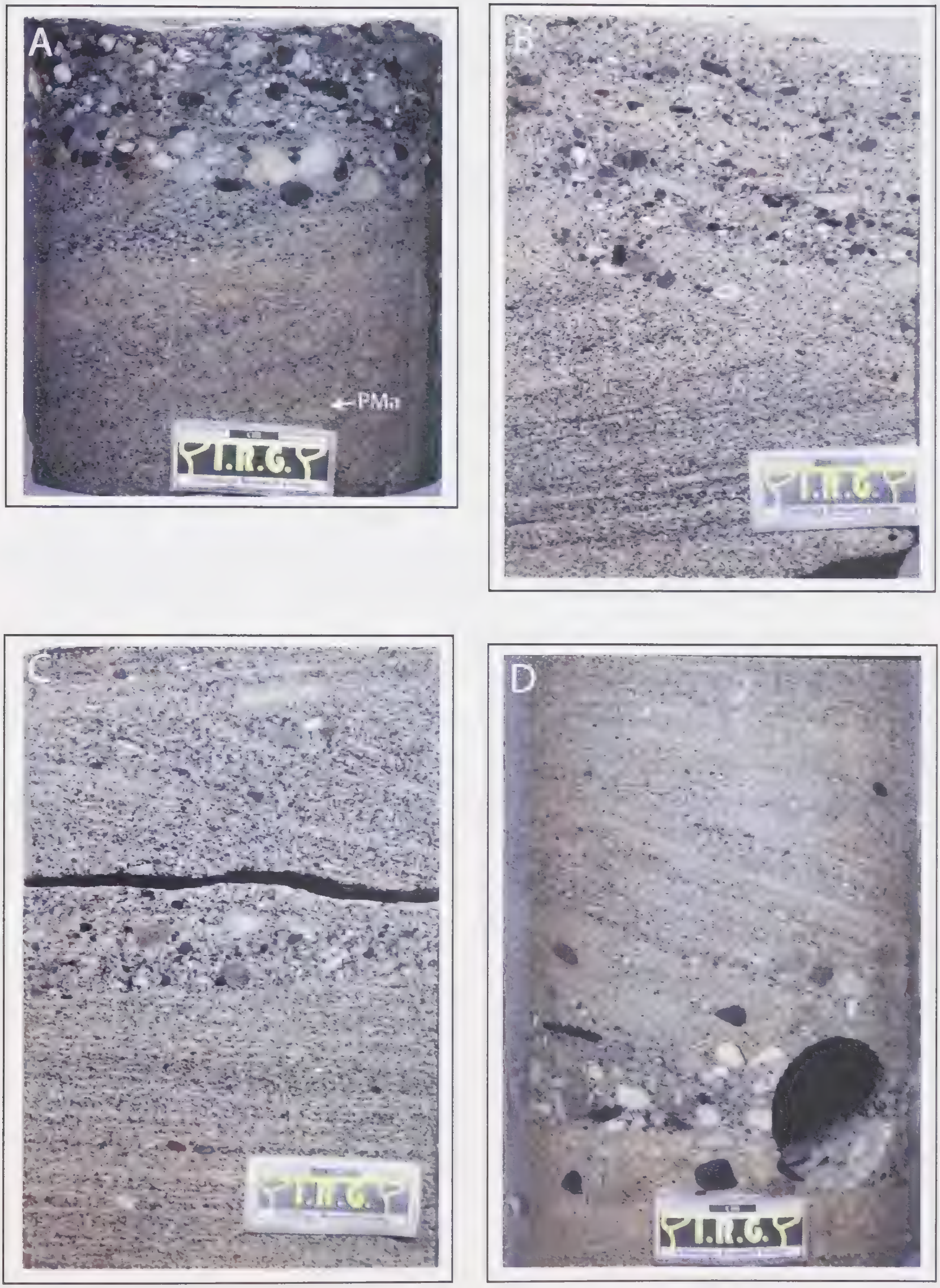
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Fig. 2.12 - Selected examples of bioturbation from Facies 4b – Sporadically Bioturbated Very fine- to fine-grained Trough Cross-bedded Sandstone: (A) Pervasively bioturbated very fine-grained sandstone containing abundant *Macaronichnus* burrows. Rare organic-rich mudstone clasts are also present (09-02-68-13W6, 2588.5m); **(B)** Abundant *Macaronichnus* and Para-*Macaronichnus* burrows within a fine-grained sandstone. Rare organic-rich mudstone clasts and pebbles are also present (11-07-68-12W6, 2508.6m); **(C)** Pervasively bioturbated sandstone containing large Para-*Macaronichnus* and small *Diplocraterion* burrows sharply overlain by a planar laminated very fine-grained sandstone (06-25-68-11W6, 2218.0m); **(D)** Multiple vertical *Diplocraterion* burrows within a pebbly fine-grained sandstone (14-09-68-09W6, 2270.6m).


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structures present include cryptic bioturbation (r-c), *Palaeophycus* (c), *Ophiomorpha* (r), *Macaronichnus simplicatus* (r), Para-*Macaronichnus* (a), *Diplocraterion* (r), *Skolithos* (r), *Conichnus* (r), and fugichnia (r). Para-*Macaronichnus* is the most abundant trace fossil present within Facies 4b. This trace fossil is normally found within the lower sections of the facies near the contact with Facies 4a. Other common traces include *Palaeophycus* and *Ophiomorpha*. This trace fossil suite represents a low diversity expression of the *Skolithos* ichnofacies (Fig. 3.1) (MacEachern and Pemberton, 1992).

Interpretation – Abundant multidirectional trough cross bedding and the overall coarsening upward nature indicate a typical upper shoreface environment and/or wave-dominated proximal delta front. The trough cross-stratification within this facies is a result of current-generated migrating subaqueous dunes generally found within the surf zone (Reineck and Singh, 1980; Elliott, 1989). These features are formed by wave-forced currents directed onshore and along shore (Boggs, 2001). The presence of low-angle bidirectional cross-beds may indicate deposition under strong longshore currents (Reinson, 1992). Evidence of high-energy storm events is mostly erosional and is characterized by sharp-based well to poorly sorted conglomerate beds (Walker and Plint, 1992; MacEachern, 2000). The coarse nature of the sediment as well as the low diversity *Skolithos* ichnofacies also indicates a high-energy environment (MacEachern and Pemberton, 1992; Walker and Plint, 1992). Suspension-feeding, dwelling and passive carnivore structures are all common and result from a rapidly shifting sandy substrate, high-energy nature of environment, and fact that most food would be kept in suspension (MacEachern, 2000; Pemberton et al., 2001). The low intensity, diversity, and sporadic distribution of bioturbation also support the interpretation of a high-energy environment. The specialized feeding strategy of Para-*Macaronichnus* and *Macaronichnus* that occurs below the sediment-water interface protects these organisms and increases their preservation potential. Other common traces include *Palaeophycus* and *Ophiomorpha*, both of which stabilize their burrows by lining their walls with fecal pellets or mucus. Most traces are dominated by heavily lined, vertical, and deeply penetrating burrows in order to cope with the high-energy setting.

Increased concentrations and thicknesses of conglomeratic material indicate proximity to a deltaic point source as well as fluvial input (Bhattacharya and Walker, 1992). The proximal delta front tends to be largely similar to the upper shoreface and is dominated by trough cross-stratified and current rippled sandstones. Storm events result in erosional surfaces and also transport conglomeratic material from the foreshore into the shoreface. Delta front deposits tend to have relatively lower concentrations of suspension feeding structures (Gingras et al., 1998; Coates, 2001; MacEachern et al., 2005). This is attributed mainly to high water turbidity and possible post-storm mud deposition resulting from fluvial input (MacEachern, 2000; Coates and MacEachern, in press). However, it is generally difficult to distinguish between storm-dominated upper shoreface and a wave-dominated proximal delta front (Elliott, 1989; Bhattacharya and Walker, 1992; MacEachern, 2000). Differentiating deltaic and strandplain environments will be discussed in greater detail in Chapter Three.

(2.8) Facies 4c - Very fine-grained Planar Laminated Sandstone

Physical Sedimentary Structures – Facies 4c consists of very fine-grained, with rare medium to coarse, sandstones (Fig. 2.13). These sandstones are either poorly to moderately sorted or very well sorted. The dominant stratification types include planar parallel to low angle laminations and less commonly massive, apparently structureless, intervals. Locally abundant organic-rich and heavy mineral laminations are common. The uppermost sections of Facies 4c are generally rooted and contain abundant coal lenses and organic detritus. Soft sediment deformation and angular mudstone rip-up clasts are only locally abundant and are characteristic of the fine to medium grained poorly to moderately sorted sandstones.

Biogenic Sedimentary Structures - This facies is generally not bioturbated with the exception of rare intervals of *Macaronichnus segregatis* (r) and cryptic bioturbation (r-c).

Interpretation – This facies occurs in a number of different depositional environments. The planar to low angle lamination is characteristic of the upper flow regime and may be associated with shallow surging waters of the foreshore (Reineck and Singh, 1980;

Fig. 2.13 - Selected examples from Facies 4c – Very fine-grained Planar Laminated Sandstone: (A) Fine-grained planar laminated sandstone interpreted to have formed within a fluvial channel (06-10-68-10W6, 2251.5m); **(B)** Planar to sub-planar laminated sandstone with pebble stringers (06-13-68-11W6, 2279.7m); **(C)** Cryptically bioturbated planar laminated sandstone (06-30-69-13W6, 2371.4m); **(D)** Planar laminated sandstone sharply overlain by a well sorted conglomerate bed (06-25-68-11W6, 2214.3m); **(B-D)** Interpreted to have formed within a high-energy foreshore environment.


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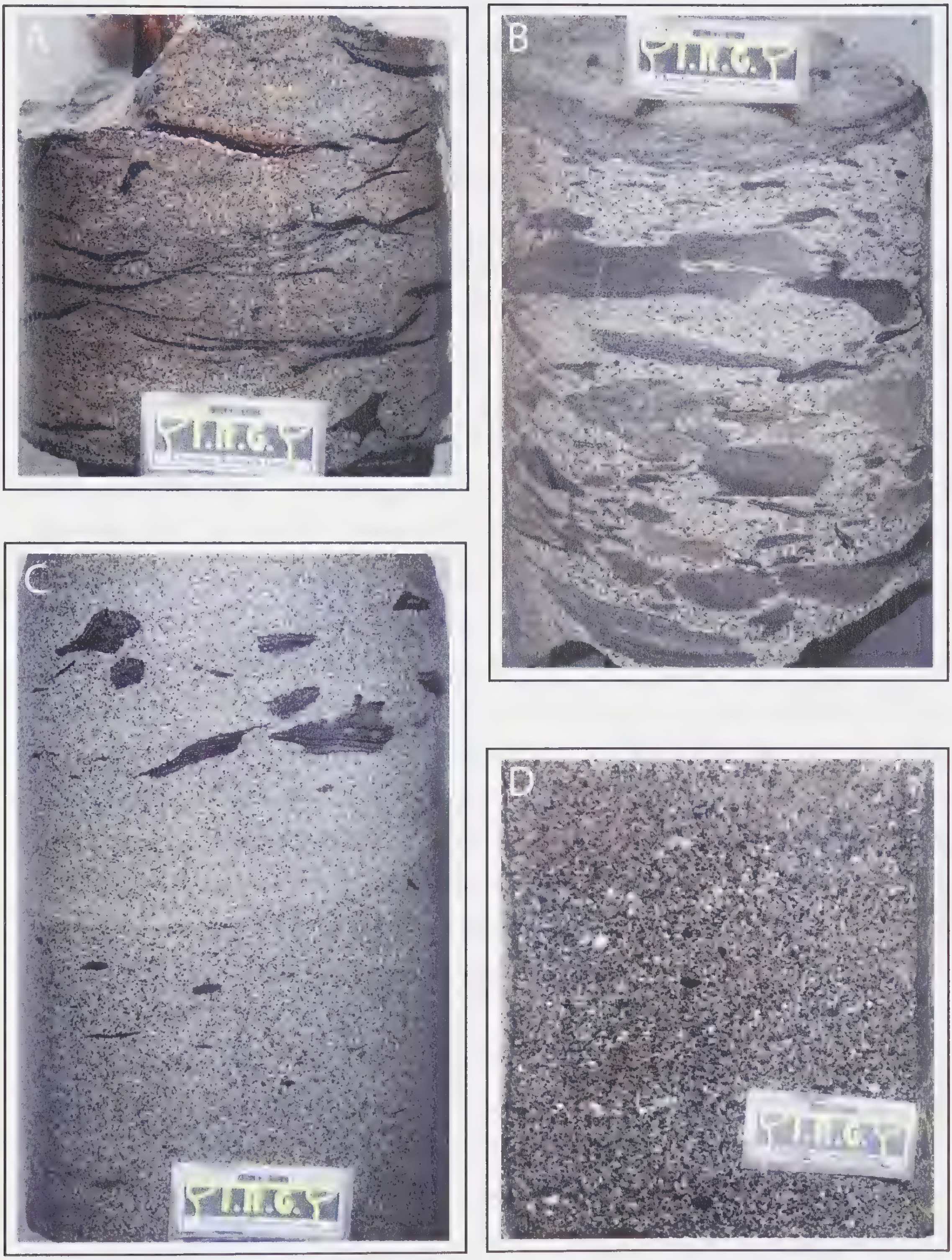
Elliott, 1989). Very well sorted sandstones are also characteristic of high-energy foreshore deposits. This beach environment occurs between high and low tide and is dominated by swash and backwash, which generates seaward dipping low angle laminations (Reading, 1989). Thin lenticular sets of low-angle laminae may be formed from antidune migration during backswash (Boggs, 2001). Rare horizons of locally abundant *Macaronichnus segregatis* occur within the foreshore. This represents a selective deposit feeding behavior below the sediment-water interface and is typical of very high-energy environments (Pemberton, 2001). This is consistent with previous interpretations (Clifton & Thompson 1978, Saunders et al., 1994 and Pemberton et al., 2002).

The planar to low angle laminated poorly to moderately sorted sandstones occur within the backshore environment. The horizontal laminations are a product of surging waves during unusually high water conditions (Reineck and Singh, 1980). Intermittent storm-wave deposition and eolian sand transport are the dominant processes affecting the backshore (Boggs, 2001). Heavy mineral placers are common and result from the relative sorting by water during storms (Reineck and Singh, 1980). Root traces are locally common and may extend down into the underlying foreshore deposits. The planar laminated to massively bedded sandstone with common mudstone rip-up clasts and soft sediment deformation is generally found within fluvial channel fill deposits (Elliott, 1989). These deposits are generally associated with the fining-upward sandstones from Facies 5.

(2.9) Facies 5 - Fine- to Coarse-grained Trough Cross-bedded and Planar Laminated Sandstone

<u>*Physical Sedimentary Structures*</u> – Facies 5 forms a fining-upwards succession of very fine- to coarse-grained sandstone with rare pebble sized grains (Fig. 2.14). Grain sizes most commonly only range from fine- to medium-grained and are poorly to moderately sorted. The typical internal stratification types include abundant trough cross-bedding and planar parallel laminations. Apparently massively bedded intervals containing numerous large angular mudstone rip-up clasts are also quite common (Fig. 2.14b). The mudstone rip-up clasts range in size from 0.5 cm to greater than 10 cm and are elongated.

Fig. 2.14 - Selected examples from Facies 5 - Fine- to Coarse-grained Trough Cross-bedded and Planar Laminated Sandstone: (A) Massive to weakly cross-bedded fine- to medium-grained sandstone containing abundant coal lenses and organic-rich mudstone clasts (09-16-68-10W6, 2211.0m); **(B)** Massive fine- to coarse-grained sandstone with large angular mudstone rip-up clasts. Some of the larger mudstone clasts show planar laminations, contorted bedding, and possible bioturbation (09-16-68-10W6, 2212.5m); **(C)** Weakly cross-bedded scoured fine-grained sandstone containing angular mudstone rip-up clasts (09-16-68-10W6, 2212.8m); **(D)** Fine- to very coarse-grained weakly planar laminated sandstone (06-10-68-10W6, 2252.6m); **(A-D)** Interpreted to have formed within a tidal or fluvial channel system.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Other common internal stratification types include current ripples and sub-planar parallel laminations. Organic detritus and coal lenses are also common and increase upwards through facies 5 (Fig. 2.14a). The basal contacts are sharp and erosional, where as the upper contacts are gradational with overlying mudstones.

Biogenic Sedimentary Structures - Facies 5 does not exhibit visible bioturbation.

Interpretation – Medium-scale trough cross-bedding, the presence of angular mudstone rip-up clasts, and the overall fining-upward tend indicate a fine to coarse-grained channel succession (Coleman and Prior, 1982; Galloway and Hobday, 1996). The upward transition from trough cross-stratified coarser-grained sandstones into rippled laminated finer-grained sandstones is common within distributary channels and channels in general (Elliott, 1989). The overall fining-upward trend is a result of either lateral migration of the channel or channel abandonment (Coleman and Prior, 1982). Angular mudstone rip-up clasts suggest current transport of mudstone fragments from bank collapse into the channel possibility during flood conditions (Reineck and Singh, 1980; MacEachern, 2001). A fully non-marine interpretation is supported by the complete lack of bioturbation, which suggests dominantly freshwater conditions (MacEachern and Pemberton, 1992). Channel fill successions are also present within the lower and upper delta plain as well as within lagoonal environments. Facies 5 can also be present within tidal channels cutting through barrier bars along the coast. These environments are however extremely rare within prograding wave-dominated environments. In all likely hood, tidal channels would only form temporarily during beach and barrier bar overwash during large storms (Elliott, 1989). This will be discussed further in Chapter Three.

(2.10) Facies 6 – Very Coarse-grained Sandstone

Physical Sedimentary Structures – Facies 6 consists of well to very well sorted medium- to very coarse-grained sandstones (Fig. 2.15). The sandstones tend to coarsen upwards. Finer sediment such as fine sand, silt, and interstitial clay is very rare to absent. Individual beds range in thickness from 5-20 cm with common, subtle grain size variations throughout. Overall most of facies 6 appears massively bedded however the

Fig. 2.15 - Selected examples from Facies 6 – Very Coarse-grained Sandstone: (A) Planar to gently dipping parallel laminated very coarse-grained sandstone (06-19-68-13W6, 2675.9m); **(B)** Planar laminated very well sorted very coarse-grained sandstone with rare pebbles (06-19-68-13w6, 2675.6m); **(C)** Massive coarse- to very coarse-grained sandstone (06-19-68-13W6, 2675.3m); **(D)** Gently dipping medium- to very coarse-grained sandstone. Note the numerous grain size variations, however each bed is still well to very well sorted (07-14-68-13W6, 2514.1m); **(A-D)** Interpreted to have formed within a foreshore beach environment.


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contacts between individual beds are planar to gently inclined (Fig. 2.15c). Weak planar to sub-planar parallel laminations are also common throughout. There are also rare examples of low angle cross-bedding, internal irregular scoured contacts, and randomly distributed chert pebbles and granules. The sand grains are very well rounded and generally spherical with only very rare examples of elongated grains. This facies is very similar to Facies 8a with regard to physical sedimentary structures.

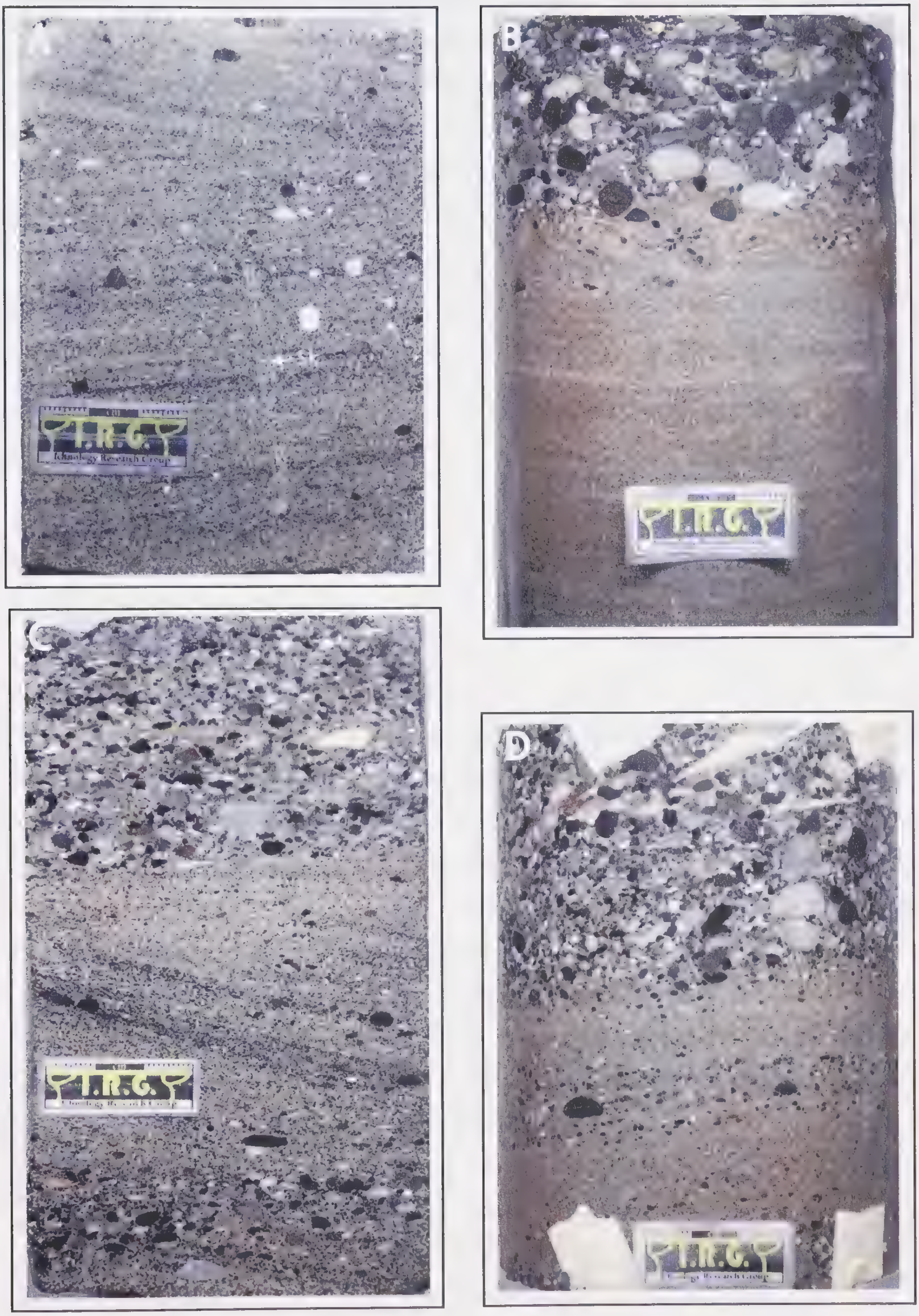
Biogenic Sedimentary Structures – Facies 6 does not exhibit visible bioturbation.

Interpretation – The overall very well sorted nature of this facies combined with the dominance of planar parallel to gently inclined laminations indicates a high-energy foreshore beach environment (Elliott, 1989; MacEachern and Pemberton, 1992). This is interpreted to represent swash zone cross-stratification forming within the beach swash zone (Boggs, 2001). The complete lack of finer sediment and high degree of sorting indicate constant reworking and removal of such sediment. This is accomplished through constant wave action within the beach environment between high and low tide (Reineck and Singh, 1980). Continuous breaking waves with swash and backwash within this zone physical sort the sediment and produces the planar to gently inclined laminations common in this facies (Walker and Plint, 1992). The extremely well sorted nature of this facies limits the possible environment of formation to the foreshore. The fact that shoreface and foreshore conglomerates tend to be better sorted than fluvial conglomerates supports this claim (Clifton, 1973; Hart and Plint, 1995). However, high- energy storm events may transport coarser sediment into the shoreface.

(2.11) Facies 7 - Interbedded Sandstone and Conglomerate

Physical Sedimentary Structures - This facies consists of interbedded conglomerate and very fine- to fine-grained sandstone (Fig. 2.16). The sandstone contains abundant pebbles and coarse sand stringers as well as randomly dispersed pebbles. Sorting ranges from very poorly to well sorted but generally displays moderate sorting. Internal stratification includes trough cross stratification and less commonly planar parallel lamination. Organic-rich laminations are rare. The pebbles comprising the

Fig. 2.16 - Selected examples from Facies 7 - Interbedded Sandstone and Conglomerate: (A) Trough cross-bedded fine-grained sandstone with abundant pebbles and rare *Skolithos* burrows (06-15-68-11W6, 2319.7m); **(B)** Well sorted planar laminated very fine-grained sandstone with overlying poorly sorted conglomerate. Note the interesting contact between the two lithologies where the pebbles appear to "sink" into the sandstone (09-16-68-10W6, 2202.7m); **(C)** Interbedded trough cross-bedding sandstone and well sorted planar laminated conglomerate (15-12-68-09W6, 2200.35m); **(D)** Planar laminated sandstone with very coarse-grained sand stringers gradationally underlying a moderately sorted conglomerate (06-25-68-11W6, 2220.1m); **(A-D)** Interpreted to have formed within the proximal upper shoreface or proximal delta front.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conglomerates within Facies 7 vary dramatically in grain size, sorting, and stratification type. Most conglomerates are clast-supported with very poor to moderate sorting, with only rare examples of very well sorted varieties. Matrix, when present, ranges in grain size from very fine- to medium-grained with only rare examples of interstitial clay. Clast sizes range from coarse upper to 3 cm pebbles, which are subrounded to well rounded and have low to moderate sphericity. Beds range from 2 cm to 40 cm in thickness and display abundant trough cross-stratification with lesser amounts of planar parallel laminations and massive bedding. Contacts between beds are generally sharp and contain significant erosion. However, rare examples of gradational and sharp non-erosive contacts are also present. This facies generally has a sharp erosional basal contact with underlying facies (facies 4a or 4b).

Biogenic Sedimentary Structures - Facies 7 contains very little bioturbation and where present ichnofossils are only found within the sandy intervals. The only trace fossils observed within this facies are very rare *Thalassinoides*, *Skolithos*, and cryptic bioturbation (Fig. 2.16a).

Interpretation – The overall coarse-grained nature of this facies coupled with the presence of trough cross-stratification as the dominant physical sedimentary structure indicates an upper shoreface or delta front environment (Bhattacharya and Walker, 1992; Hart and Plint, 1995). Facies 7 is most commonly found within the proximal upper shoreface and delta front above the sandstone-rich Facies 4b and below the conglomerate-rich Facies 8a, 8b, and 8c. Proximal upper shoreface deposits tend to have thinner conglomerate beds and less fine sediment (very fine-grained sand, silt, and clay) than delta front deposits. Increased concentrations of conglomerate indicate possible proximity to distributary channels (Arnott, 1991), which are interpreted to be the source of most conglomeratic material. Thick intervals of Facies 7 may therefore indicate possible deltaic point sources. Less frequently, Facies 7 is present within the lower portions of distributary channels. These successions are generally overlain by the fine- to coarse-grained fining-upward sandstones of Facies 5. These deposits tend to have lower degrees of sorting and increased concentrations of organic material and fine sediment

(Clifton, 1973). The rounding and sphericity of grains is also noticeably lower than those described above.

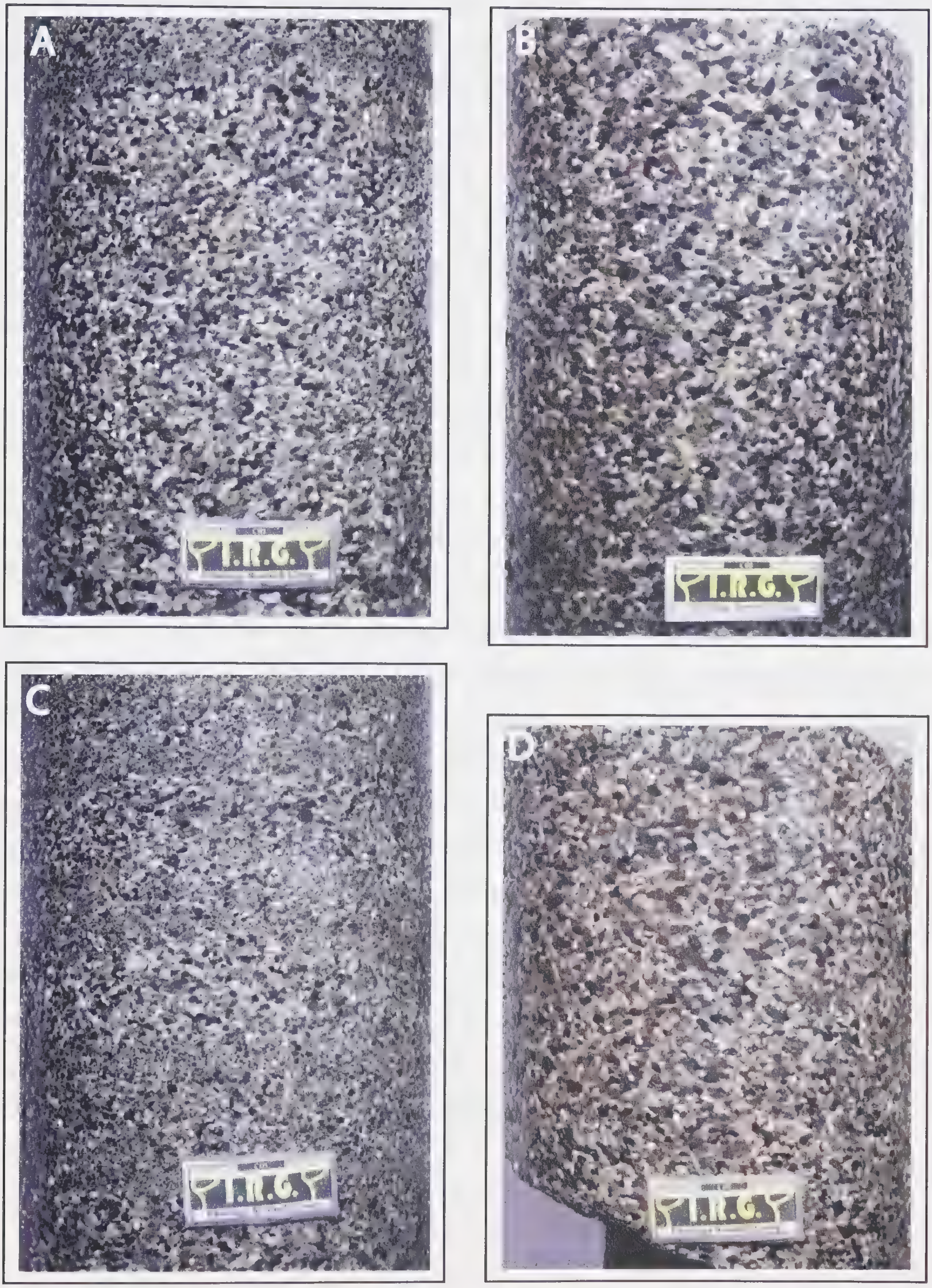
(2.12) Facies 8a - Unimodal Chert Granule Conglomerate and Very Well Sorted Coarse-grained Sandstones

Physical Sedimentary Structures – The very well sorted conglomerates of Facies 8a are clast-supported with very little to no clay or sand sized grains (Fig. 2.17). Clast sizes range from 2 mm – 10 mm and are well rounded. The clast sizes for Facies 8a are considerably smaller than the other 3 conglomerate-rich facies (Facies 7, 8b, and 8c). Internal stratification includes planar parallel and low angle (less than 10 degrees) laminations interpreted to represent swash zone cross-stratification. However, most stratification is difficult to observe and therefore appears massively bedded. Bedding ranges in size from 5 cm – 35 cm and includes moderate grain size variations between individual beds, however each bed is still very well sorted. As in Facies 6, most grains are very well rounded, spherical, and overall very mature.

Biogenic Sedimentary Structures – Facies 8a contains no visible bioturbation.

Interpretation – The extremely high sorting and planar to low angle laminations indicate a high-energy foreshore environment (Clifton et al., 1971; Coleman and Prior, 1982). The presence of planar swash zone stratification implies an intertidal beach environment (Elliott, 1989). The high levels of sorting indicate a large degree of winnowing of finer sediment and support this interpretation. The coarse-grained nature of this facies points toward the presence, at least locally, of a gravel-dominated foreshore beach (Hart and Plint, 1995). The very low levels of bioturbation are a result of the high physico-chemical stresses associated with a high-energy foreshore setting (MacEachern et al., 2005). Foreshore beach environments also occur within the delta front, however a lower degree of sorting would be expected. As well, thicker intervals would be expected within deltaic environments. The reduced clast size compared to other conglomeratic-rich facies may indicate prolonged reworking by wave action or lateral displacement by longshore drift (Arnott, 1991; Hart and Plint, 1995). The downdrift fining develops in response to

Fig. 2.17 - Selected examples from Facies 8a - Unimodal Chert Granule Conglomerate: (A-D) Granule to small pebble very well sorted conglomerate. These units appear massive however gently dipping laminations are commonly observed. Most grains are spherical, very well rounded and composed of chert. Interpreted to have formed in a high-energy foreshore beach environment from the reworking of previously deposited delta front and delta plain deposits; **(A)** 07-01-68-12W6, 2437.1m **(B)** 06-19-68-13W6, 2678.2m **(C)** 07-01-68-12W6, 2435.9m **(D)** 07-14-68-13W6, 2513.5m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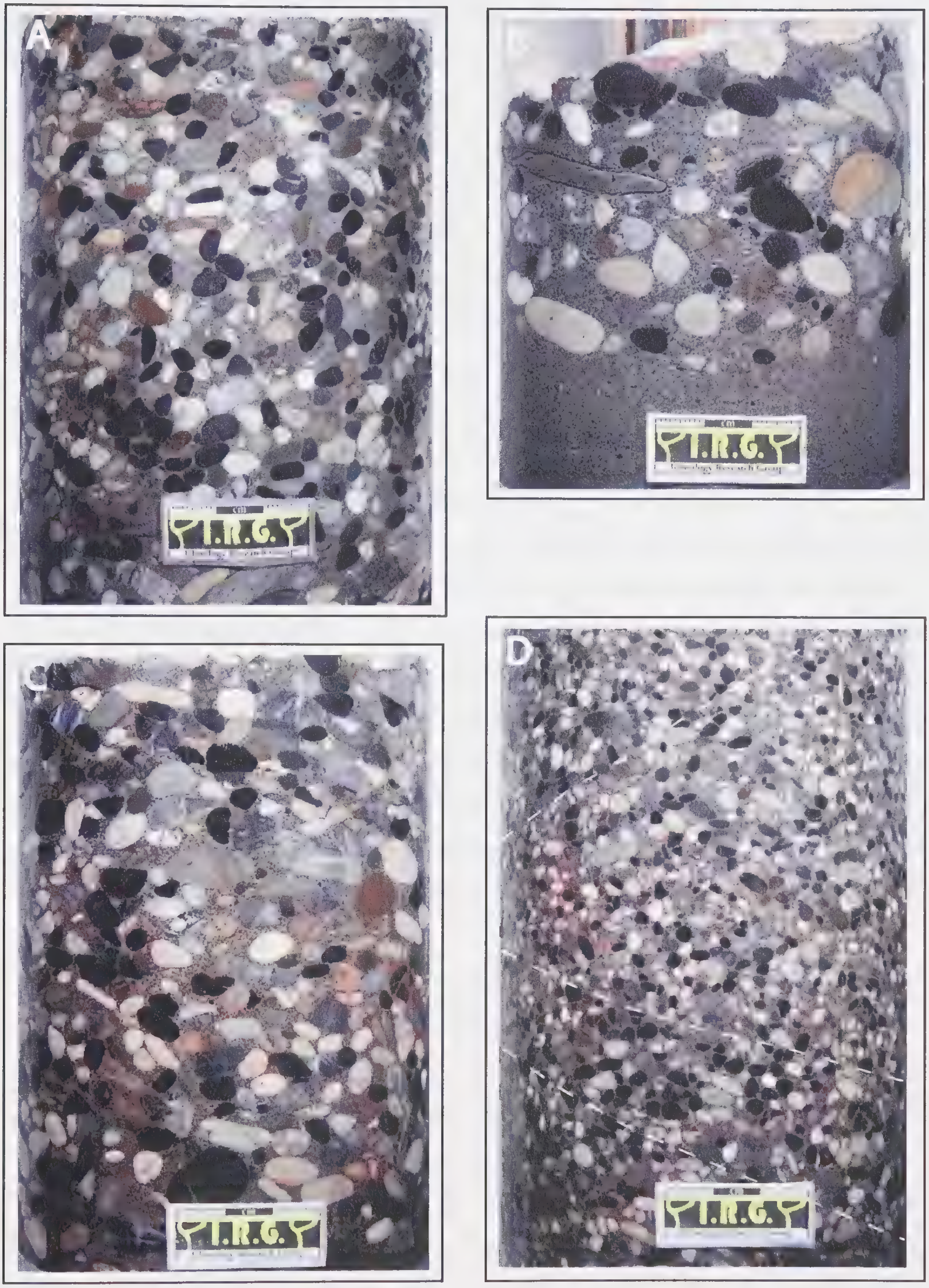
preferential longshore transport of finer grains, with smaller clasts transported farther than larger ones (Carter, 1988; Arnott, 1991; Pattison and Walker, 1992; Hart and Plint, 1995). This could occur through the reworking of older more poorly sorted deltaic deposits after channel avulsion and a reduction in sediment input. This will be discussed further in Chapter Three. As in Facies 6, it is also possible than high-energy storms events may transport coarser sediment into the shoreface. During fair-weather conditions, coarser sediment would be reworked landward, however appreciable volumes may be preserved in the shoreface (Carter, 1988; Hart and Plint, 1995; Galloway and Hobday, 1996).

(2.13) Facies 8b - Bimodal Chert Conglomerate

Physical Sedimentary Structures – The conglomerates of Facies 8b have an obvious bimodal grain size distribution (Fig. 2.18). These conglomerates are clast-supported however they do include a significant proportion of fine sandy matrix (roughly 30-40%). The grain size of the matrix ranges from very fine- to fine-grained and is completely lacking in interstitial clay. The clast size varies dramatically between each different bed, from about 0.2 cm to 2.5cm. However, the clast size distribution of each individual bed is very low. The clasts are always very well rounded but do show common to abundant dissolution of grains (pressure solution). The sphericity of the clasts within Facies 8b is very variable with a mix of spherical and elongated. A general trend shows that the large clast sizes (0.5 cm and greater) tend to be more elongated than the smaller clasts (0.2-0.5 cm). The internal stratification of Facies 8b appears to be primarily massively bedded due to its bimodal nature. However upon further investigation Facies 8b shows abundant high angle cross bedding, trough cross-stratification, and planar parallel laminations (Fig. 2.18a,c-d). This facies is generally interbedded with or occurs just below the very well sorted unimodal conglomerates of Facie 8a. Facies 8b is also generally found directly above the interbedded sandstones and conglomerates of Facies 7.

Biogenic Sedimentary Structures - Facies 8b shows no visible bioturbation.

Fig. 2.18 - Selected examples from Facies 8b - Bimodal Chert Conglomerate: (A) Bimodal conglomerate with 0.4-0.8 cm pebble clasts and a very fine-grained sand matrix. Cross-bedding is common however it is difficult to observe due to the bimodal nature (11-07-68-12W6, 2499.8m); **(B)** Sharp apparently non-erosion contact between a bimodal conglomerate and a gently dipping fine-grained sandstone (06-19-68-13W6, 2680.5m); **(C)** Bimodal conglomerate with 0.5-1.5 cm pebble clasts and a fine-grained sand matrix. Weak cross-bedding is commonly observed (06-19-68-13W6, 2678.8m); **(D)** Very small pebbles clasts within a very fine-grained sand matrix. Weak cross-bedding is shown with dashed line (06-19-68-13W6, 2678.2m); **(A-D)** Note, in comparison with conglomerates from facies 8a, a greater proportion of elongated very well rounded grains instead of spherical very well rounded grains.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Interpretation – Facies 8b appears to represent a transitional facies between the very well sorted conglomerates of Facies 8a and the more poorly sorted conglomerates of Facies 8c. This facies may also represent a "hybrid" between the interbedded sandstone and conglomerate Facies 7 and the well-sorted conglomerate Facies 8a. This would explain the seemingly well-sorted matrix and clasts as well as the internal stratification. The considerable increase in clast size compared to Facies 8a may indicate that the sand was able to infiltrate the larger pore throats of the coarser pebbles but not the more restricted openings between the smaller granules or fine pebbles (Hart and Plint, 1995). A proximal upper shoreface to proximal delta front depositional environment is proposed based to the abundance of cross-stratification and the proximity to Facies 7, 8a, and 8c (Elliott, 1989; Orton and Reading, 1993).

(2.14) Facies 8c - Polymodal Chert Conglomerate

Physical Sedimentary Structures – The conglomerates of Facies 8c are clast-supported and very poorly to moderately sorted (Fig. 2.19). The finer-grained matrix comprises between 20-50% and ranges in grain size from very fine- to coarse-grained. The clast sizes range from very coarse to 5 cm pebbles and are always very well to well rounded. The clasts sphericity varies between spherical and elongated. The internal stratification is dominated by trough cross stratification and planar tabular cross stratification with less common massive bedding and planar parallel laminations. Bed thicknesses range from 5 cm to 50 cm and thicken near the middle of the study area. These trends will be discussed further in Chapters Three and Four. Organic rich laminae and mudstone rip-up clasts are present locally.

Biogenic Sedimentary Structures – Facies 8c shows no visible bioturbation.

Interpretation – The decreased sorting compared to other conglomeratic-rich facies, the lateral distribution of the facies, and the dominance of trough and planar tabular cross stratification point to a deltaic environment. A proximal delta-front and corresponding distributary channel network environment is proposed for Facies 8c. The poorly sorted nature of the conglomerates indicates higher sedimentation rates and less reworking by

Fig. 2.19 - Selected examples from Facies 8c - Polymodal Chert Conglomerate: (A) Very poorly sorted conglomerate sharply overlain by a planar laminated sandstone (06-25-68-11W6, 2213.9m); **(B)** Very poorly sorted weakly cross-bedded clast-supported conglomerate. Clast size varies from medium sand sized to large 3 cm pebbles (11-7-68-12W6, 2502.2m); **(C)** Deformed poorly sorted conglomerate with coal and organic-rich laminae (09-16-68-10W6, 2198.6m); **(D)** Moderately sorted conglomerate gradationally overlain by a massive to weakly planar laminated sandstone (07-14-68-13W6, 2516.2m); **(A-D)** Note, in comparison with conglomerates from facies 8a and 8b, a greater proportion of elongated grains and an overall lower rounding of grains. This unit is interpreted to have formed in distributary channels and mouth bars within the delta plain as well as within the delta front.


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waves than other more well sorted facies (i.e. Facies 8a). Facies 8c is better developed near identified distributary channels and grades laterally into thinner, finer-grained, and well-sorted facies such as Facies 7 and 8a. This is consistent with other conglomeratic bodies including the Cardium Formation (Arnott, 1991). Matrix-supported conglomerates found on the landward margin of more dominantly distributed clast-supported conglomerates, were interpreted to have been deposited in the vicinity of fluvial distributary mouths (Arnott, 1991; Pattison and Walker, 1992; Hart and Plint, 1995). Clifton (1973) suggested that rapid deposition of sand and gravel in fluvial deposits would produce pebbly sands, whereas prolonged reworking by waves will tend to segregate the two. Reworking by waves would transport finer grain sizes offshore and coarser grains landward (Reading, 1988; Hart and Plint, 1995) producing a noticeable coarsening upward profile. The overall thickness of this facies also decreases dramatically along-strike as the distance from the distributary mouth increases. Facies 8c is therefore interpreted to represent the along-strike source of gravel for other conglomeratic-rich facies. Abandoned delta lobes consisting of large volumes of facies 8c may also provide a source of sediment for adjacent strandplains as they are reworked into very well sorted conglomerates of Facies 8a (Arnott, 1993). This hypothesis will be discussed further in Chapter Three. Facies 8c is also found sporadically within the upper and lower shoreface. However these deposits tend to be slightly better sorted and contain less of the finer sand grain sizes.

(2.15) Facies 9 - Organic-rich Shale and interbedded Coal

Physical Sedimentary Structures – Facies 9 consists of organic-rich mudstone and siltstone with interbedded coal (Fig. 2.20). The mudstones tend to be massive with common thin planar parallel laminated siltstone and less common very fine-grained sandstone laminae. Abundant rooting results in thorough pedogenic alteration. Coal lenses and 10 cm to 50 cm coal beds are interbedded throughout and increase upwards through the facies. Soft sediment deformation and siderized internals are abundant but generally do not exceed 10-15cm in thickness. This facies is commonly interbedded with facies 5.

Biogenic Sedimentary Structures – Facies 9 shows no visible bioturbation.

Interpretation – The high organic and coal content, abundant rooting, fine-grained nature, and absence of bioturbation indicate a non-marine floodplain environment (MacEachern, 2000; Wadsworth et al., 2003). This facies is also present within the laterally equivalent upper delta plain. Extensive pedogenic alternation and abundant rooting imply extended periods of subaerial exposure. Thick well-developed coaly intervals are generally found directly above sandy foreshore deposits. This is consistent within wave-dominated settings where the high water table results in large swampy regions, prefect for coal development, very near the to shoreline (Cant, 1995; MacEachern, 2000; Wadsworth et al., 2003). The channel-fill deposits of Facies 5 commonly erode into Facies 9 and are associated with sandier intervals. As well, backshore lagoonal deposits from Facies 1a and 1b can also be interbedded with Facies 9 near the coastline.

Fig. 2.20 - Selected examples from Facies 9 - Organic-rich Shale and interbedded Coal: (A) Mottled silt-rich mudstone with possible pedogenic alteration (04-34-67-08W6, 2209.8m); **(B)** Rooted pedogenicly altered silt-rich mudstone containing common pyrite nodules (04-34-67-08W6, 2208.4m); **(C)** Abundant rooting within an organic-rich silty mudstone grading upward into a coal-rich mudstone (06-10-68-10W6, 2255.7m); **(D)** Organic-rich mudstone overlying a rooted siltstone (04-34-67-08W6, 2208.0m).


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Chapter 3: Facies Associations and Depositional Model

Chapter two included detailed descriptions of the sedimentology, ichnology, and interpreted depositional environments of the fifteen facies observed from core (Table 3.1). This chapter builds on this information by placing these facies into recurring, genetically related packages, which will be spatially mapped and correlated in numerous cross-sections in Chapter Four. These packages are referred to as facies associations (FA), which are defined as a "group of facies genetically related to one another and which have some environmental significance" (Collinson, 1969).

Chapter Three describes five facies associations observed within the Falher "D" succession within the study area. These facies associations are described, based on the interpreted depositional environment, in a roughly distal to proximal arrangement (Fig. 3.1, 3.2). Each facies association will include an overall description, facies relationships, and environmental significance. The five facies associations are as follows; FA1 – Lower Shoreface/Distal Delta-Front, FA2 – Upper Shoreface and Foreshore, FA3 – Proximal Delta-Front, FA4 – Lower Delta-Plain/Brackish-Water Environments, FA5 – Coastal Plain/Upper Delta-plain (Table 3.2).

(3.1) Facies Associations

The primary objective of this study, as discussed in chapter one, is to identify and interpret sedimentological, ichnological, and stratigraphic variations along depositional strike. Analysis of the facies succession within the Falher "D", suggests a depositional system that varies considerably along-strike and includes elements of both shoreface and deltaic environments (Fig. 3.3). Within wave-/storm-dominated settings, substantial overlap exists between facies that occur in shoreface and deltaic environments (Fig. 3.4). Conversely, a number of facies associations will include both environments, while some will possess lateral equivalents. Figure 3.4 illustrates the strandplain and deltaic environment terminology utilized in this study. Facies Association One encompasses the distal elements of both shoreface and deltaic systems, including the distal lower to middle shoreface and laterally equivalent prodelta to distal delta-front environments. Facies Association Two, on the other hand, encompasses only the proximal elements of

Facies	Lithology	Physical Structures	Biogenic Structures	Depositional Environment
1a	Bioturbated Silt-Rich Mudstone	Planar to wavy lenticular siltstone laminae, current-rippled	Pl(c), Te(c), Ch(c), Di(r), Th(r)	Lagoon, Interdistributary Bay
1b	Unburrowed Silty Mudstone and Massive Shale	Planar to wavy lenticular siltstone laminae, syneresis cracks, deformation, pyrite nodules	Pl(r),Th(r), Bivalve Shells(r)	Lagoon, Interdistributary Bay, Delta-Plain, Floodplain, Bay-Fill
2	Sandy Siltstone	Massive, convolute laminations, large angular mudstone rip-up clasts	None	Fluvial Overbank
3a	Bioturbated Interbedded Mudstone and Very Fine-Grained Sandstone	Planar/sub-planar sandstone laminations, bioturbated mudstone	Th(c), Ch(m), Pl,(m), Ch(c), Hm(r), Te(c), Pa(c), Op(r), Di(r), Rh(r), Sch(r), fu(c)	Upper Offshore to Distal Lower Shoreface, Lagoon
3b	Non-bioturbated Interbedded Mudstone and Fine-Grained Sandstone	Wavy to current-rippled lenticular laminae, planar to massive mudstone, rare bioturbation	Pl(r), Te(r)	Prodelta to Distal Delta-Front, Lagoonal, Delta-Plain
4a	Very Fine-Grained Hummocky Cross-Stratified Sandstone (HCS/SCS)	Planar parallel to sub-planar (HCS) VWS sandstone, rare organic laminae, rare thin Cgl beds	Pa(c),Paramac(c), Op(r), Co(r), Sch(r), Di(r), Te(r), Th(r), As(r), Cryptic (a)	Distal to Proximal Lower Shoreface, Distal Delta-Front
4b	Sporadically Bioturbated Very Fine- to Fine-Grained Trough Cross-Bedded Sandstone	Trough cross-bedded, MS-WS, common pebble stringers, common thin PS Cgl beds	Pa(m), Di(r), Op(r), Sk(r), Co(r), Ra(r), fu(r), Sch(r), Th(r), Ma(r)	Distal to Proximal Upper Shoreface, Proximal Delta-Front

Table 3.1 – Facies summary from Chapter Two.

Facies	Lithology	Description	Biogenic Structures	Depositional Environment
4c	Very Fine-Grained Planar Laminated Sandstone	VWS-MS, massive to planar, rare pebbles, upper portions rooted	None	Upper Shoreface Foreshore, Fluvial, Backshore
5	Fine- to Coarse-Grained Trough Cross-bedded and Planar Laminated Sandstone	PS-WS, massive to cross-bedded, large angular mst rip-up clasts, coal lenses, fining-upward trend	None	Fluvial Channel Fill
6	Very Coarse-Grained Sandstone	VWS, cL-vcU planar to sub-planar sandstone, rare cross-beds	None	Reworked Delta-Front, Foreshore, Upper Shoreface
7	Interbedded Sandstone and Conglomerate	vfL-fU trough cross-bedded sandstone, pebble stringers, VPS-WS, matrix-rich Cgl	Pa(r)	Upper Shoreface, Proximal Delta-Front, Delta-Plain, Fluvial
8a	Unimodal Chert Granule Conglomerate	VWS, no matrix, granule - small pebble, mostly massive, rare imbrication	None	Reworked Delta-Front/ Delta-Plain, Foreshore
8b	Bimodal Chert Conglomerate	Bimodal, ~30% vfL-fU matrix, 1-2cm well rounded pebbles, massive to cross-bedded imbrication	None	Upper Shoreface, Foreshore
8c	Polymodal Chert Conglomerate	VPS-MS, ~35% vfU matrix, well rounded, massive to cross-bedded imbrication	None	Proximal Delta-Front, Delta-Plain, Fluvial
9	Organic-rich Shale with Interbedded Coal	Thin planar siltstone laminae, rooted, coal lenses, pyrite nodules, deformed	Pedogenic Alteration	Coastal Plain, Floodplain, Swamp

Table 3.1 – Facies summary from Chapter Two continued.

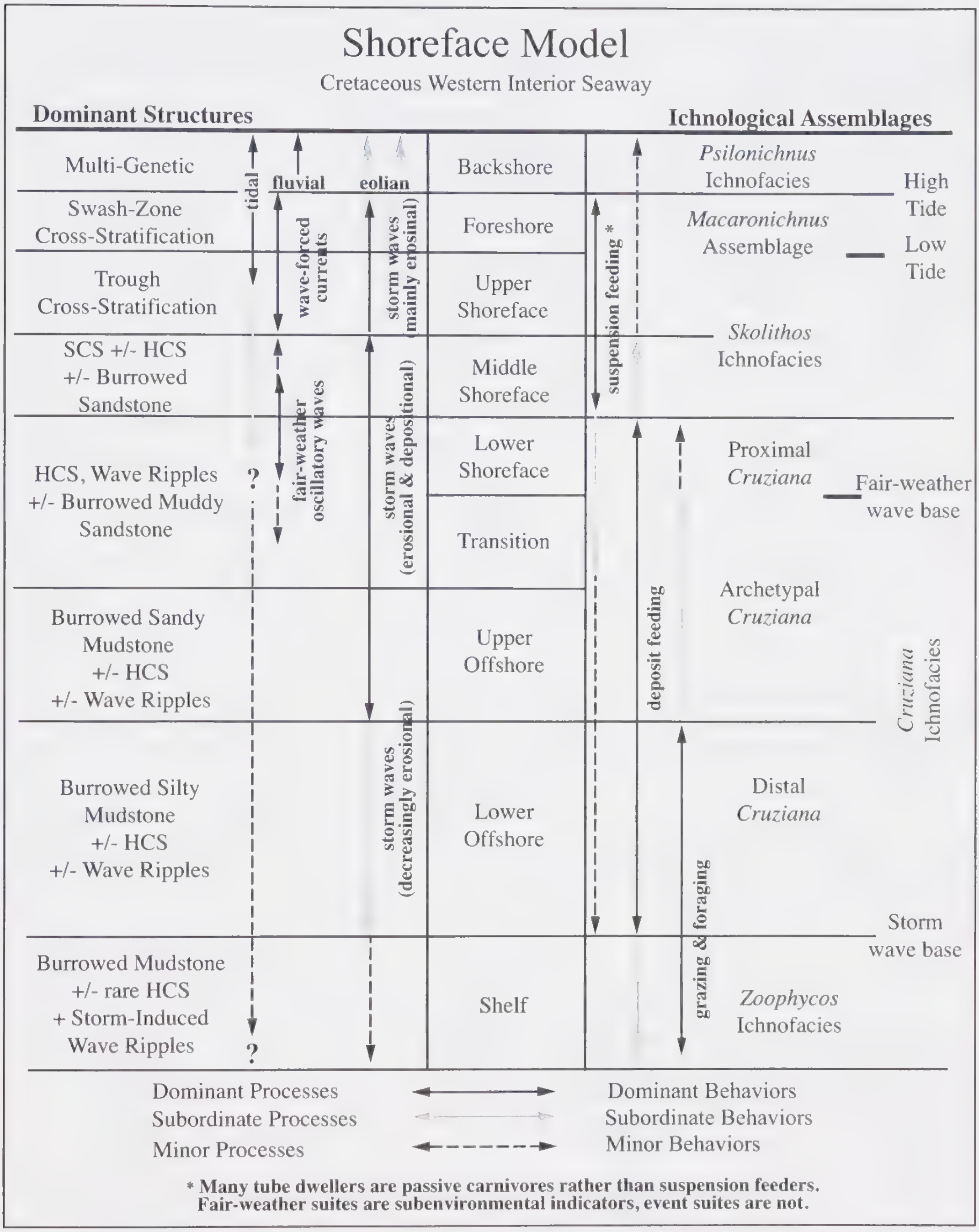

Fig. 3.1 - Schematic ichnological-sedimentological model of shoreface deposition based on the Cretaceous Western Interior Seaway (modified from MacEachern et al., 1999).

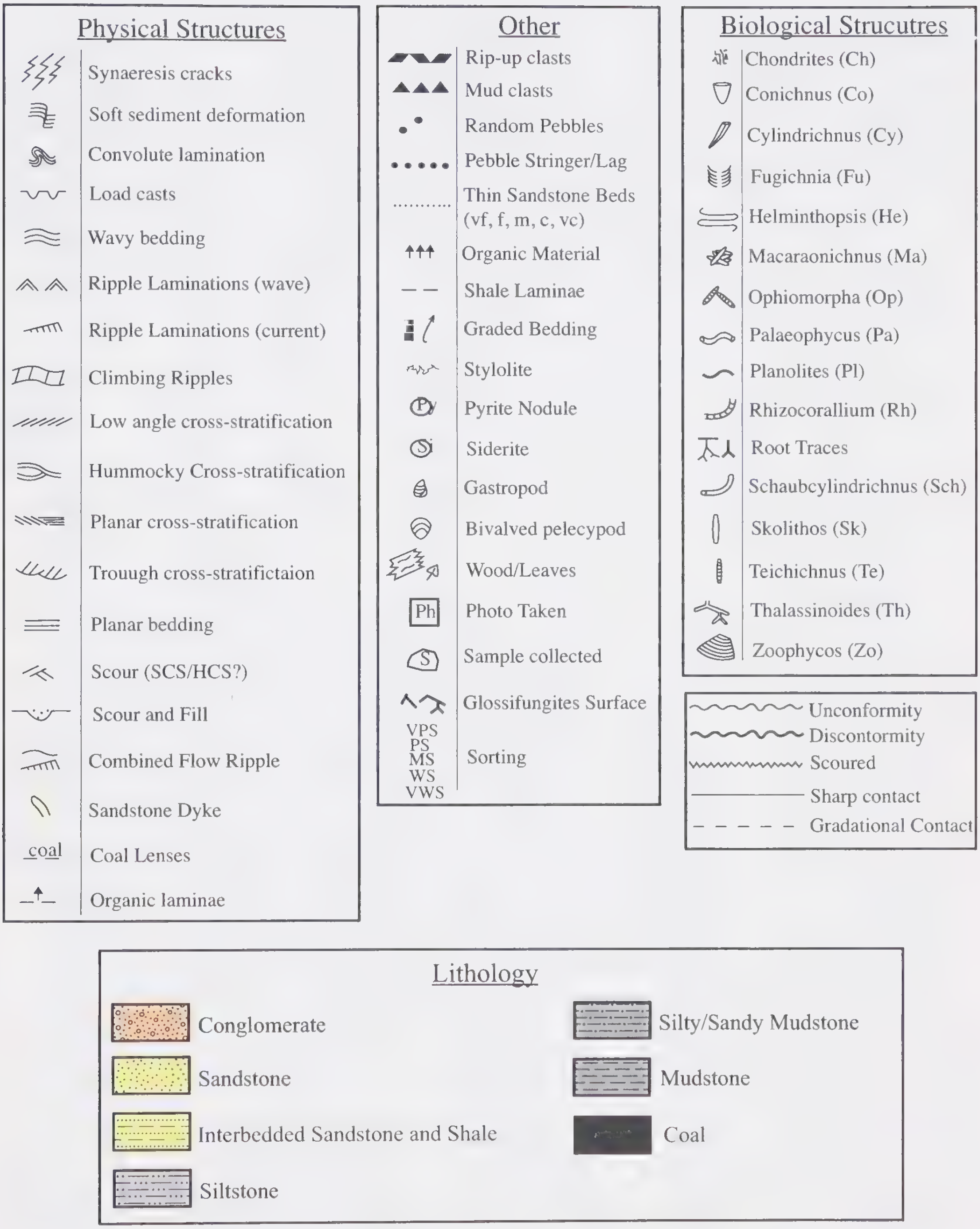

Fig. 3.2 - Legend of symbols and abbreviations utilized in this study.

Facies Association	Description	Recurring Facies	Environments
FA1: Storm-Dominated Lower Shoreface /Distal Delta Front	Interbedded laminated mudstone and very fine-grained sandstone; HCS/SCS; rare conglomerate; rare to moderately bioturbated (Mixed Skolithos-Cruziana Ichnofacies)	F3a, F3b, F4a	Offshore Transition, Lower Shoreface, Middle Shoreface, Prodelta, Distal Delta-Front
FA2: Wave-Dominated Upper Shoreface and Foreshore	Fine- to very coarse-grained sandstone and very well-sorted granule and pebble conglomerate; trough cross-stratification and horizontal planar parallel stratification; rare bioturbation (Skolithos Ichnofacies)	F4b, F4c, F6, F7, F8a, F8b	Upper Shoreface, Foreshore, Proximal Delta-Front
FA3: Wave-Dominated Proximal Delta-Front	Fine- to very coarse-grained sandstone and poorly-sorted granule and pebble conglomerate; trough cross-stratification, planar tabular cross-stratification, and horizontal planar parallel stratification; very rare bioturbation (Low diversity Skolithos Ichnofacies)	F4b, F7, 8c (Delta Front) F5 (Channel)	Proximal Delta-Front, Distributary Channels
FA4: Lower Delta-Plain/Marginal-Marine Brackish-Water Environments	Interbedded laminated mudstone, siltstone, and very fine-grained sandstone; current ripples, oscillation ripples, combined flow ripples, planar parallel lamination, lenticular bedding; syneresis cracks (Low diversity mixed Skolithos-Cruziana Ichnofacies)	F1a, F1b, F3a, F3b	Lagoon, Bay-fill, Intertidal Flat, Lower Delta Plain (Distributary Channels, Interdistributary Bay, interstrandplain Lagoon)
FA5: Upper Delta-Plain/Coastal Plain	Organic-rich rooted interbedded coal, mudstone, siltstone, and very fine-grained sandstone; massively bedded, planar parallel lamination; cross-bedded fining-upward sandstone; pedogenic alteration; No bioturbation	F1b, F9 (Coastal Plain) F4c, F5, F7, F8c (Channel)	Coastal Plain, Floodplain, Overbank, Swamps, Lakes, Fluvial Channel, Upper Delta Plain (Floodplain, Distributary Channel, Overbank, Swamp)

Table 3.2 Summary of the facies associations listed in the approximate depositional order. Facies include: F1a - bioturbated silt-rich mudstone, F1b - unburrowed silty mudstone and massive shale, F2 - sandy siltstone, F3a - bioturbated interbedded mudstone and fine-grained sandstone, F3b - non-bioturbated interbedded mudstone and fine-grained sandstone, F4a - very fine-grained hummocky cross-stratified sandstone, F4b - sporadically bioturbated very fine-grained to fine-grained trough cross-bedded sandstone, F4c - very fine-grained planar laminated sandstone, F5 - fine- to coarse-grained trough cross-bedded and planar laminated sandstone, F6 - very coarse-grained sandstone, F7 - interbedded sandstone and conglomerate, F8a - unimodal chert granule conglomerate, F8b - bimodal chert conglomerate, F8c - polymodal chert conglomerate, F9 - organic-rich shale with interbedded coal.

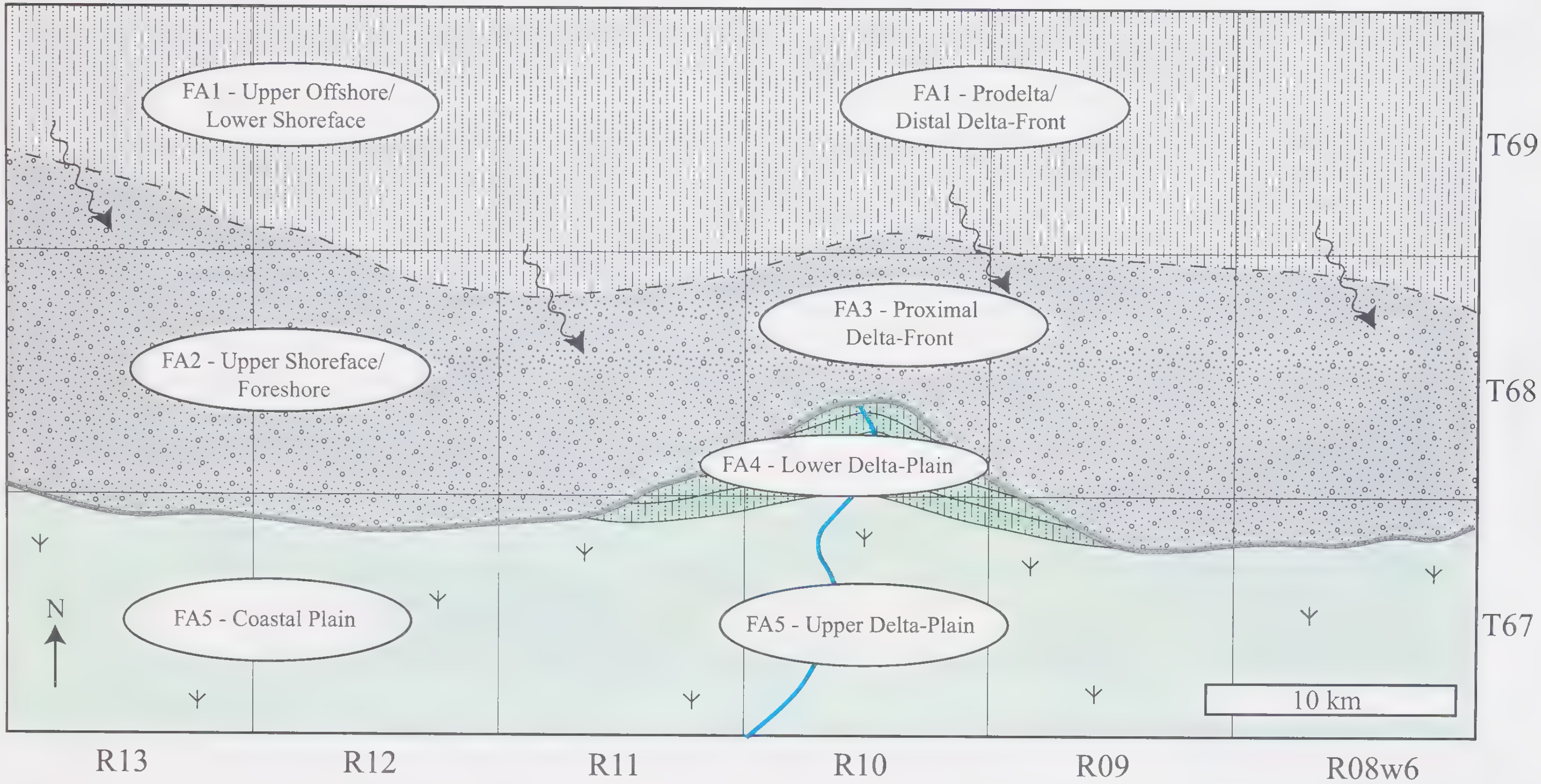

Fig. 3.3 - Paleogeographical overview of the along-strike variations in the Falher "D". Note the shift from typical strand-plain environments in the west to more deltaic environments in the east. The longshore drift is interpreted to be in a west to east direction (arrows). More detailed paleogeographic maps can be found in Chapter Four.

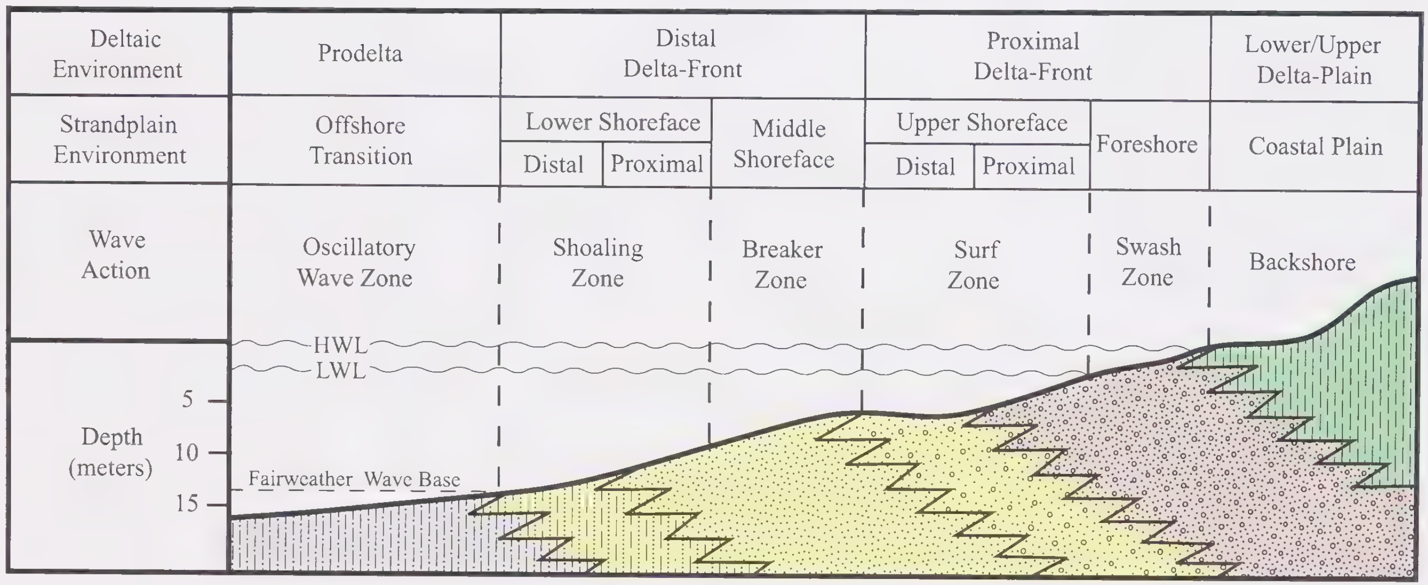

Fig. 3.4 - Generalized cross-sectional profile of the nearshore zone, illustrating the principal zones of wave activity, strandplain environment terminology, and deltaic environment terminology.

shoreface settings, including the distal upper shoreface to foreshore environment. Consequently, the proximal deltaic environments, including the proximal delta-front environment, are located in Facies Association Three. Marginal-marine environments, including the lower delta-plain and other brackish water settings, are incorporated into Facies Association Four. All non-marine environments, including the coastal plain and upper delta-plain, are discussed in Facies Association Five. These settings are described in a roughly distal to proximal arrangement, beginning with the distal lower shoreface and prodelta to distal delta-front environments.

Facies Association One (FA1) – Storm-Dominated Lower Shoreface/Distal Delta-Front

Facies Association One represents the most distal depositional environments encountered within the study area and includes the distal lower to middle shoreface and corresponding prodelta to distal delta-front environments within adjacent wave-dominated deltas (Bhattacharya and Walker, 1992; MacEachern and Pemberton, 1992). Ideally, offshore/shoreface deposits and prodelta/delta-front deposits would be in separated into different facies associations. However, a limited number of cored intervals within these environments has greatly restricted the sedimentological and ichnological data available. The storm-dominance of the Falher "D" succession compounds this problem with the erosional amalgamation of distal delta-front sandstone beds. This produces nearly identical proximal lower shoreface and distal delta-front deposits within strandplains and wave-dominated deltas respectively. This issue will be discussed in greater detail below.

Three of the facies described in Chapter Two are included within FA1: Facies 3a, 3b, and 4a. Of these, Facies 4a makes up the majority of the observed FA1 due to the lack of cored intervals in the distal regions of the study area. The facies making up FA1 are found throughout the Falher "D" within the study area except the extreme south. In general FA1 occupies the basal portion of the Falher "D" succession and erosively overlies non-marine deposits of the Falher "E". In the northern half of the study area, FA1 can often constitute the entire volume of the Falher "D" marine succession

Description and Facies Relationships

Facies 3a is typically composed of sharp-based very fine-grained sandstone beds displaying planar to sub-planar laminations interbedded with bioturbated silt-rich mudstones. Combined flow and planar laminations are common in the muddier intervals however physical sedimentary structures are difficult to observe due to the high degree of biogenic reworking. A proximal *Cruziana* assemblage dominates intervening mudstones beds, while a mixed *Skolithos-Cruziana* assemblage dominates the upper portions of sandstones beds (see Chapter Two) (MacEachern and Pemberton, 1992; Pemberton et al., 2001). The intensity of biogenic reworking and the diversity of trace fossils is relatively high compared to other facies. Rare mudstone rip-up clasts and organic-rich laminae are common locally. Sandstone beds generally thicken upwards from roughly 3 cm until there are no intervening mudstone beds.

The interbedded sandstones and mudstones of Facies 3a eventually grade upward into the very fine-grained sandstones of Facies 4a. Facies 4a consists of sharp-based 10 cm – 50 cm thick sandstone beds displaying low-angle convex-up and –down curvilinear laminations (Fig. 3.5). Bioturbation intensities within Facies 4a are relatively low as a result of the erosional amalgamation of sandstone beds. However, the overall diversity of trace fossils appears reasonably high (see Chapter Two). These sandstone beds tend to be very well-sorted with very rare randomly dispersed pebbles. Thin erosionally based poorly sorted conglomerate beds are rare. Thin mudstone and organic-rich laminae, mudstone rip-up clasts, and wood fragments are uncommon but locally abundant. Other less common sedimentary structures include oscillation ripples, massive bedding, combined flow-ripples, and planar parallel laminations. Facies 4a coarsens-upwards from very fine-grained lower to fine-grained lower with thin conglomerate beds and randomly dispersed pebbles also increasing upwards.

In some localities, Facies 3a is replaced with the interbedded very fine-grained sandstones and sparsely bioturbated mudstones of Facies 3b (Fig. 3.6). The sharp-based sandstone beds display a similar low-angle sub-planar laminated character as compared to Facies 3a. The intervening mudstone beds are sparsely bioturbated with current-rippled, combined-flow rippled, and planar laminated siltstone laminae. Oscillation-ripples and lenticular bedding is less common. Intervals of abundant organic-rich muds,

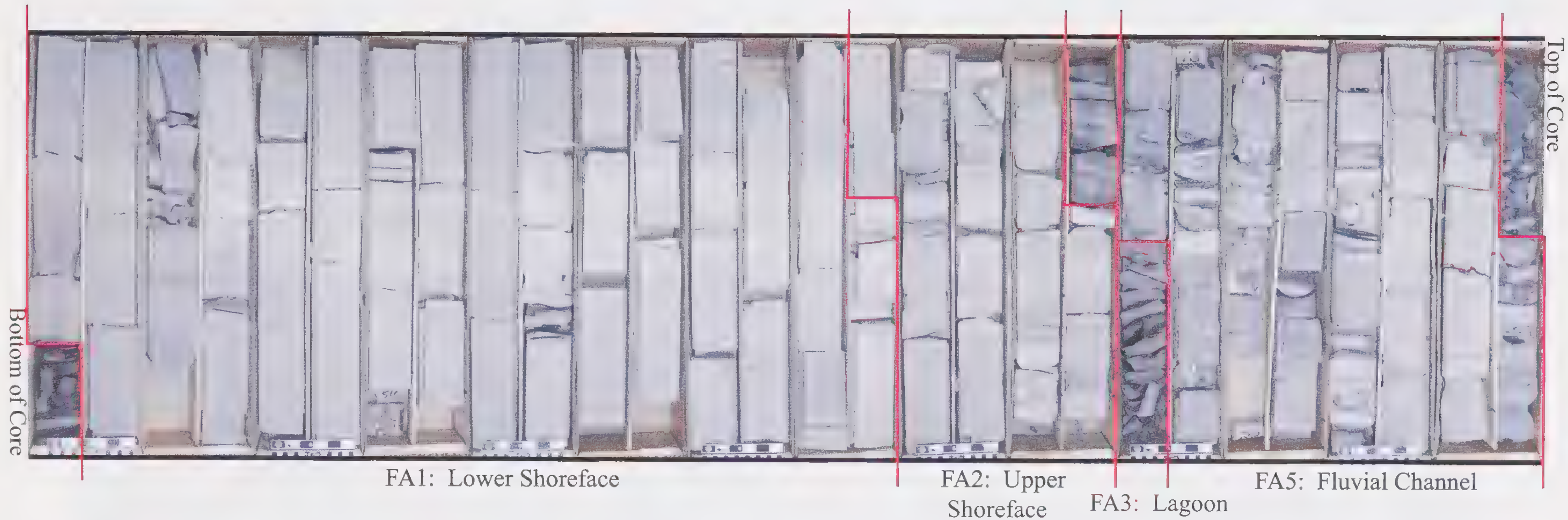

Fig. 3.5 - Strandplain succession from the Falher “D”. Coarsening-upward succession of storm-amalgamated HCS sandstones (FA1) and trough cross-bedded sandstone (FA2). A thick fining-upward fluvial channel sharply overlies thin lagoonal deposits. 14-09-68-09W6, 2263.7-2284.3m.

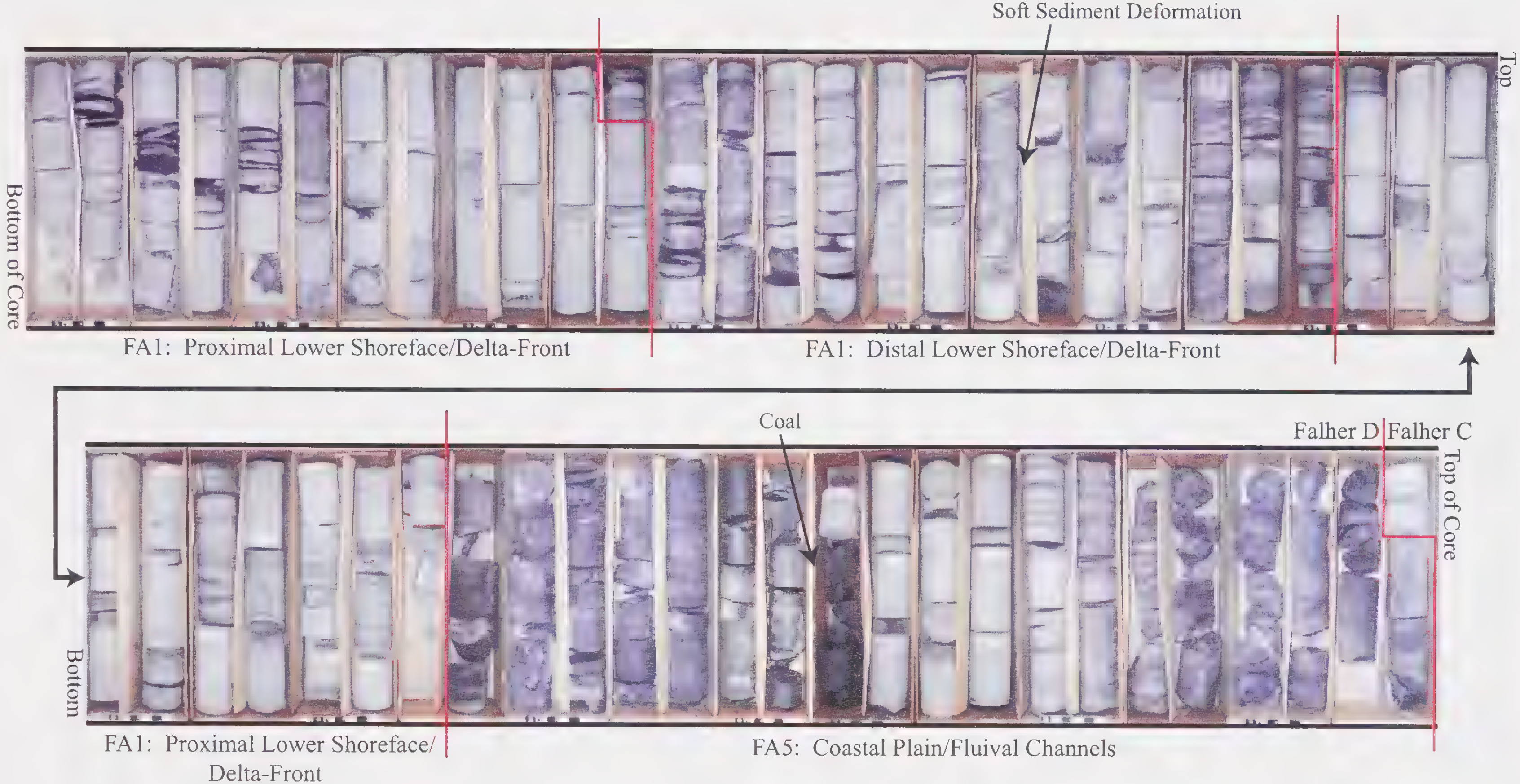

Fig. 3.6 - Distal shoreface succession from the Falher "D". This represents the most distal core within the study area. A thick succession of lower shoreface/distal delta-front deposits is overlain by coastal plain mudstones and coals. Note the thick soft sediment deformed interval. This along with high concentrations of organic-rich laminae and weakly to non-bioturbated mudstones, indicates a deltaic environment. Location: 07-26-69-09W6, 1870.1-1901.7m.

convolute bedding, and siderite are common. Bioturbation is typically of low intensity, sporadically distributed, and of very low diversity (see Chapter Two).

Environment

This facies association represents a shoaling upward sequence with fair-weather deposited muds interbedded with storm-emplaced sands within a storm-dominated lower shoreface environment (MacEachern and Pemberton, 1992; Walker and Plint, 1992; MacEachern and Hobbs, 2004). The low-angle convex-upward and –downward curvilinear sub-planar laminated sandstone beds within Facies 3a, 3b, and 4a are interpreted as hummocky cross-stratification (Harms et al., 1975; Walker and Plint, 1992). The low-angle sub-planar convex-downward laminations found in the upper portion of Facies 4a are interpreted as swaley cross-stratification (SCS). Hummocky cross-stratification forms during storm sedimentation with sediment suspension fallout reworked into hummocks and swales by strong wave oscillation (Harms et al., 1975; Dott and Bourgeois, 1982). Storms rework the sediment through storm-generated long-period oscillatory-dominant combined flows generated by shoaling swell waves propagating onshore (Leckie and Walker, 1982; Myrow and Southard, 1996; Dumas et al., 2005). Swaley cross-stratification has a similar origin. However, it forms in a higher energy shallower water environment, with the hummocks eroded off by subsequent storms (Leckie and Walker, 1982). During these storms, sediment is transported into the lower shoreface and by offshore directed, geostrophic flows (Myrow and Southard, 1996). This is responsible for the emplacement of thin conglomerate beds in the lower shoreface (i.e. Facies 4a). The exact formation of HCS still remains controversial but will not be discussed further in this thesis.

In more distal regions (i.e. Facies 3a), these tempestites are interbedded with thoroughly bioturbated mudstones. A typical succession includes thoroughly bioturbated mudstones overlain by sharp-based hummocky cross-stratified sandstones containing escape structures, a bioturbated upper portion of the sand bed, and finally thoroughly bioturbated mudstones again (Pemberton and MacEachern, 1997). In this succession sandier intervals were emplaced by storms, while the bioturbated mudstone beds were deposited during fair-weather conditions (Walker and Plint, 1992; Pemberton and

MacEachern, 1997). The fact that the bioturbated mudstone beds are preserved and not eroded by the next storm event indicates extended periods of fair-weather deposition, reduced erosional capability, and greater water depths compared to other higher-energy facies (i.e. Facies 4a) (Pemberton and Frey, 1984; Saunders et al., 1994; Pemberton and MacEachern, 1997). Facies 3a contains two distinct trace fossil assemblages associated with varying energy conditions, pre-storm and post-storm (Pemberton and MacEachern, 1997). The post-storm assemblage consists of trace fossils with characteristics of the *Skolithos* Ichnofacies (MacEachern and Pemberton, 1992). These characteristics include ichnogenera with primarily vertical burrows and are dominated by suspension feeding behaviors. This trace fossil suite represents opportunistic (r-selected behaviors) organisms burrowing the uppermost portion of each storm-generated sandstone bed (Pemberton and MacEachern, 1997; MacEachern, 2000; Pemberton et al., 2001). Opportunistic communities are quick to colonize the new uninhabited post-storm substrates (MacEachern, 2000). These communities are gradually replaced by normal fair-weather equilibrium (k-selected behaviors) suites and represent the pre-storm, or fair-weather assemblage (Pemberton and MacEachern, 1997; Pemberton et al., 2001). This assemblage shares characteristics with the *Cruziana* Ichnofacies and represents a stable benthic community with a high degree of bioturbation. Facies 3a represent deposition within a storm-dominated distal lower shoreface environment (Moslow and Pemberton, 1988; MacEachern and Pemberton, 1992).

The interbedded storm-emplaced sandstones and fair-weather mudstones of Facies 3a transition upward into the storm-amalgamated sandstone beds of Facies 4a. At shallower water depths (i.e. above fair-weather wave base) high-energy storms have significant erosion associated with the deposition of thick HCS sand packages (Leckie and Walker, 1982). This produces a set of amalgamated HCS sandstone beds with no intervening fair-weather mudstone beds preserved (Fig. 3.5). The fact that these sandstones contain very little bioturbation indicates rapid deposition and that the uppermost, likely burrowed, portion of the previous sandstone bed was most likely eroded. Based on these trends, FA1 is interpreted to represent shallowing upward deposition from the distal lower shoreface to the middle shoreface and lies progressively higher above fair-weather wave base (Massari and Parea, 1988; Moslow and Pemberton,

1988). This is supported by the upward increase in grain size, randomly dispersed pebble content, and occurrence of conglomerate beds. The shallowing upward trend within Facies 4a is evident in the upward transition from HCS (proximal lower shoreface) to SCS (middle shoreface) as well as the erosional amalgamation of sand beds (Leckie and Walker, 1982; Myrow and Southard, 1996; Dumas et al., 2005). As sandstone beds continue to amalgamate in progressively higher-energy (i.e shallower water) settings the hummocks (convex-upward) are eroded off and only the swales (convex-downward) are preserved (Leckie and Walker, 1982). The pre- and post-storm subdivision does not apply in the proximal lower shoreface due to the erosional amalgamation of successive beds. In this case only deeply penetrating vertical burrows and escape structures are preserved (Pemberton et al., 1992c). In the proximal lower shoreface, bioturbation is generally only found within thin para-*Macaronichnus*, *Palaeophycus,* and *Macaronichnus segregatis* burrowed intervals near the top of FA1. This interval has been referred to as the "burrowed zone" by other authors (e.g. MacEachern, 1994; Saunders et al., 1994) and is discussed in detail in Chapter Two. This extensive amalgamation of HCS/SCS sandstones within Facies 4a indicates the presence of frequent high-energy storm events. This also indicates that storm events have occurred with some regularity in order to produce consistent amalgamation. Hurricanes, along with intense high-frequency winter storms occurring on a yearly basis are interpreted to be the cause (Saunders et al., 1994). This interpretation is supported by paleoclimatic models, which indicate a relatively heightened potential for winter storms in the Cretaceous Interior Seaway (Barron, 1989; Erickson and Slingerland, 1990).

Facies Association One also represents the proximal prodelta/distal delta-front environment considering differentiating it from the upper offshore/lower shoreface in wave-/storm-dominated settings is difficult (Moslow and Pemberton, 1988; Gingras et al., 1998). Similar wave- and storm-generated physical structures occur in both environments, which produce similar successions. However, the presence of Facies 3b and thicker muddier successions may indicate a deltaic environment (Fig. 3.6). The presence of abundant organic-rich muds, convolute bedding, syneresis cracks, and siderite are also preliminary indicators for deltaic environments (Moslow and Pemberton, 1988; MacEachern, 1994; Gingras et al., 1998; Coates, 2001; Bann and Fielding, 2004;

Coates and MacEachern, in press). Dark organic-rich mudstones can be associated with river-flood events following prolonged storms (Leithold, 1989; MacEachern, 1994). Also associated with river-flood discharge is the mantling of storm beds with increased concentrations of plant debris washed seaward from the delta-plain (Raychaudhuri and Pemberton, 1992; Saunders et al., 1994). Convoluted bedding is reasonably distinctive of deltaic environments and is indicative of increased sedimentation rates (Bhattacharya and Walker, 1992; MacEachern, 1994; Coates, 2001). Syneresis cracks generally indicate fluctuating salinities associated with freshwater input (Burst, 1965; Plummer and Gostin, 1981; Pemberton and Wightman, 1992). And increased sideritic intervals are produced by the degradation of increased quantities of organic-material by bacterial action (Coleman, 1993). Ichnology can be the most useful tool in distinguishing between the two settings due to the environmental stresses introduced by deltaic point sources (Moslow and Pemberton, 1988; Gingras et al., 1998, Coates, 2001). Non-bioturbated or sparsely bioturbated mudstones in these settings can indicate a stressful environment in which bioturbation was not present or was greatly suppressed during fair-weather time. Facies 3b is therefore interpreted to represent a prodelta to distal delta-front environment where fluvial influences result in freshwater and sediment input, thereby greatly decreasing the abundance and diversity of bioturbation (MacEachern et al., 2005).

Differentiating these environments becomes even more difficult in the distal delta-front (Moslow and Pemberton, 1988). In this setting most of the distal delta-front environment is dominated by the storm-amalgamated very fine-grained sandstones from Facies 4a. Without intervening fair-weather mudstone beds to illustrate the different ichnological suites present, proximal lower and middle shoreface deposits are sedimentologically very similar to their deltaic counterparts. Wave-dominated delta front deposits when protected from frequent storm erosion, can show some of the most diverse trace fossil assemblages (Gingras et al., 1998; MacEachern et al., 2005; Gani et al., 2007). However, due to significant storm-bed amalgamation and a general lacking of trace fossils, ichnology cannot be used to its full potential in this case. In these settings, the low trace fossil abundance may be a reflection of the high-energy and high frequency of sediment reworking along the delta-front during storms (MacEachern, 1994; Saunders et al., 1994; Gingras et al., 1998; MacEachern et al., 2005). Therefore, delta-front and

lower/middle shoreface deposits are very difficult to distinguish in wave-/storm-dominated settings due to similar process acting on both environments. An extended discussion focusing on differentiating proximal prodelta/distal delta-front deposits from upper offshore/lower shoreface deposits is included within the depositional model section below.

Facies Association Two (FA2) – Wave-Dominated Upper Shoreface and Foreshore

Facies Association Two represents the distal upper shoreface to foreshore environment (Clifton et al., 1971; MacEachern and Pemberton, 1992). This is volumetrically the most dominant facies association present in core intervals within the study area. There are seven facies present within FA2. These include, in a distal to proximal arrangement, Facies 4b, 7, 8a, 6, and 4c. They generally occur in a predictable coarsening-upward trend with Facies 4b at the base and Facies 8a, 6, and 4c at the top (Fig. 3.7). In most cases Facies 4b sharply overlies deposits of FA1 in a commonly erosional relationship. Facies 8a and 4c are then overlain by muddier facies from FA4 and/or FA5. The component facies of FA2 generally comprise the uppermost portion of the Falher "D" sandbody and form a coarsening upward succession. Locally, FA2 can make up the entire Falher "D" marine succession. The vertical and lateral variability of FA2 is greater than any other facies association in regards to grain size, thickness, and facies variability. Due to the increased grain size compared to the other facies associations, rock within FA2 constitutes the greatest reservoir potential. Coarse-grained sandstones and conglomerate of FA2 host the Falher "D" pool located in the west-central portion of the study area (Arnott, 1994). As such, the greatest core control occurs within these regions.

Description and Facies Relationships

The very fine- to fine-grained trough cross-bedded sandstones of Facies 4b represent the most distal facies present within FA2. This facies sharply overlies the HCS/SCS sandstones from Facies 4a. Organic detritus, coal fragments, and wood fragments are all locally common and found along bedding planes. Interbedded mL-cU

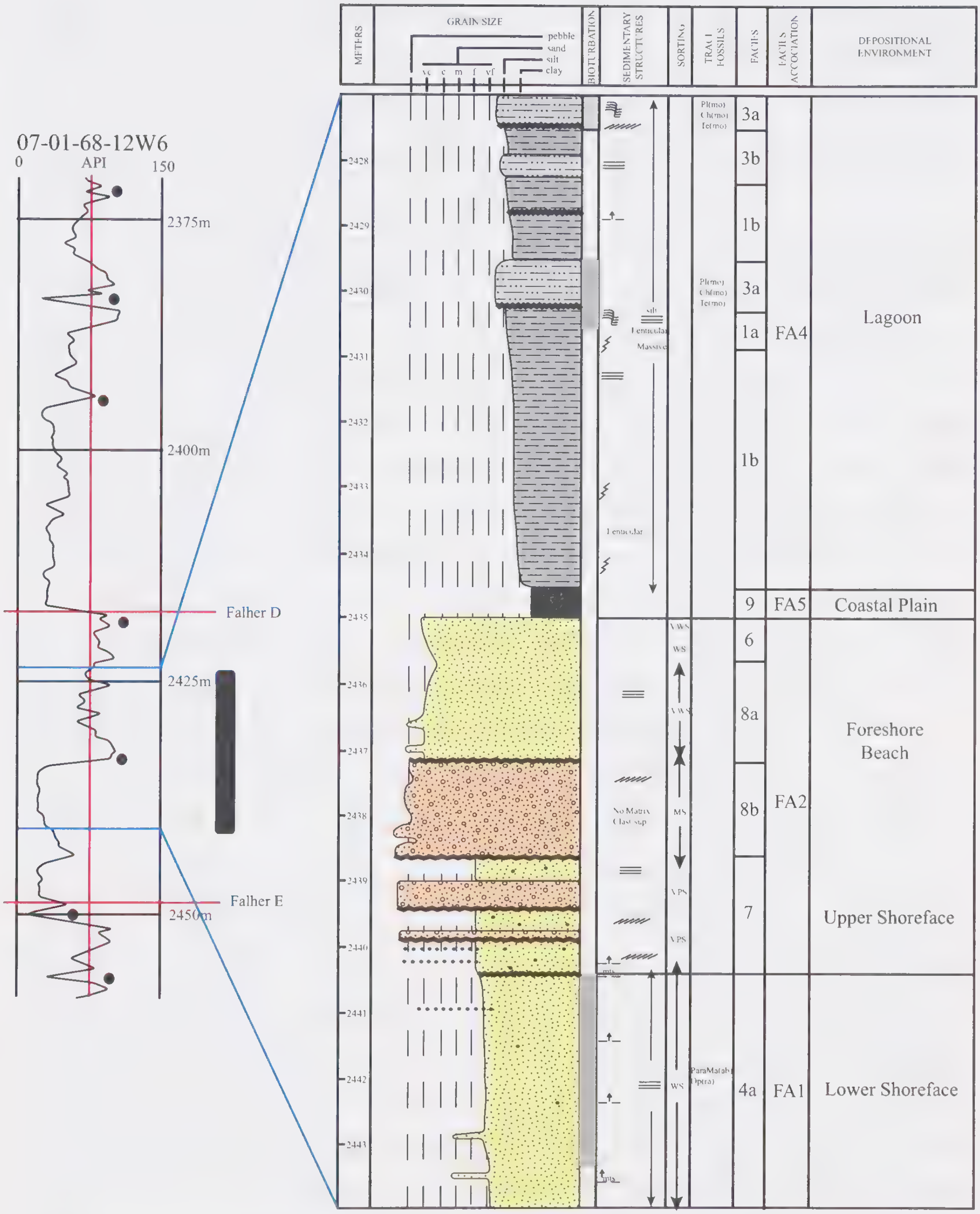

Fig. 3.7 - Typical Falher “D” succession. The very fine-grained lower shoreface is sharply overlain by the well-sorted upper shoreface and foreshore. Location: 07-01-68-12W6, 2427.1m - 2443.8m.

sand stringers, randomly dispersed pebbles, and thin conglomerate beds are common and generally increase upward. Bioturbation is very sporadically distributed and contains relatively low diversities. Burrows are generally dominated by vertical structures with the exception of para-*Macaronichnus*. The trace fossil suite present within Facies 4b represents a low diversity expression of the *Skolithos* Ichnofacies (Pemberton and MacEachern, 1992).

Facies 4b grades upward, continuing the coarsening upward profile, into the interbedded sandstones and conglomerates of Facies 7. Sandstone beds contain abundant randomly dispersed pebbles and coarse sand stringers. Sorting ranges from very poorly to well sorted but generally displays moderate sorting. Internal stratification includes trough cross stratification with less common planar lamination. Intervening conglomerate beds are clast-supported with poor to moderate sorting. Matrix, when present, ranges in grain size from vfL-mU sand. Clast sizes range from cU sand grains to 3 cm pebbles, which are subrounded to well rounded and have low to moderate sphericity. Beds range from 2 cm to 40 cm in thickness and display abundant trough cross-stratification with lesser amounts of planar laminations and massive bedding. Most conglomerate beds are generally sharp-based and contain significant erosion. The thickness of conglomerate beds generally increases upward through facies.

In the western portion of the study area (R12W6-R13W6) Facies 6, 8a, and 8b erosively overlie Facies 7. Facies 8a includes well to very well sorted clast-supported small pebble conglomerates (Fig. 3.8). Clast sizes range from 2 mm – 10 mm and are well rounded. Internal stratification includes planar parallel laminations, low angle (less than 10 degrees) laminations, and apparently massive bedding. Facies 8b consists of bimodal clast-supported conglomerates. Clasts are comparatively large ranging from 0.5 cm to 3 cm and generally very well rounded. These conglomerates are clast-supported however they do include a significant proportion of very fine sandy matrix (roughly 30-40%). The grain size of the matrix ranges from vfL–fL sand. The internal stratification of Facies 8b appears to be primarily massively bedded due to its bimodal nature. However upon further investigation Facies 8b shows abundant high angle cross bedding and trough cross-stratification. Facies 8b is interbedded locally within the lower part of Facies 8a or lies directly below. Facies 6 consists of well to very well sorted medium- to

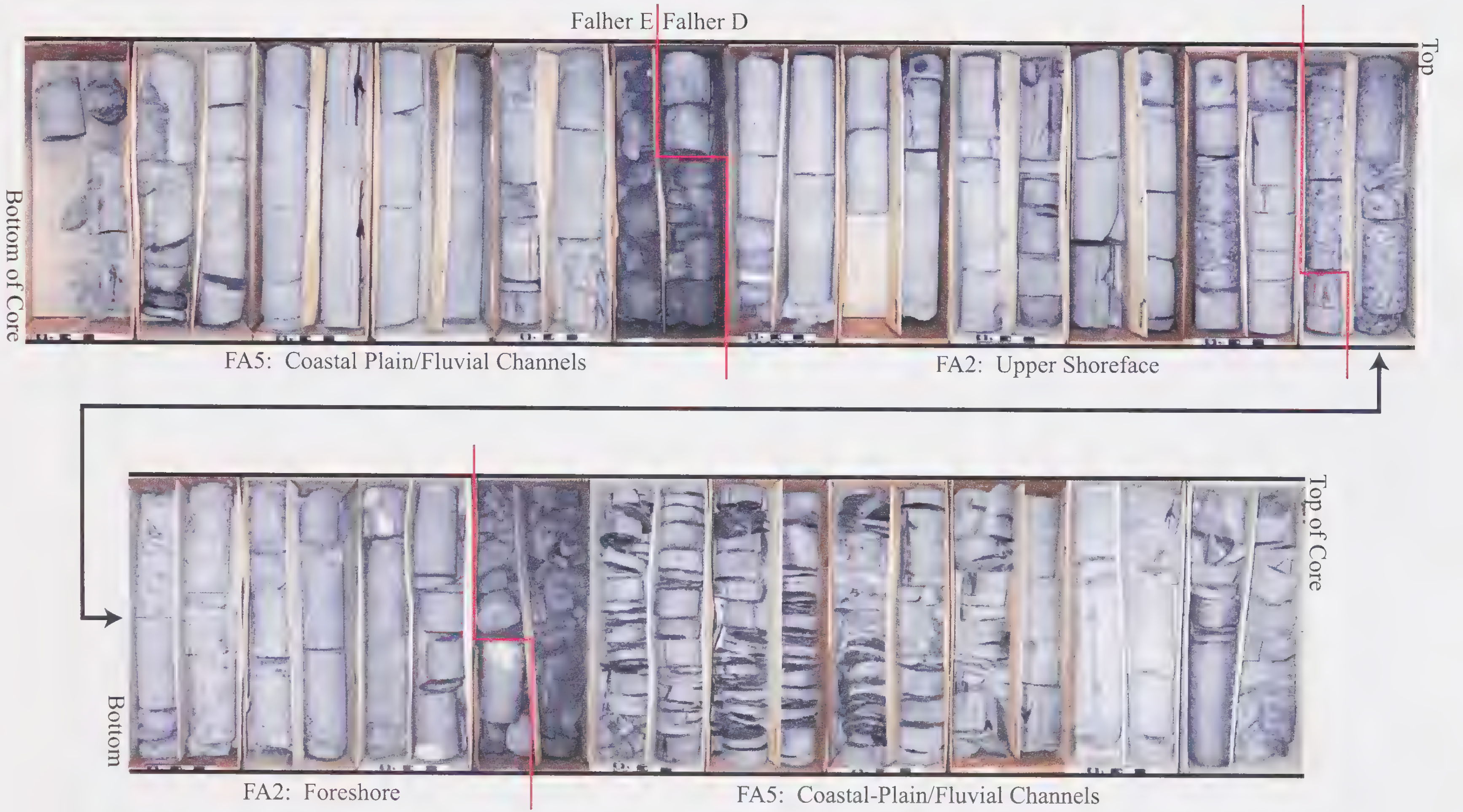

Fig. 3.8 - Strandplain succession from the Falher "D". Trough cross-bedded sandstones (FA2) from the Falher "D" sharply overlie coastal-plain deposits (FA5) from the Falher "E". This surface represents a major transgressive surface of erosion. These sandstones coarsen upwards and are sharply overlain by unimodal and biomodal conglomerates deposited within the foreshore (FA2). Location: 11-07-68-12W6, 2490.5-2515.5m.

very coarse-grained sandstones. Overall most of this facies appears massively bedded however the contacts between individual beds are planar to gently inclined. Weakly defined planar to sub-planar laminations are also common throughout. There are also rare examples of low angle cross-bedding, internal irregular scoured contacts, and randomly distributed chert pebbles and granules. Facies 6 is present above Facies 8a in most of the western portion of the study area however in some localities Facies 6 completely replaces Facies 8a. In some locations very fine- to fine-grained planar laminated sandstones from Facies 4c cap FA2. These sandstones are very well sorted with locally abundant heavy mineral laminations. The uppermost sections of Facies 4c are generally strongly rooted and contain abundant coal lenses and organic detritus.

In the central portion of the study area (R10W6) FA2 is replaced with thicker, more poorly-sorted facies including Facies 7 and 8b. This region will be discussed within FA3. Facies Association Two in the eastern portion of the study area (R8W6-R9W6) is noticeably absent of conglomerate-rich facies. Very fine-grained trough cross-bedded sandstones from Facies 4b and fine-grained planar laminated sandstones from 4c dominate FA2. In this region Facies 7 is very rare, and Facies 8a and 8b are absent.

Environment

The upward coarsening succession in FA2 from the trough cross-stratified sandstones of Facies 4b to the planar laminated conglomerates and sandstones of Facies 8a and 4c respectively, indicate a wave-dominated upper shoreface to foreshore succession (Clifton et al., 1971; MacEachern and Pemberton, 1992). The trough cross-bedded fine-grained sandstones of Facies 4b are interpreted to have formed in a distal upper shoreface environment (Hunter et al., 1979; Massari and Parea, 1988). As incoming waves approach the shoreface (i.e. above fair-weather wave base) they make contact with the substrate and become steeper (Reading, 1989; Walker and Plint, 1992). These shoaling fair-weather waves produce oscillation-ripples or, in the presence of weak currents, combined flow ripples (Dott and Bourgeois, 1982; Dumas et al., 2005). Eventually, the waves become over-steepened and break within the breaker zone. Through wave breaking, oscillatory wave motion is converted into wave-forced currents in the surf zone (i.e. upper shoreface) (Dumas et al., 2005). When fair-weather wave

approach the shoreline at oblique angles, along shore directed wave-forced currents are produced (Komar, 1977; Reineck and Singh, 1980). This results in a portion of the wave being deflected laterally parallel to shore. These currents are referred to as longshore currents and result in the formation of trough cross-stratification (Harms et al., 1975). Longshore currents are important in redistributing sediment along-strike due to their high velocities and lateral displacement of water (Komar, 1977). However, the overall effect of such transport has been interpreted to be relatively small (Reineck and Singh, 1980). Rip-currents are formed when longshore currents return seaward as narrow near-surface currents. The sharp contact between Facies 4a and 4b, and hence between FA2 and FA1, is attributed to the migration of rip-channels cutting through the longshore bar (i.e base of the distal upper shoreface) (Reading, 1989). This represents an erosional surface as the coarser-grained upper shoreface progrades over the underlying middle and lower shoreface. These offshore-directed rip-currents result in the deposition of coarser material into the proximal lower shoreface. It should be noted that the slope of the shoreface controls the width of the surf zone (Komar, 1976). Gently dipping shorefaces tend to have very wide surf zones where as more steeply dipping shorefaces tend to have very narrow surf zones. The fine-grained sandstones of Facies 4b eventually coarsen upward into the interbedded sandstones and conglomerates of Facies 7. These deposits represent deposition within the proximal upper shoreface.

The foreshore occurs within the intertidal portion of the shoreface and directly overlies the proximal upper shoreface (Clifton, 1971). In this setting the surf zone transitions landward into the swash zone. This zone is affected by rapid swash flow up the beachface and is followed immediately by backwash flow down the beachface. This results in the formation of very well sorted sediment and seaward dipping (3-12 degrees) sub-planar lamination (Clifton, 1971; Massari and Parea, 1988; MacEachern and Pemberton, 1992). In this setting the largest clasts are only moved during high-energy storm events. This results in the coarser sediment typically sitting higher up in the foreshore, above the storm ridge (Leithold and Bourgeois, 1984). Coarse sand and conglomerate-rich Facies 6 and 8a would be formed in this environment where storm activity would be greatest. Very well-sorted unimodal granule and fine pebble

conglomerates would result from the intense winnowing of the finer sediment. This occurs due to the constant "back and forth" action that takes place within the foreshore.

In was proposed in Chapter Two that gravel for Facies 8a and 8b could be sourced from nearby deltaic point sources and reworked along-strike by longshore drift. Therefore, the poorly sorted conglomerates of Facies 8c (FA3) could be the updrift source for better-sorted conglomerates in Facies 6 and 8a (FA2). Longshore drift would carry sediment deposited at distributary mouths downdrift and thereby increase the level of sorting the farther the sediment is transported. This explains why Facies 6 and 8a tend to be significantly finer grained than Facies 8c (see FA3). Another possibility is the in-place reworking of delta-front and delta-plain deposits after delta lobe abandonment (Arnott, 1994). Subsidence of the delta front and delta-plain would result in the apparent "transgression" of that delta lobe even though the overall region is prograding. This would result in the formation of well-sorted conglomerates from Facies 6 and 8a near the original location of the delta lobe. Longshore drift would undoubtedly rework and transport such sediment downdrift, however the displacement of gravel is interpreted to be relatively minor (Komar, 1977; Reading, 1989; Hart and Plint, 1995). This issue will be discussed in greater detail in Chapter Four.

Discussion: Reservoir Potential

The coarse-grained well-sorted conglomerate-rich facies (Facies 6 and 8a) represent the greatest reservoir potential due to the high degree of sorting and large grain size. A general lack of fine-grained quartz within Facies 8a greatly reduces the formation of quartz overgrowths and therefore allows for greater porosity and permeability compared to more quartz-rich facies (Cant and Ethier, 1984). As well, the original pores were very large due to the increased grain sizes. This results in much higher porosities and permeabilities than any other facies within the Falher "D". However, local carbonate and clay cementation has adversely affected reservoir properties (Smith, 1984). In general most sandstones (Facies 4a and 4b) have undergone a significant reduction in permeability as a result of quartz overgrowth formation, compaction of sedimentary rock fragments, carbonate cementation, and clay cementation (Cant and Ethier, 1984). This results in "tight sandstones" containing large quantities of gas with very low

permeabilities (0.01-1.5 md) (Smith, 1984). However, with the aid of hydraulic fracturing methods, significant gas production is possible (Masters, 1979).

Facies Association Three (FA3) – Wave-Dominated Proximal Delta-Front

Facies Association Three represents the proximal delta-front and is the lateral deltaic equivalent of FA2 (Fig. 3.9) (Bhattacharya and Walker, 1991; MacEachern, 2000). In general, the proximal delta-front is largely similar to the upper shoreface and foreshore due to the fact that both environments are subjected to similar marine processes. However, due to the deltaic influence, FA3 contains a number of significant variations from FA2 and justifies a separate facies association. It should be noted that FA2 and FA3 can be separated as a result of the excellent core control present within the proximal locations of the study area as compared to more distal regions (i.e. FA1). This is the primary reason for the prodelta to distal delta-front and distal lower shoreface to middle shoreface environments being included within the same facies association and the reason why upper shoreface/foreshore and proximal delta-front environments are not. However, both FA2 and FA3 do contain similar facies and a similar facies succession. The facies present within FA3, in a distal to proximal arrangement, include Facies 4b, 7, 8c, and 5. These facies gradationally replace the facies from FA2 along-strike within the central portion of the study area.

Description and Facies Relationships

The facies and facies succession present within FA3 shares a number of sedimentological and ichnological characteristics with those of FA2. However, a number of important differences do occur and this is the rational for separating these associations. The very fine- to fine-grained Facies 4b forms at the base of the FA3 succession and again has a sharp erosional contact with the underlying deposits from Facies 4a (Fig. 3.9). Facies 4b contains a strong coarsening-upward profile with interbedded coarse mL-cU sand stringers, randomly dispersed pebbles, thin conglomerate beds, and the overall grain-size increasing upward. In general, Facies 4b is coarser-grained and contains more randomly dispersed pebbles and thin conglomerate beds in FA3 as compared to FA2. Internal stratification is dominated by trough cross-stratification with lesser amounts of

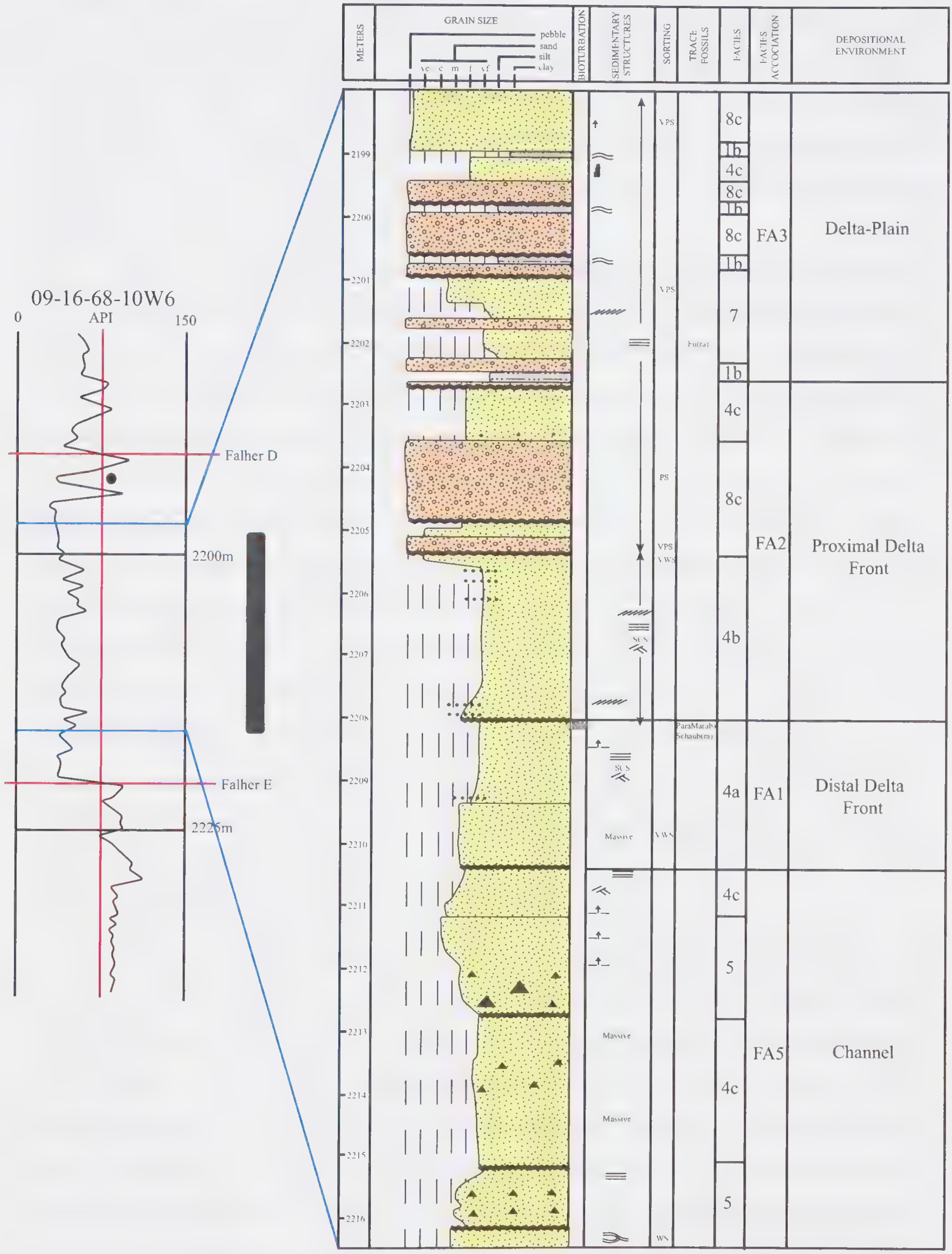

Fig. 3.9 - Typical Proximal Delta-Front environment. The proximal delta-front tends to be a poorly sorted mix of sandstone and conglomerate. Location: 09-16-68-10W6, 2198.0m - 2216.3m.

current-ripples and planar laminations. Organic detritus, coal fragments, and wood fragments are all locally common and found along bedding planes. Bioturbation is generally very sparse with most intervals unburrowed. In FA3, Facies 4b tends to be relatively thin and is quickly overlain by the interbedded sandstones and conglomerates of Facies 7. In some locations, Facies 4b is absent and Facies 7 directly overlies Facies 4a (i.e. FA1).

Sandstone beds from Facies 7 contain abundant randomly dispersed pebbles, coarse sand stringers, and thin conglomerate beds. Grain sorting is generally poor with only rare examples of moderate to well sorting. Internal stratification includes trough cross stratification and less common planar lamination. Overall, the segregation of sandstone and conglomerate is much less distinct for Facies 7 in FA3 as compared to FA2. This is evident with the sandstone beds containing abundant conglomeratic material and conglomerate beds containing an abundant poorly sorted sandy matrix. These intervening conglomerate beds are clast-supported with very poor to moderate sorting. Matrix ranges in grain size from vfL-cU and clast sizes range from cU to 3 cm pebbles. Beds range from 2 cm to 40 cm in thickness and display abundant trough cross-stratification with lesser amounts of planar laminations and massive bedding. Most conglomerate beds are generally sharp-based and contain significant erosion. The thickness of conglomerate beds generally increases upward through the facies. The thickness of the conglomerate beds as well as the overall thickness of Facies 7 contains considerable lateral variation. Facies 7 is thickest in the center of the study area (Range 10W6) and thins rapidly in both eastward and westward directions.

The conglomerate-rich beds of Facies 7 generally thicken upward and amalgamate to form Facies 8c. In some locations, Facies 8c completely replaces Facies 7 and sits sharply above Facies 4b (Fig. 3.9). Facies 8c is very similar to the conglomerate beds present within Facies 7. Conglomerates are clast-supported and very poorly to moderately sorted. The finer-grained matrix comprises between 20-50% and ranges in grain size from vfU-cU. The clast sizes range from vcL to 5 cm pebbles and are generally well rounded. The clasts sphericity varies between spherical and elongated. The internal stratification is dominated by trough cross stratification and planar tabular

cross stratification with less common massive bedding and planar laminations. Organic rich laminae and mudstone rip-up clasts are present locally.

In a number of locations, the fining-upward sandstones of Facies 5 have replaced portions of Facies 4b, and/or 7, and/or 8c. Facies 5 contains fine- to very coarse-grained sandstones with common randomly dispersed pebbles and thin poorly sorted conglomerate beds. Sorting is generally moderate however poor to well sorting does occur locally. The dominant internal stratification types include trough cross-bedding and planar laminations with lesser amounts of current ripples and sub-planar laminations. Mudstone rip-up clasts are common and generally found associated with coarser grain sizes. The basal contact of Facies 5 is sharp and erosional, where as the upper contacts are typically gradational.

Environment

A coarsening-upward profile similar to FA2 combined with the increased thickness and amount of conglomeratic-material, decreased sorting, and association with channelized facies indicates a proximal delta-front environment within a wave-dominated delta (Bhattacharya and Walker, 1992; Orton and Reading, 1993; Hart and Plint, 1995). The proximal delta-front is separated from the underlying distal delta-front and prodelta by a sharp erosional surface created during progradation. As the delta-front progrades over the distal delta-front, migration of rip-channels, created as longshore currents return seaward, erodes the underlying deposits (Reading, 1989). This is similar to the contact between the upper shoreface and the lower shoreface (see FA2). However, distributary channels are present within the proximal delta-front and serve to erode and redistributed sediment across this surface.

Overlying this erosional surface are the trough cross-bedded interbedded sandstones and conglomerates (Facies 4b, 7, 8c) of the proximal delta-front. These facies undergo reworking by waves, wave-induced currents, longshore drift, and storm scour similar to FA2 (Orton and Reading, 1993). They therefore have a remarkable similarity to those facies deposited within the upper shoreface and foreshore. However, these facies contain four primary differences from their FA2 counterparts: (1) an overall increase in facies thicknesses and increased thickness of conglomerate-rich beds; (2) dramatically

decreased sorting; (3) increased grain sizes (i.e. larger pebbles); (4) reduced sand and gravel segregation. Other than these key differences, the proximal delta-front is formed by similar processes as discussed in FA2 and will not be elaborated further here. The differences listed above are highlighted in the lateral variability of Facies 8a/8c with the replacement of the well-sorted small pebble conglomerates of Facies 8a (FA2) with the poorly sorted large pebble conglomerates of Facies 8c (FA3). These differences are attributed primarily to the close proximity and association with distributary channels. Distributary channels erode underlying deposits and supply sediment to the shoreline. As sediment is deposited at the river mouth, wave processes serve to redistribute it along depositional strike (Bhattacharya and Walker, 1992). Due to this input of clastic material, the Falher “D” succession along with Facies 7 and 8c, tend to be thickest near fluvial point sources.

Proximity to distributary channels can result in the deposition of sediment much faster than wave processes can redistribute it during flood events (Dominguez, 1994; Rodriguez et al., 2000). Increased sedimentation rates limit the time available for wave reworking and therefore lead to the preservation of thicker, more poorly sorted deposits. This is especially true for conglomerate-rich Facies 7 and 8c. The decreased sorting and increased thickness of Facies 7 and 8c supports the assertion of rapid deposition at rates faster than can be redistributed along strike by wave processes. This would also explain the increased grain sizes of facies present in FA3 compared to their lateral equivalents in FA2. Significant lateral displacement of the largest pebbles would not be expected. This claim is supported through comparisons of the maximum pebble sizes between Facies 8a and 8c, 0.8 cm and 2.5 cm respectively.

Previous studies on gravelly shorefaces have indicated shoreface conglomerates tend to be better sorted than fluvial conglomerates, and that sand and gravel factions tend to be better segregated in deposits of shallow marine environments (Clifton, 1973; Leithold and Bourgeois, 1984; Orton and Reading, 1993; Hart and Plint, 1995). This has been attributed to the fact that rapid deposition would produce pebbly sands, while prolonged reworking of sand and gravel would segregate and sort the two constituents (Clifton, 1973). This reduced grain size segregation is evident in the Falher “D” with thick intervals of matrix-rich very poorly-sorted conglomerate from Facies 8c found

directly adjacent to distributary channel successions. The reduced sorting and presence of abundant finer grain sizes indicates deposition in a setting where thorough sorting of the sediment is not possible. As such, this facies association is interpreted to represent the sediment deposited in the immediate vicinity of fluvial sources. The consequences of this are thicker, more conglomerate-rich, and more poorly sorted sediment. As the distance from distributary channel mouths increases the amount of sediment deposited decreases and the ability of wave-related processes to rework the sediment increases. This results in a lateral gradation from delta-influenced successions to a typical strandplain succession (i.e. FA2). This supports the earlier hypothesis that the well-sorted sandstones and conglomerates of FA2 were most likely sourced from updrift deposits of FA3, either by longshore drift or through delta lobe abandonment and in-place reworking.

The architecture and geometry of the proximal delta-front of wave-dominated deltas is very similar to typical strandplain environments (Weise, 1980; Coleman and Prior, 1982; Bhattacharya and Giosan, 2003). In wave-dominated deltas localized mouth bars do not normally form and progradation generally involves the entire delta-front (Elliott, 1989). Mouth bars would form immediately after large river floods, however intense wave action would redistribute the sediment downdrift (Rodriguez et al., 2000). This results in a regular shoreline profile (strike-elongated) with very little shoreline protuberance and possible deflection of the distributary mouth (Bhattacharya and Giosan, 2003). Delta-fronts tend to be relatively steep in wave-dominated deltas and progradation tends to be much slower than other delta types (Elliott, 1989). As sediment is supplied to the shoreline by wide, relatively deep distributary channels, longshore drift reworks and carries the sediment downdrift (Coleman and Prior, 1982). Coarser sediment is reworked into nearshore bars near the mouth of the channel and finer sediment is transported into the distal delta front and prodelta (Giosan, 1998). Once these nearshore bars (i.e. barrier bars) received enough sediment they coalesce and become emergent (Bhattacharya and Giosan, 2003). The barrier bar is then reworked shoreward and downdrift by wave action until the downdrift flank is welded to the shoreline (Rodriguez et al., 2000). This will become the new shore or beach of the downdrift flank of the delta. Delta evolution is manner can be highly episodic, characterized by rapid

phases of sediment influx during major river floods and subsequent rapid delta growth (Rodriguez et al., 2000). Slower delta growth, greater reworking, and formation of back-bar lagoons (described in FA4) occurs in-between flood events. This process occurs repeatedly and results in the formation of an amalgamated beach ridge complex with possible intervening lagoons. Fraticelli (2006) expanded on this idea and noted that flood events alone cannot explain the formation of channel mouth-bars. He correlated the development of emergent channel mouth-bars in the Brazos Delta to large climatically induced flood events that follow prolonged droughts. Prolonged droughts removed the vegetation cover in the drainage areas of the Brazos River and allowed sediment to be eroded that would otherwise be protected. These drought-flooding cycles were linked to El Nino-induced floods immediately following La Nina-induced droughts. This illustrates the importance of climatic factors on the formation of deltaic beach ridges as well as the progradation of deltas in general. In this setting each beach ridge complex may contain an intervening lagoon. This appears to be the case in the Falher "D" in the eastern half of the study area. These lagoons tend to be filled in by storm-washover and more fluvial-dominated processes such as possible bay-head delta formation (see FA4). Overall these processes result in the progradation of a sheet-like sandbody, which parallels the shoreline. An excellent example of this is the modern wave-dominated delta along the coast of Costa de Nayarit, Mexico (Curray et al., 1969).

Facies Association Four (FA4) – Lower Delta-Plain and Marginal-Marine Brackish-Water Environments

Facies Association Four encompasses all marginal-marine brackish-water environments present within the study area. This includes the lower delta-plain as well as non-deltaic brackish-water deposits present along the Falher "D" coastline. These environments generally fall between the high and low tide (intertidal region) marks along the Falher "D" shoreline. However, the lower delta-plain would not include the intertidal region along the foreshore. The deltaic equivalent of the foreshore would instead be included within the proximal delta-front (FA3) due to the dominance of wave related processes. All other marginal-marine environments within deltas would be included in the lower delta-plain, including active distributary systems, abandoned distributary-fill,

interdistributary bay deposits, intertidal flats, and inter-abandoned barrier-bar lagoons (MacEachern, 2000). Both marine and fluvial processes, with varying amounts of each, operate within these environments. In general, the facies present in FA4 display a wide range of sedimentary structures and lithologies, however they maintain a distinctive set of ichnological characteristics. This facies association includes the following facies: Facies 1a, 1b, 3a, 3b, 4c, and 5 (Fig. 3.10).

Within the Falher “D” succession FA4 is generally underlain by the proximal marine sandstones and conglomerates of FA2/FA3 and overlain by the non-marine mudstones of FA5. The three regions with the greatest abundance of FA4 are the large extensive lagoons within R8W6 and R9W6, the lagoonal and interdistributary bays in R10W6, and the brackish-water deposits incased within coastal plain near the top of the Falher “D” succession (R13W6). Non-deltaic brackish-water environments are fairly uncommon along wave-dominated coasts, however there are significant local accumulations. The spatial distribution of FA4 will be discussed further in Chapter Four.

Description and Facies Relationships

This facies association is dominated by sand-rich and silt-rich mudstones with variable biological reworking. The facies present within FA4 can also be separated into 2 broad groups based on the amount of biogenic reworking: bioturbated (Facies 1a and 3a) and sparsely-bioturbated (Facies 1b and 3b). The silt-rich mudstones of Facies 1a and 1b are the finest grained facies present in the study and are confined to FA4 and FA5. Facies 1a and 1b are dominated by pin-striped planar laminations and combined flow ripples. Other prominent sedimentary structures include current-ripples and wavy through lenticular bedding. Massive and rhythmic bedding is also commonly found within Facies 1b, as well as pyrite-rich nodules, siderite, and rare bivalve shells. Both facies contain abundant syneresis cracks and localized soft sediment deformation. Very rare desiccation cracks are found within both facies. Facies 1a contains a low diversity trace fossil suite with *Teichichnus, Planolites*, and *Chondrites* burrows the most common. Intervals of abundant reworking by only one ichnofossil (e.g. *Teichichnus*) are abundant

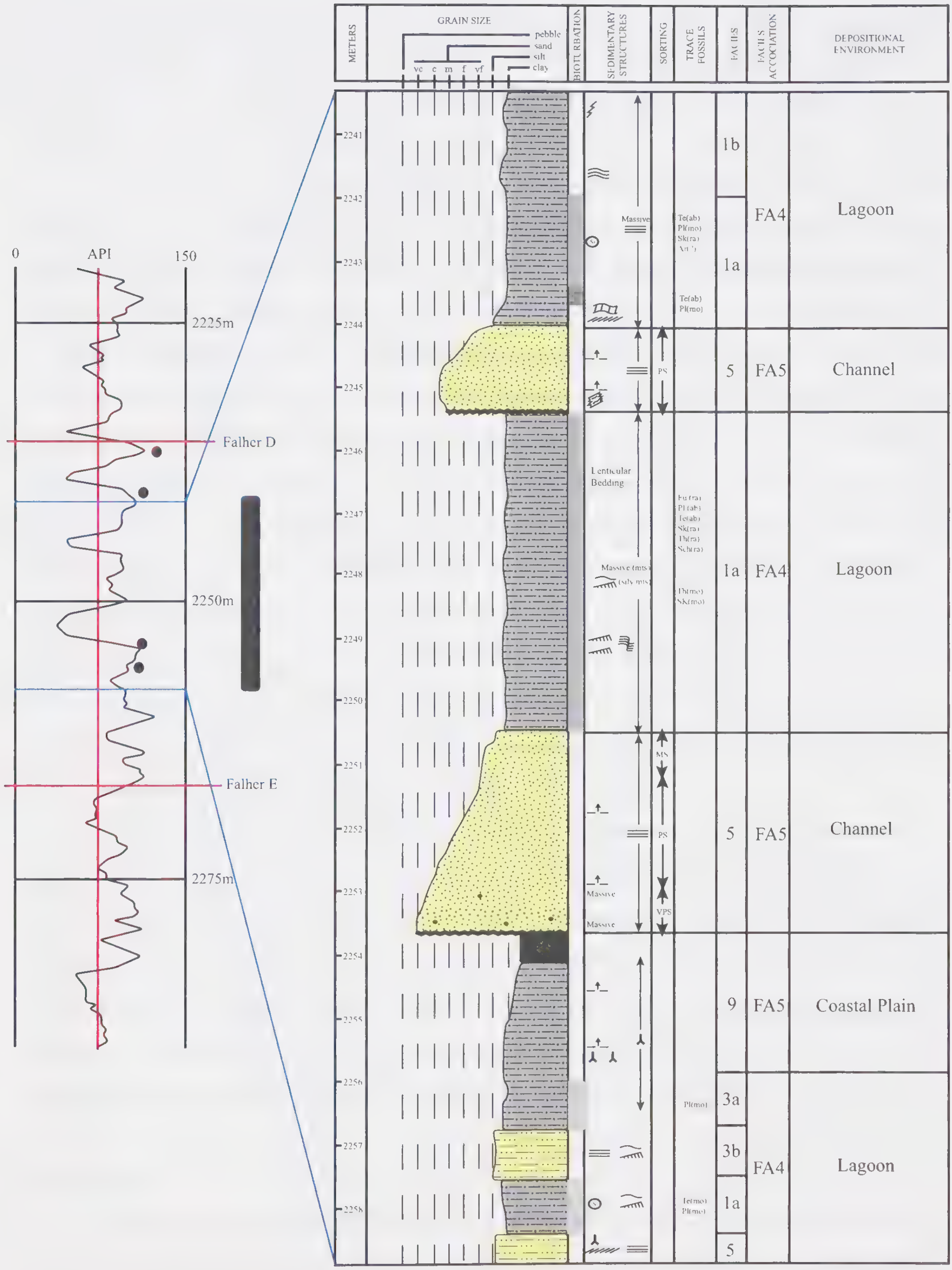

Fig. 3.10 - Typical lower delta-plain deposit. Bioturbated silt-rich mudstones (Facies 1a) in-between fining-upward channel deposits (Facies 5). Location: 06-10-68-10W6, 2240.5m - 2258.8m.

and represent the most common form of bioturbation. However, the intensity of biogenic reworking can be quite high. Facies 1b on the other hand contains very little bioturbation with only very rare *Planolites* burrows. These facies form gradational contacts with the sandier facies (Facies 3a, 3b, and 4c).

Facies 3a and 3b represent interbedded sandstones and mudstones with varying amounts of bioturbation. Combined flow ripples and planar laminations are the dominant types of internal stratification. Muddier intervals contain syneresis cracks and locally abundant rooting, micro faulting, and soft sediment deformation. These facies are very similar to Facies 1a and 1b except they contain a much greater proportion of sand. Grain sizes generally do not exceed fine-grained sand and sandstone beds are not greater than 10cm thick. Facies 1a and 3a contain a similar trace fossil suite with *Planolites*, *Chondrites*, and *Teichichnus* burrows the most common with lesser amounts of *Diplocraterion* and *Thalassinoides*. Facies 3b on the other hand contains only very rare *Planolites* and *Teichichnus* burrows. The planar laminated very fine- to fine-grained sandstones of Facies 4c are also present within FA4 but to a much lesser degree than those described above. These sandstones are generally moderately to well sorted with locally abundant organic-rich laminae and rooting. Other less common stratification types include sub-planar laminations and massive bedding. These sandstones tend to have gradational contacts with Facies 3a and 3b.

These facies are also commonly associated with sharp-based fining-upward sandstones from Facies 5. Grain sizes vary from very fine to coarse sand sized with common small pebbles. The typical internal stratification types include abundant trough cross-bedding and planar laminations with less common current-ripples. Massively bedded intervals containing numerous large angular mudstone rip-up clasts are also quite common. Sandstones from Facies 5 eventually grade upwards into interbedded sandstones and mudstone of Facies 3a and 3b, and eventually into Facies 1a and 1b.

Environment

Facies Association Four represents a wide variety of marginal-marine brackish-water environments present within back-barrier lagoons, as well as within the lower delta-plain (Wightman et al., 1987; Pemberton and Wightman, 1992; Dominguez, 1996;

MacEachern, 2000; Pemberton et al., 2001). Non-deltaic brackish-water environments are fairly uncommon along prograding wave-dominated coastlines, however there are significant local accumulations (Galloway and Hobday, 1998). However, brackish-water deposits comprise a considerable portion of the lower delta-plain especially on the downdrift side of wave-dominated deltas (Dominguez, 1996; Bhattacharya and Giosan, 2003). Environments present in FA4 range from storm washover deposits on the seaward side, to silt-rich mudstones in the central lagoon, to bay-head delta deposits on the landward side.

Immediately landward of the beach and barrier bar deposits (FA2/3), fine-grained planar laminated sandstones of Facies 4c are most abundant and are interpreted as storm washover deposits (McCubbin, 1982). Washover fans are lobe-shaped sand units formed when large storm waves wash sediment over-top of the barrier bar. These deposits can be associated with tidal inlets. Permanent tidal inlets are rare in wave-dominated microtidal environments however large storms can create short-lived temporary tidal-inlets (Elliott, 1989). These channels are cut through the beach face and supply sediment-laden storm-waters to the back-barrier environment (Elliott, 1989). Longshore drift and constant wave-action quickly seal-off most tidal-inlets however they do migrate quickly and can form significant deposits (McCubbin, 1982). The absence of permanent communication with the marine realm and episodic storm-influence will produce widely fluctuating water salinities. These sandier, wave-/storm-dominated facies transition landward into interbedded lagoonal mudstones and sandstones of Facies 3a and 3b. The interbedded sandstones and mudstones of Facies 3a and 3b represent an increased accumulation of sand sized sediment in the lagoon/bay. The presence of common syneresis cracks among interbedded sands and muds indicate that freshwater input may have been associated with deposition of the sand (Burst, 1965). The rarity of mudcracks implies that subaerial exposure was not common and supports the assertion that this was a microtidal environment. As facies are positioned farther landward, marine processes (i.e. waves/storms) decrease and fluvial processes increase (Dalrymple, 1992). The wave-dominated estuary model with its tripartite distribution of total energy, depositional environments, and facies heterogeneity best illustrates this transition (Dalrymple et al., 1992).

Landward of the coastal beaches, the interbedded sands and muds from Facies 3a and 3b transition gradationally into the silt-rich mudstones located in the central basin of the lagoon. The central basin lagoonal mudstones (Facies 1a and 1b) are characterized by planar to current rippled silty mudstones with common syneresis cracks and a characteristic ichnological signature consisting of *Teichichnus*, *Planolites*, and *Chondrites* (Wightman et al., 1987; Beynon and Pemberton, 1992). Trace fossils present within this environment contain a series of similar characteristics that are well documented in the brackish-water model (Pemberton et al., 1992). These characteristics include: a low diversity trace fossil suite, sometimes dominated by a single ichnogenera; predominance of diminutive trace fossils; morphologically simple marine forms constructed by opportunistic trophic generalists; vertical and horizontal traces; and locally dense ichnofossil populations. The characteristics listed above are best observed within the Falher “D” in the monospecific assemblage of *Teichichnus*, which is readily observed within lagoonal mudstones (Wightman et al., 1987). These characteristics are all related to the highly physiologically stressful environment resulting from large salinity fluctuations (Pemberton and Wightman, 1992). Salinity fluctuations occur due to varying amounts of freshwater, from rivers and runoff from land, and saltwater input, from storm-washover and tidal inlets. In general, the diversity and abundance of traces fossils will increase seaward as salinities increase (Beynon and Pemberton, 1992; MacEachern, 2000). Therefore facies 1b and 3b, depending on lithology, will dominate regions with greater freshwater input and the most stressful environments, where as facies 1a and 3a are more typical of brackish water ichnological assemblages. The relative amount of sand and silt also varies depending upon the position within the system (i.e. more sand near the active shoreline and fluvial sources with more mud in the in-between).

On the landward side of the lagoon, fluvial processes are more dominant than marine processes (Dalrymple, 1992). Bay-head delta formation would be expected in regions with active distributaries (MacEachern, 2000; Pemberton et al., 2001). However, that environment was not observed in the core selected for this study. This is attributed to a lack of cored intervals within these environments. Bay-head delta formation would be expected to form significant deposits within the lower delta-plain especially on the downdrift flank of the delta (Rodriguez et al., 2000; Bhattacharya and Giosan, 2003).

These fluvial-dominated systems would be expected to "fill-in" the lagoonal environments in-between beach ridges. Tidal flats, tidal creeks, or salt marshes may flank the margins of lagoonal mudstones (MacEachern, 2000). However, all tidal deposits are extremely rare. This is interpreted to support the claim that this is a microtidal setting.

The lower delta-plain tends to have numerous elongate lagoons existing between abandoned shore parallel beach-ridges (Elliott, 1989). Where as typical non-deltaic brackish-water environments tend to have one large lagoon located between the barrier island (i.e. active shoreline) and the coastal plain (McCubbin, 1982). Lower delta-plain environments also differ in that they have abandoned and active distributary networks cutting through them. The sharp-based poorly sorted conglomerates of Facies 7 and 8c and the fining-upward sandstones of Facies 5 are interpreted as distributary channel fill deposits. In wave-dominated settings distributary channels tend to be volumetrically minor (Bhattacharya and Walker, 1992), however the main channel tends to be wide and deep (MacEachern, 2000). The main channel tends to be relatively stable with much less avulsion than seen with river-dominated deltas (Coleman and Prior, 1982). Interdistributary bays are also present and are contained in-between distributary channels. These bays appear quite similar to lagoons except for greatly reduced biogenic reworking.

Discussion: Asymmetrical Deltas

The processes described above (FA3/FA4) would produce a series of narrow barrier-shoreface sandstones separated by topographically lower areas filled with mostly finer-grained sediment on the downdrift side of the wave-dominated delta (Dominguez, 1996; Bhattacharya and Giosan, 2003). Sediment immediately downdrift of distributary mouths would be the least mature texturally within the system. Extensive lagoons or lakes would also be expected to form downdrift. In contrast, the updrift regions would consist of sheet sandstones/conglomerates representing widespread beach deposits and dramatically less clay and silt (see FA2). These deposits would have resulted from extensive reworking by longshore drift and in the case of the Falher "D" transport from the west. Therefore, the sediment on the updrift flank is not sourced from the immediate distributary channel but rather from other sediment sources farther to the west

(Dominguez, 1996). Possible sources include older abandoned delta lobes (described above), other active deltaic point sources, and other coastal formations. This description fits the asymmetrical wave-dominated delta model developed by Bhattacharya and Giosan (2003). They predicted considerable river-borne muds and a lower maturity of sediment in downdrift areas, and well sorted texturally mature sediment updrift. This appears to be the case in the Falher "D" and will be discussed in greater detail below.

Facies Association Five (FA5) – Coastal Plain and Upper Delta-Plain

This facies association comprises all non-marine environments present above high tide and is the most proximal facies association in this study. This region is dominated by fluvial processes and includes the following environments; fluvial channels, channel overbank/levees, crevasse splays, floodplains, swamps, lakes, and marshes (Wadsworth et al., 2002). These environments exhibit little to no bioturbation and generally include high concentrations of organic matter (Wadsworth et al., 2003). Facies present, in order of increasing grain size, include, Facies 9, 1a, 2, 4c, and 5. Within the study area most deposits in FA5 are interbedded with or closely related to coal deposits. The deltaic regions above the high tide mark are referred to as the upper delta-plain. These deposits are separated from coastal plain deposits based on associated environments, however based upon lithic character alone they are nearly identical (MacEachern, 2000).

This facies association is present throughout the study area and generally makes up the uppermost portion of the Falher "D" succession. Deposits of FA5 tend to either directly overlie marine sandstones and conglomerates of FA2/FA3 or the marginal-marine sandstones and mudstones of FA4. Facies Association Five is overlain by the marine sandstones (FA1) of the Falher "C" succession. High organic content, presence of roots, coal-rich horizons, and a complete lack of trace fossils typify this facies association.

Description and Facies Relationships

This facies association is divided into two subdivisions based on lithology; sandstone-dominated and mudstone-/coal-dominated. The first subdivision includes sand-rich facies with less common mud and rare conglomerate. These facies form clearly

fining-upward successions with interbedded sandstone and conglomerate (Facies 7 and 8c) located at the base, grading upward into the sandstones of Facies 5 and 4c, and finally into silt- and mud-rich Facies 1b and 9. Facies 7 and 8c are generally only found along the bottom 30-40 cm of the succession and are very sharp-based. The fining-upward very fine- to very coarse-grained trough cross-bedded sandstones of Facies 5 gradationally overlie Facies 7 as the conglomerate-rich beds disappear upward. Facies 5 comprises most of the coarser-grained portion of FA5 and can form up to 15 m thick intervals. In some locations, Facies 5 is overlain by Facies 4c. Facies 4c contains planar laminated very fine-grained sandstones. Mudstones rip-up clasts and soft sediment deformation are characteristic of Facies 4c in FA5. These sandstone-rich facies form a gradational upper contact with the overlying silt-rich mudstones and are often interbedded over 10-30 cm intervals. Facies 2 is uncommon within the study area however; it tends to be close associated with Facies 5. Facies 2 consists of massive siltstone and more rare very fine-grained sandstone with interbedded organic-rich deformed mudstone beds. Large angular mudstone rip-up clasts and soft sediment deformation are characteristic of Facies 2.

The second subdivision within FA5 includes the finest-grained facies present within the study area: Facies 1b and 9. Facies 1b contains non-bioturbated silt-rich mudstones, while Facies 9 consists of organic-rich mudstones with interbedded coal. Both facies tend to be massive with common thin planar laminated siltstones and less common very fine-grained sandstone laminae. Abundant rooting results in thorough pedogenic alteration. Coal beds are common and are interbedded throughout. Facies 1b and 9 can comprise most of the Falher "D" succession in the southern most regions of the study area with rare fining-upward sandstone-rich bodies eroding into them.

Environment

This facies association represents the most proximal environments within the study area. This encompasses all non-marine environments located above high-tide and includes both typical coastal plain and the upper delta-plain environments. The upper delta-plain is only distinguishable from FA5 based upon its association with the lower delta-plain and delta-front. Therefore, the coastal plain and upper delta-plain will not be separated in this study.

Based on lithology and environmental interpretations, FA5 is divided into two subdivisions. These subdivisions correspond to those described above. The first subdivision includes the sandstone-dominated facies and include, in order of decreasing grain size, Facies 8c, 7, 5, 4c, and 2. This facies succession is interpreted to represent fining-upward channels and channel margin complexes (Miall, 1992). Facies 2 is interpreted to represent fluvial overbank or levee deposits, which tend to be closely associated with channels. Common large-scale angular mudstone rip-up clasts are thought to represent bank collapse (Pemberton et al., 2001). Fining-upward fine-grained sandstone to large pebble conglomerate successions represents lateral accretion of a fluvial point bar. Channels incising into floodplain deposits create the sharp erosive base of these units. Thickly bedded trough cross-bedded sandstones represent deposition within the main channel (Facies 5), while very fine-grained sandstones and siltstones represent deposition toward the inner portion of channel (Facies 4c and eventually Facies 1b) (Galloway and Hobday, 1996). These channels supply sediment to wave-dominated deltas along the coast, which in-turn supply sediment to the shoreface. Numerous large to small scale fluvial channels are located "behind" the Falher "D" shoreline (T67W6). Fluvial channel networks are most commonly found south the wave-dominated proximal delta-front complexes (FA3) in R10W6. These networks run roughly perpendicular to the paleoshoreline (i.e. north-south) and correspond to the distributary channels of FA3. Wave-dominated deltas are typically limited to one or two distributary channels (Bhattacharya and Walker, 1992). Therefore, it is inferred that most of the recognized channel deposits come from the same main channel network. These channels play an important role in the distribution of sediment along the coast. Channel avulsion can lead to delta lobe abandonment and subsequent establishment at another location (Penland et al., 1985; Arnott, 1994). There are also a number of recognized channel complexes located above the Falher "D" shorefaces. These channels are interpreted as distributary channels feeding wave-dominated deltas farther to the north.

The second subdivision, described above, includes the fine-grained, organic-rich mudstones facies from Facies 1b and 9. These facies are interpreted to represent a wide variety of non-marine environments including floodplain, swamps, lakes, and marshes. This set of environments dominates most of FA5 with only localized occurrences of

fluvial channels cutting through them. Thick coaly mudstones and extensively rooted horizons are generally indicative of swampy environments (Leckie and Kalkreuth, 1990). Low-lying areas behind the active shoreline are typically close to the water table, resulting in conditions favorable to coal development. Sizeable coal accumulations are abundant in the Falher Member/Gates Formation and form significant economic deposits in British Columbia. These coals form above the extensive sand sheets produced from strandplain and deltaic progradation (FA2/3). In this setting the strandplain would begin to subside immediately after deposition and allow ample accommodation space (Leckie and Kalkreuth, 1990). The reduced number of distributary channels associated with wave-dominated systems creates large areas of coastal plain removed from active sedimentation and therefore protected enough to allow significant coal accumulations to form (Dissel et al., 2000). Relatively low ash and sulphur contents indicating protection from fluvial flooding support this claim (Kalkreuth and Leckie, 1989). However, many coals show large amounts of components (ex: inertodetrinite and vitrinite B) that indicate sporadic flooding from river and more commonly storm events (Kalkreuth and Leckie, 1989). Coal-bearing units within the Falher Member can reach up to 12 m in thickness and can be traced laterally east-west for over 230 km. This is expected since wave-dominated systems, particularly wave-dominated deltas, tend to form regional extensive coal horizons near the shoreline (Leckie and Kalkreuth, 1990; MacEachern, 2000).

(3.2) Depositional Model: The Presence of Wave-dominated Deltas along a Storm-/Wave-dominated Coastline

The deposits of the Falher "D" within the study area are undoubtedly storm- and wave-dominated and consist of extensive linear strandplains. Typical coastlines contain numerous fluvial channels terminating along the shoreline and the Falher "D" is no different (Fig. 3.11). These channels supply sediment to the shoreline and produce localized deltaic point sources. However, due to the strong wave-/storm-climate, marine processes rework these deposits and redistribute sediment along the shoreline. This results in the formation of strike-elongated wave-dominated deltas. As with all deltas, the wave-dominated variety contains a delta-plain, delta-front, and prodelta. These environments vary in their similarity to their laterally equivalent strandplains and have historically been very difficult to differentiate (Moslow and Pemberton, 1988). Therefore long stretches, sometimes greater than a 100 km, of wave-dominated coastline will labeled as a continuous strandplain. This is undoubtedly incorrect and has important implications in potential exploration and reservoir morphology. There are however a number of important characteristics that can be used to differentiate the two. Recently a number of authors have attempted to differentiate wave-dominated deltas from typical strandplains (e.g. Coastes, 2001; Bhattacharya and Giosan, 2003; Hobbs, 2004; MacEachern et al., 2005; Coates and MacEachern, in press) and have made important contributions. The following section will describe the along-strike transition from delta to strandplain in the Falher "D" succession, the characteristics of wave-dominated deltas, and possible methods of differentiating such environments.

Typical Vertical Succession and Along-strike Transition

The Falher "D" succession, based upon the facies associations described above, is interpreted to be composed of a wave-/storm-dominated strandplain and laterally equivalent wave-dominated deltas. The most distal facies association described in this study is the Lower Shoreface/Distal Delta-Front (FA1). This facies association is composed of a coarsening-upwards succession of storm-dominated shoreface and delta-front environments. Facies 3a and 4a represent distal lower shoreface to middle shoreface deposits in strandplains. Laterally equivalent prodelta to distal delta-front

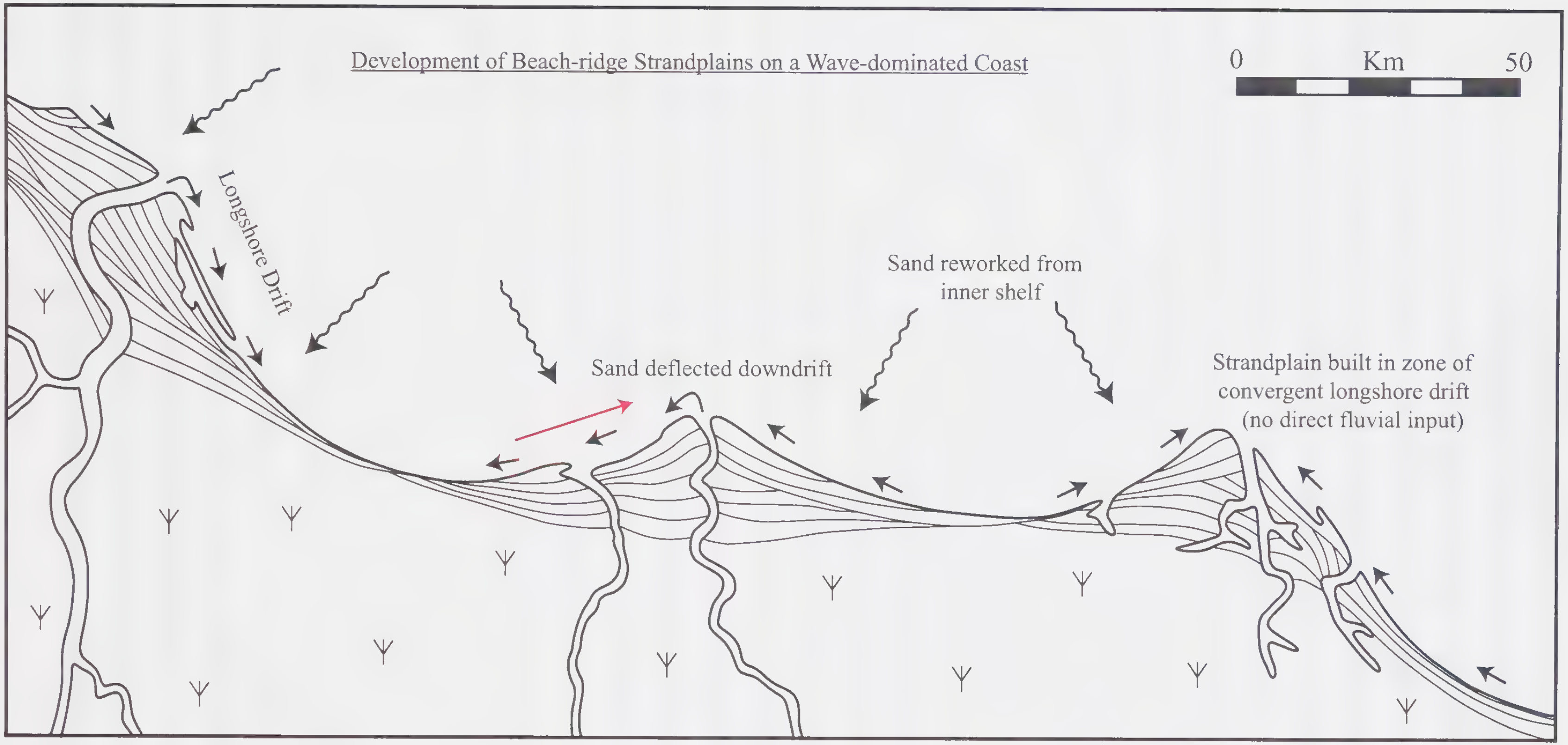

Fig. 3.11 - Idealized diagram illustrating the development of beach-ridge strandplains on a wave-dominated coast undergoing relative sea level fall. Most sand supplied by rivers is deflected alongshore and contributes to the downdrift strandplain (Modified from Dominguez et al., 1987; Walker and Plint, 1992). The asymmetrical delta model (Bhattacharya and Giosan, 2003) predicts that the bulk of sediment deposited on the updrift flank of some deltas may come from the alongshore drift of sediment from another delta located farther updrift. This would suggest that the longshore drift direction maybe incorrect in these cases (red arrow indicates the revised longshore drift direction).

deposits contain Facies 3b and 4a. The extremely high storm reworking of all deposits within FA1 makes the differentiation of these two subenvironments very difficult. However, distal delta-front deposits tend to have more mudstone, soft sediment deformation, syneresis cracks, organic muds, and reduced ichnological signatures compared to its along-strike counterparts (Elliott, 1989; MacEachern, 1994; Gingras et al., 1998; MacEachern et al., 2005; Coates and MacEachern, in press). Most fair-weather deposition, with rare exceptions, has been eroded by subsequent storm events and therefore is not preserved. This indicates the presence of frequent intense storms along the entire Falher "D" coastline in the study area (Saunders et al., 1994).

Sharply overlying FA1 are the wave- and storm-dominated upper shoreface and foreshore (FA2) or proximal delta-front deposits (FA3). Due to the effects of fluvial point sources along the shoreline, the proximal facies associations contain a much greater degree of along-strike variability. Associated with these fluvial point sources are wave-dominated deltas, which form as sediment from distributary channels is deposited at the shoreline (FA3). This sediment is then reworked and redistributed by wave action and longshore drift in a downdrift direction into deltaic barrier bars that eventually form beach ridge complexes separated by intervening lagoons (FA4) (Dominguez, 1996). The updrift component of the delta is formed from the along shore transport of sediment from the west and closely resembles a typical strandplain (FA2). Deltaic deposits tend to form thick coarsening-upward successions, have thicker more poorly sorted conglomerate-rich intervals, tend to be located in proximity to fluvial systems, and have a greater proportion of organic material, mudstone rip-up clasts, and other characteristics associated with fluvial deposition.

Fluvially influenced deposits grade laterally into purely wave-/storm-dominated strandplain systems (FA2). Trough cross-bedded sandstones (Facies 4b) with significant pebbles and thin conglomerate beds sharply overlie FA1 and form within the distal upper shoreface. These deposits coarsen-upwards into interbedded sandstones and conglomerates (Facies 7) formed within the proximal upper shoreface, and eventually into thick very well-sorted conglomerates (Facies 8a) formed in the foreshore. Due to the extensive reworking by wave action and frequent storm activity in this environment, these foreshore beach conglomerates tend to be very well-sorted, planar-laminated, and

have good lateral continuity. Deltaic point sources, similar to FA3, supply the sand and gravel that will eventually form FA2. This results in an along-strike transition from relatively poorly sorted thicker deltaic deposits (FA3) into thinner more well-sorted strandplain deposits (FA2). Strandplain and wave-dominated deltaic environments only display minor differences and are generally difficult to differentiate.

Foreshore beaches pass landward into marginal-marine lagoonal environments from FA4 and eventually into the non-marine coastal plain environments of FA5. These environments represent the most proximal observed within the study area. Brackish-water conditions form near the coastline where rare influxes of seawater produce lagoons or bays. This commonly occurs within the lower delta-plain, especially on the downdrift flank of deltas as described above (Bhattacharya and Giosan, 2003). Non-deltaic brackish-water conditions are also present in other locations, however these tend to be volumetrically minor. The high water table associated with wave-dominated systems as well as the rapid subsidence of the delta-front and delta-plain result in the frequent flooding of the lower-lying areas and produces extensive marsh or swamp environments (Dissel et al., 2000). Regionally extensive coal and organic-rich horizons result from these conditions. These deposits are locally cross-cut by higher-energy fluvial systems feeding deltaic deposits along the coast. These fluvial systems tend to form in a north-northeast to south-southwest orientation, directly perpendicular to the shoreline.

Discussion: Wave-Dominated Deltas vs. Strandplains

Deltas are defined as "discrete shoreline protuberances formed where rivers enter oceans, semi-enclosed seas, lakes or lagoons (standing bodies of water), and supply sediment more rapidly than it can be redistributed by basinal processes" (Elliott, 1989). The morphology of each delta is controlled by two principal factors. The first and most important is the relative dominance of river sediment input, wave-energy, and tidal flux (Galloway, 1975). The second is the relative density of the river inflow with respect to the receiving basin. Where the river outflow is more dense than the standing water body, it is referred to as hyperpycnal flow, equally dense is referred to as homopycnal flow, and less dense is referred to as hypopycnal flow (Bhattacharya and Walker, 1992). The most common classification of deltas, referred to as the tripartite model, is based on the nature

of the delta-front regime: fluvial-dominated, tide-dominated, and wave-dominated (Galloway, 1975) (Fig. 3.12). Wave-dominated deltas will be examined in greater detail in the following sections and will be contrasted with strandplains.

Strandplains are prograding shorefaces built seaward by waves and currents spanning long distances along the coastline (Curray et al., 1969). They are characterized by sub-parallel to parallel amalgamated beach ridges, directly connected to the coastal plain, that form sand-dominated coarsening-upward successions (Reading and Collinson, 1996). Strandplains tend to lack extensive lagoonal environments and tidal channels, which are more common in transgressive barrier island environments. The best-documented example is the Costa de Nayarit strandplain in Mexico (Curray et al., 1969). Strandplains lack major fluvial input, as in wave-dominated deltas, however they are ultimately fed by longshore drift from fluvial point sources farther along the coast (Walker and Plint, 1992). These systems generally form vertical successions that are very similar to wave-dominated deltas in many regards. However, the lack of a direct fluvial source results in many sedimentological and ichnological differences. The purpose of the following section is to highlight these differences and relate them to the Falher "D" succession.

Characteristics and Geometry

Wave-dominated deltas normally occur in settings with strong wave climate and comparatively weak tides (Galloway, 1975). In general, wave-dominated deltas consist of one or two active river mouths, which will produce off-lapping lenses of delta-front deposits (Pemberton et al., 2001). However, high-energy wave activity causes rapid diffusion and deceleration of river flow. This occurs when fluvial outflow is considerably weaker than wave energy. Under these conditions distributary-mouth sands are reworked by waves and redistributed along the delta-front by strong longshore drift. These processes result in the formation of extensive sandy beaches, barrier bars, and delta-front deposits. Any mud present within the system will be confined to marshes and delta-plains or winnowed out and transported seaward into the prodelta (Bhattacharya and Walker, 1992). The result is an increase in energy upwards within the succession and domination by sandy wave-generated structures. The sandy nature of wave-

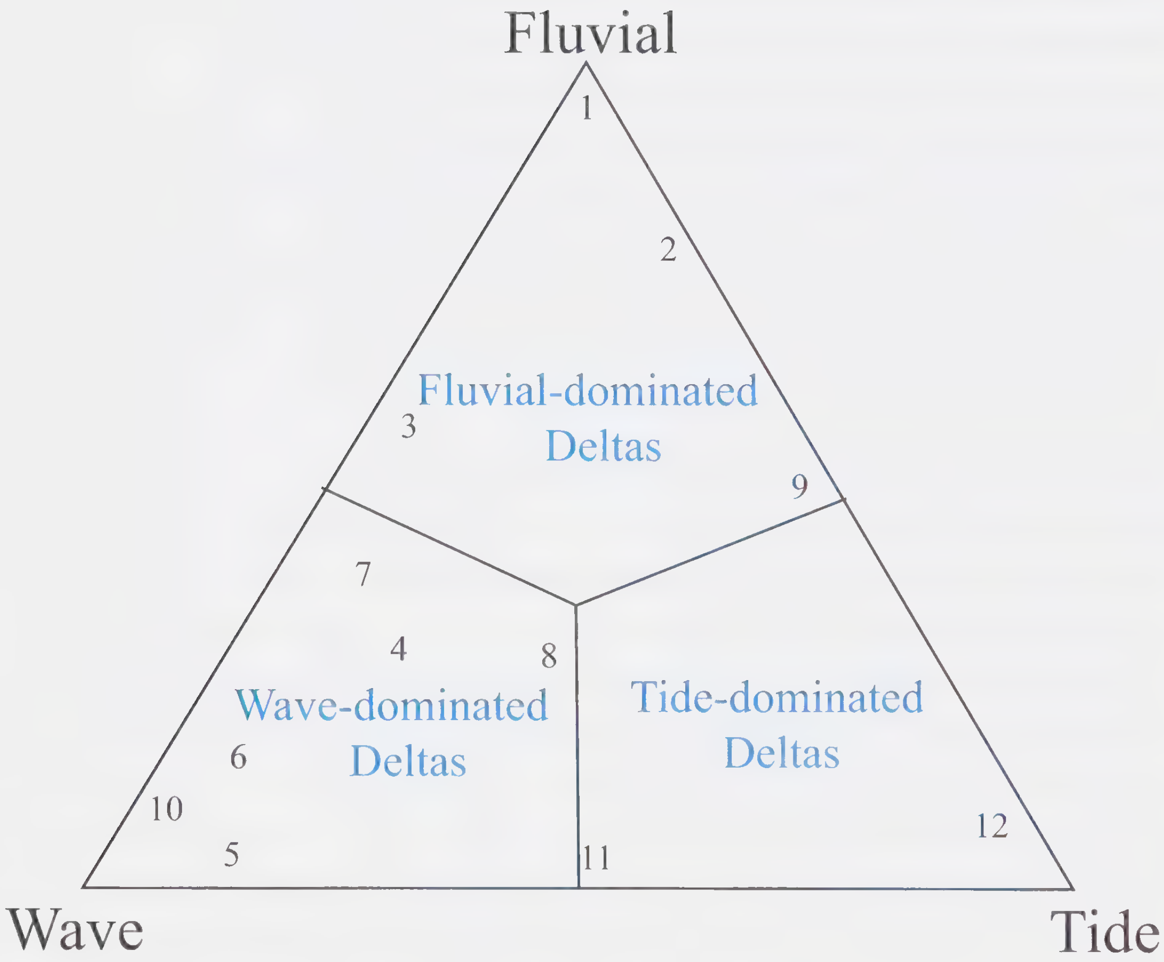

Fig. 3.12 - Tripartite classification of delta types (modified after Galloway, 1975). (1) Mississippi Delta (2) Fraser Delta (3) La Fourche Delta (4) Nile Delta (5) Sao Francisco Delta (6) Rhone Delta (7) Tiber Delta (8) Niger Delta (9) Mahakarn Delta (10) Senegai Delta (11) Copper Delta (12) Fly Delta

dominated deltas results in gamma ray log profiles that are commonly smoother than those of river-dominated deltas (Van Wagoner, 1990) (Fig. 3.13).

Although storms and fair-weather waves are distinct processes, wave dominance is frequently accompanied by, but not always, a strong storm influence (MacEachern et al., 2005). Therefore, in some cases (e.g. Falher "D") the delta-front can be dominated by storm events, resulting in hummocky cross-stratified (HCS) and swaley cross-stratified (SCS) dominated successions. These successions tend to be coarsening-upward and closely resemble storm-dominated shorefaces (i.e. strandplains). This results in great difficulty differentiating strandplains from truly wave-dominated deltas. This is the main reason why strandplains as long as 300 km long have been documented. This occurs even though no strandplain even remotely close to this length has ever been documented in modern environments.

The geometry of deltas is mainly controlled by the two principle factors discussed above. The most important factor is the degree of reworking by marine processes (Weise, 1980) (Fig. 3.14). Deltaic environments with very little marine reworking, as in river-dominated systems, result in lobate geometries. It is this lobate geometry that is generally included in the definition of deltas as "discrete shoreline protuberances". However, strong wave intensities will result in strongly modified lobate depositional patterns. This is the case in wave-dominated deltas, where lateral redistribution of sand will result in strike-elongated geometries (Fig. 3.14). With increased reworking by marine processes, deltas can become very difficult to distinguish from normal shoreface successions based on geometry alone.

Delta Asymmetry and Delta Lobe Abandonment

Wave-influenced/wave-dominated settings with strong longshore drift will have sediment preferentially move downdrift of distributary mouths. This can result in the formation of deltas with asymmetric geometries and facies distributions (Bhattacharya and Giosan, 2003) (Fig. 3.15). In this model, fluvially derived sediment and associated environmental stresses, such as turbid mud plumes and salinity fluctuations will be deflected downdrift of the river mouth. Consequently, the downdrift region will exhibit

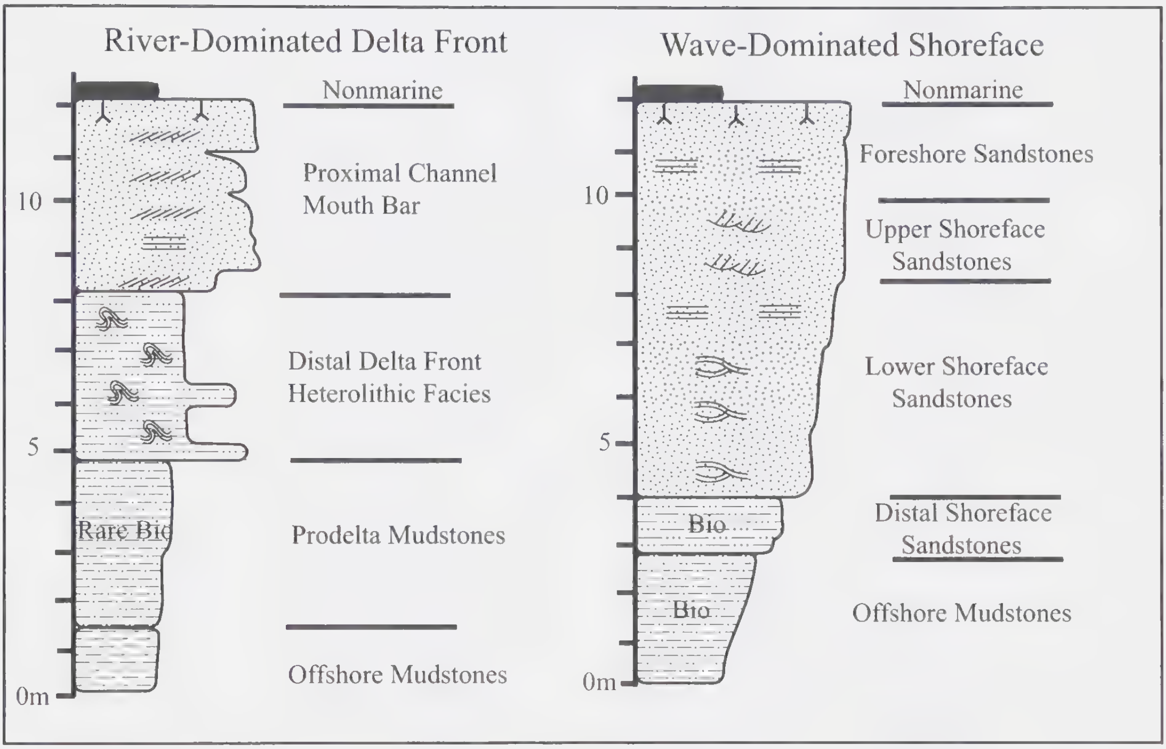

Fig. 3.13 - Comparison of delta front successions in river-dominated vs. wave-dominated successions. The sandy wave-dominated shoreface successions would be more typical of the updrift flank of a wave-dominated delta, but could also represent a prograding non-deltaic shoreface. The fluvial-dominated succession would be more typical of the downdrift flank of a wave-dominated delta (modified after Bhattacharya and Walker, 1992).

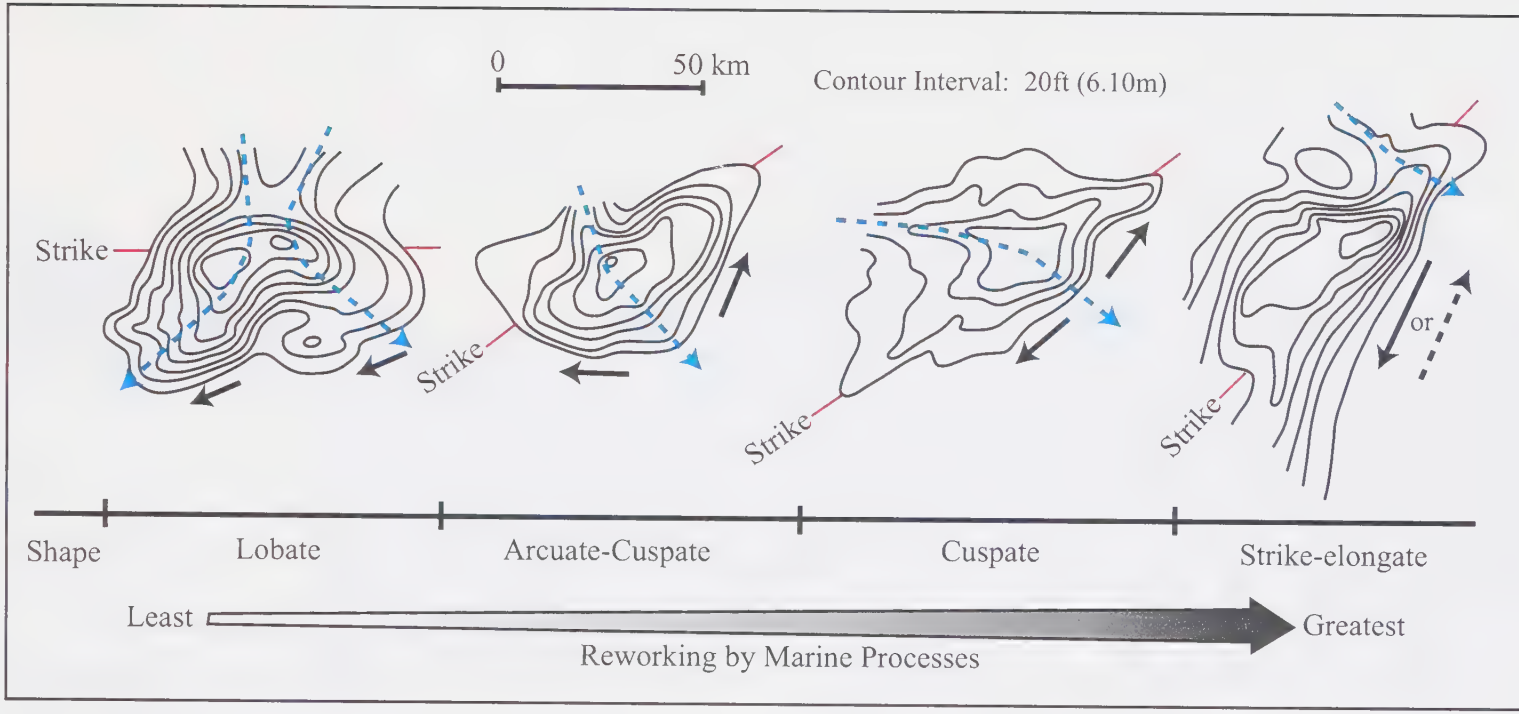

Fig. 3.14 - Range of wave-dominated delta net sandstone geometries ranging from lobate to strike-elongate, which are the result of differences in the degree of reworking by marine processes. Blue arrows represent sediment input and black arrows represent longshore drift direction (modified after Weise, 1980). The strike-elongate shaped delta has two possible longshore drift directions due to the asymmetrical delta model, which predicts that the bulk of sand deposition is on the updrift flank (Bhattacharya and Giosan, 2003).

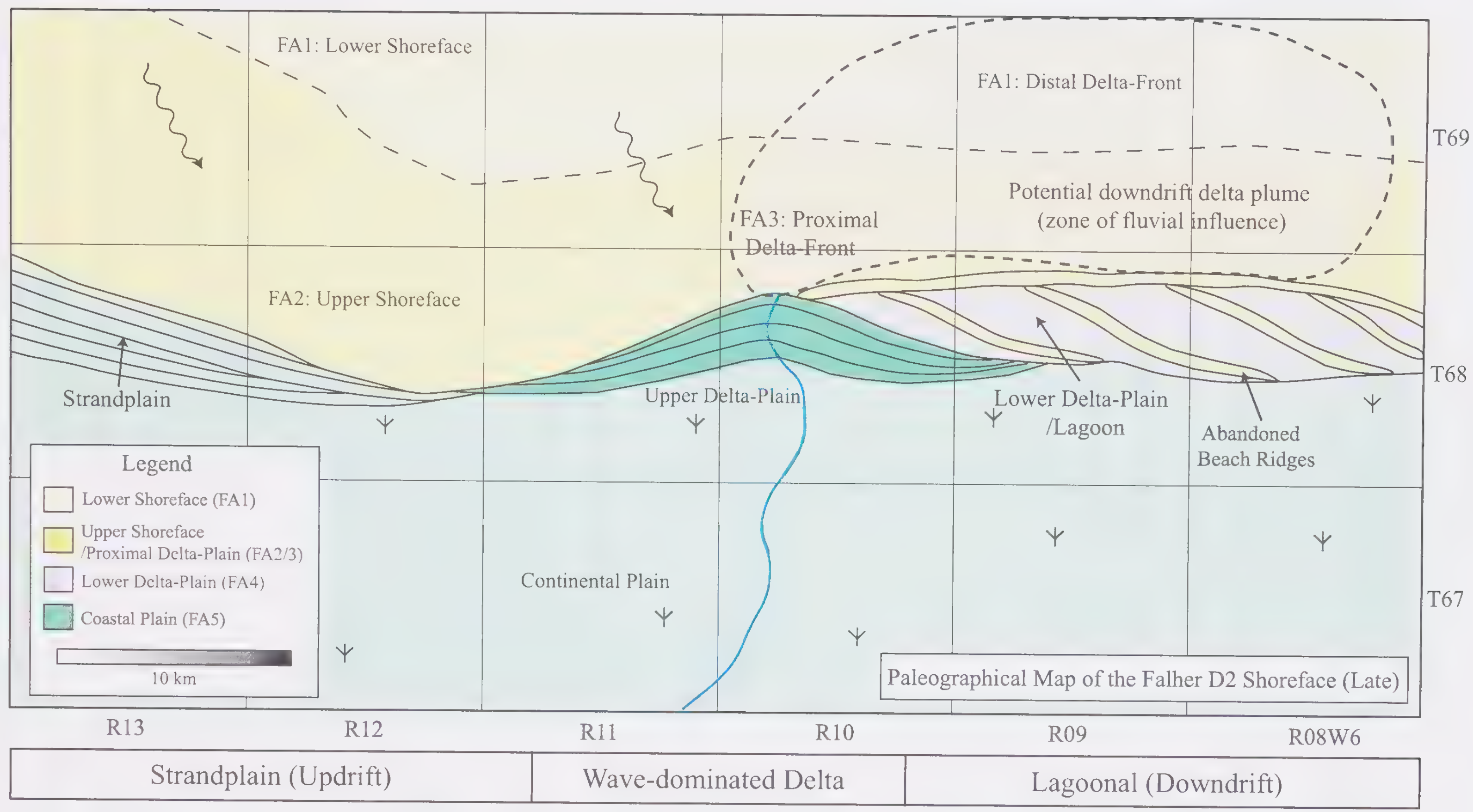

Fig. 3.15 - Paleogeographic reconstruction of the Falher D2 shoreline at the maximum northward progradation of the D2 unit. This period of the Falher "D" deposition illustrates the major components of an asymmetrical wave-dominated delta. The western portion of the study area is dominated by updrift strandplain deposits, while the central and eastern regions are dominated by deltaic complexes and downdrift lagoonal deposits respectively. This is consistent with the asymmetrical delta model discussed in ChaptersThree (Bhattacharya and Giosan, 2003).

characteristics illustrating fluvial discharge and the updrift region will not. Under these conditions, the updrift region would have sediment sourced not from the nearby fluvial channels but rather from the longshore transport of sediment from other sources farther updrift. These sources of sediment could include other active deltaic point sources and/or abandoned delta lobes.

On the downdrift side of wave-dominated deltas, one would expect a pronounced fluvial-influence on deposition; including increased rates of deposition, salinity fluctuations, turbid mud plumes, reduced oxygenation, and water stratification. However, the increased wave activity present within wave-dominated deltas serves to mediate these stresses (MacEachern et al., 2005). As well, increased storm amalgamation reduces the preserved record of fair-weather deposition and hence most fluvial indicators (Saunders et al., 1992). In these settings, wave energy is effective at removing clay/silt from the substrate and transporting it offshore. This produces a clean sandy substrate within most of the delta-front. However, the water column would remain highly turbid preventing the formation of suspension-feeding structures (Gingras et al., 1998; MacEachern et al., 2005). This would leave high-energy sandy substrates dominated by deposit-feeding structures. This distribution is evident in the Falher "D" with a general absence of suspension-feeding traces including *Diplocraterion*, *Ophiomorpha*, and *Skolithos*. Also, reduced trace fossil abundances and diversities are common on the downdrift flank of wave-dominated deltas in the Falher "D" (see Chapter Four). This is attributed to salinity fluctuations, turbid mud plumes, and reduced oxygenation linked to phytodetrital pluses during river-flood events (MacEachern et al., 2005). In more proximal settings, heterolithic successions and brackish-water conditions can form in the proximal delta-front and lower delta-plain if lower energy embyaments occur (Bhattacharya and Giosan, 2003). This forms a prominent feature in the eastern half of the study area in the Falher "D" (Fig. 3.16).

In contrast, updrift of the river mouth, one would expect very little fluvial influence. The updrift part of the delta would consist of a massive amalgamated sand-dominated (and conglomeratic if a source was available) beach ridge complex sourced from sediment input farther along the coast (Dominguez, 1996) (Fig. 3.17). The sedimentary succession in this setting would be very similar to and difficult to distinguish

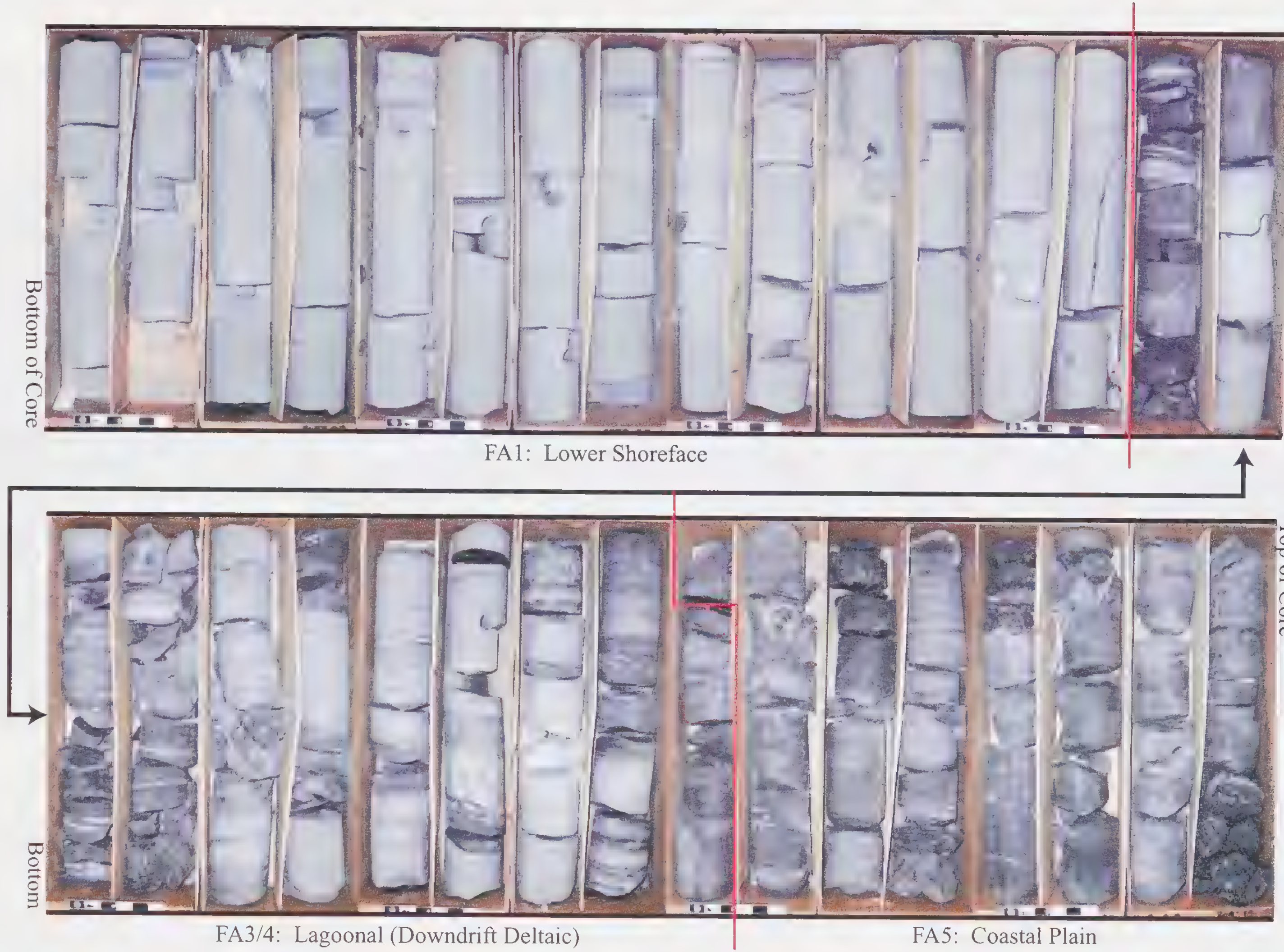

Fig. 3.16 - Deltaic influenced succession located on the downdrift portion of a wave-dominated delta from the Falher D member. The lower half of the core represents a shoaling upward succession deposited within the lower shoreface. These deposits are sharply overlain by lagoonal deposits interpreted to be present in-between barrier bars within the downdrift flank of the delta. Core photos taken from well 15-21-68-08W6, depth 2043.1-2061.6m.

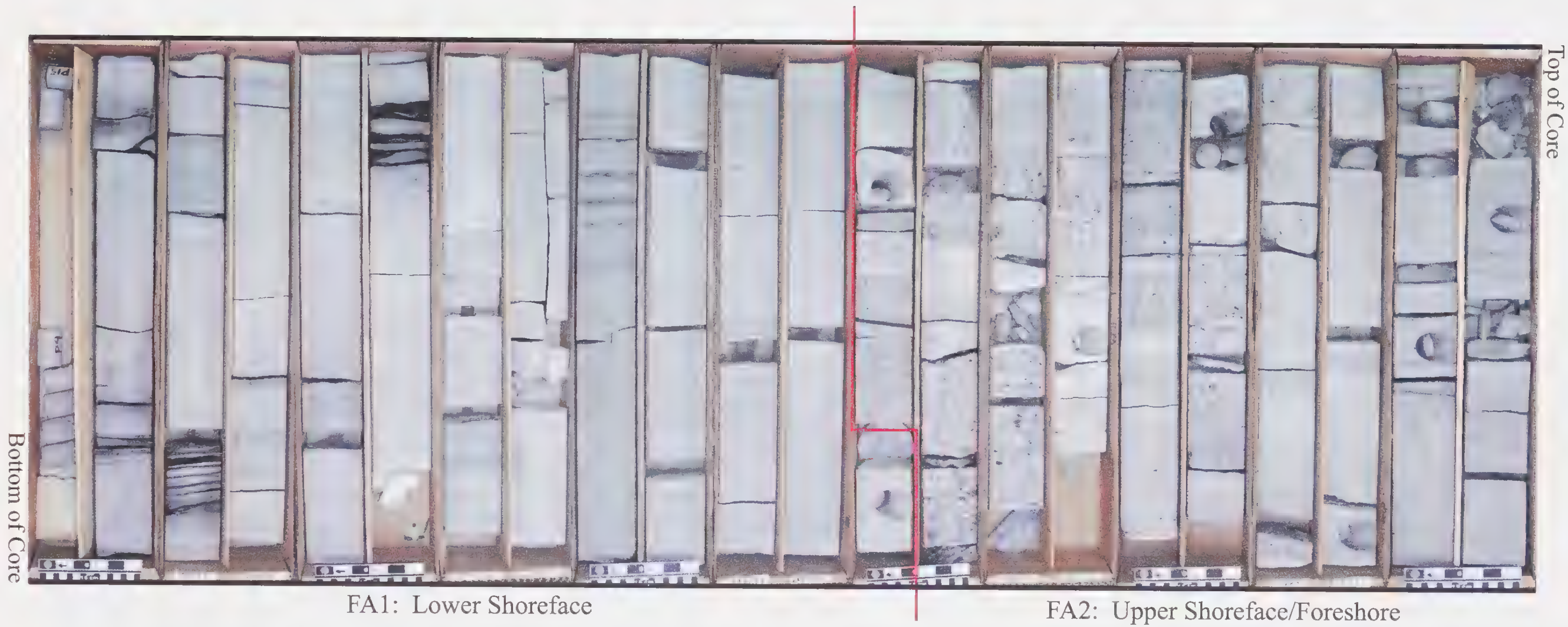

Fig. 3.17 - Strandplain succession within the Falher "D". This core is located within the updrift portion of a large wave-dominated delta. Moderately bioturbated sandstone with thin mudstone interbeds coarsens-upward into storm amalgamated HCS/SCS sandstone. These deposits are sharply overlain by trough cross-bedded sandstones and moderately sorted conglomerates. Core photos taken from well 06-15-68-11W6, depth 2317.4-2331.8m.

from typical strandplains. This is a marked departure from the classic model of wave-dominated deltas where arcuate to cuspate lobes form and all sediment is derived directly from the associated river (Bhattacharya and Walker, 1992). However, this model is still accurate in settings where the net longshore drift of sediment at the river mouth is minor and symmetrical delta geometries would be expected.

The main requirement in the development of asymmetrical deltas is the presence of strong longshore drift (Bhattacharya and Giosan, 2003). The presence of a strong longshore drift has been proven true along many shorelines in the Western Canadian Sedimentary Basin and is inferred in the Falher "D" succession (Ericksen and Slingerland, 1990; Saunders et al., 1994). Another important feature in asymmetrical delta formation is the presence of an updrift source of sediment. These can occur in the form of another active deltaic system, older abandoned delta lobes, other coastal formations, and lowstand shelf sands (Bhattacharya and Giosan, 2003). In the case of the Falher "D", the interpreted source of sediment is an older abandoned delta lobe located along the British Columbia – Alberta broader and/or other active deltas. Another requirement for asymmetrical delta formation is high levels of fluvial discharge capable of exerting a strong groyne effect in order to block sediment drift. This will result in the updrift retention of sediment moving along the coast and restrict further along-strike movement past the river mouth. If this is not the case then the updrift sediment will continue moving along-strike and will result in the deflection of the river mouth parallel to the shoreline.

In a number of recent studies, ancient and modern wave-dominated deltas have been reevaluated and interpreted as asymmetrical wave-dominated deltas (e.g., Dominguez, 1996; Giosan, 1998; Giosan et al., 1999; Rodriguez et al., 2000; Bhattacharya and Giosan, 2003; Hansen and MacEachern, in press). The modern Sf. Georghe Lobe of the Danube Delta contains clear asymmetry with sandy amalgamated beach ridges on the updrift side (north) and thin sandy ridges encased in muddy delta-plain on the downdrift side (south) (Giosan, 1999). The modern Brazos Delta is another example with a similar facies distribution as seen in the Sf. Georghe Lobe, Danube Delta (Rodriguez et al., 2000) (Fig. 3.18). However, the development of the Brazos Delta is strongly controlled by short-term river-flood events. Even the Sao Francisco delta, which

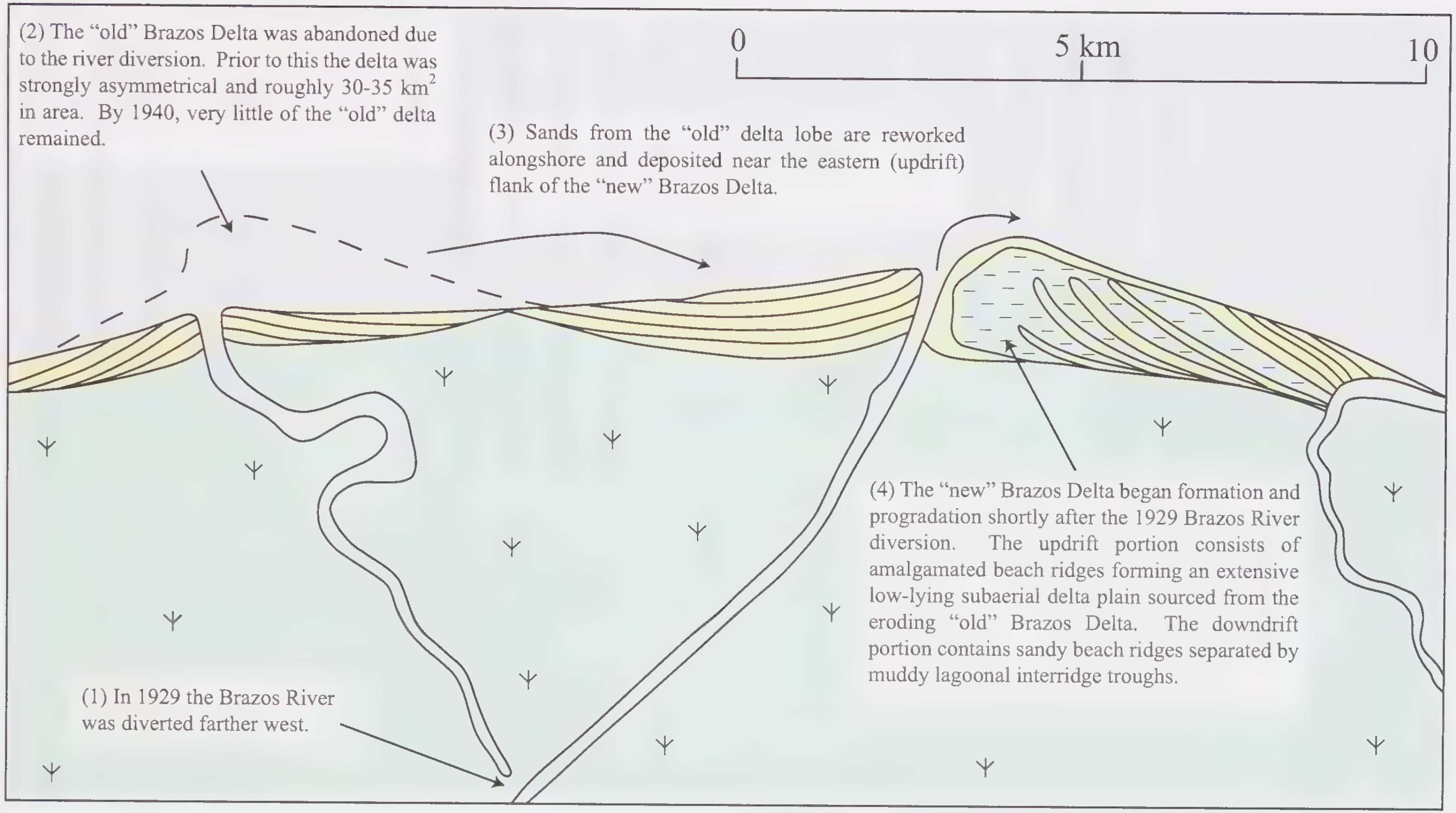

Fig. 3.18 - Line drawing of the Brazos Delta, Texas (after Rodriguez et al., 2000). This illustrates the morphology of a modern asymmetrical delta (Bhattacharya and Giosan, 2003). The morphology, evolution, and scale of the Brazos Delta servers, to an extent, as a reasonable modern analog for the Falher D Member. The lack of a pronounced protuberance, the presence of updrift strandplain deposits, the presence of downdrift lagoonal deposits, and the relative distance of the updrift source of sediment (i.e. older abandoned delta lobe) are all fairly similar to the Falher D member. The Brazos Delta tends to be strongly influenced during floods and wave influenced during intervening periods (Rodriguez et al., 2000).

has been considered a classic wave-dominated delta for years, contains clear asymmetry in facies distribution (Dominguez, 1996).

All three of these modern deltas listed above contain a similar pattern of facies distribution, with a sandstone-dominated updrift region and a heterolithic-dominated downdrift region. Each example also contains an updrift source of sediment in the form of abandoned delta lobes or other active delta lobes. If delta lobe abandonment occurs in a wave-dominated delta, extensive wave reworking would probably obliterate the potential lobe and the entire area of the former delta would be transgressed (Elliott, 1989a). The delta would then transition from a constructive phase into a destructive one. Eroded sediment would then be reworked along the shoreline in the direction of longshore drift. As mentioned above, this can provide sediment for the updrift regions of asymmetrical deltas found farther along the shoreline. This is the case in the modern Brazos delta (Rodriguez et al., 2000) as well as the Sf. Gheorghe lobe of the modern Danube delta (Giosan, 1998; Giosan et al., 1999). In the Danube delta, the Sulina lobe is largely abandoned and is being eroded. Sands from this lobe are being reworked southward by longshore drift into the updrift flank of the Sf. Gheorghe lobe. In the Brazos Delta, river diversion in 1929 resulted in the abandonment of the "Old" Brazos Delta. Sands from this lobe were reworked along shore and deposited near the eastern (updrift) flank of the "new" Brazos Delta (Fig. 3.18). By 1940, very little of the "old" Brazos Delta remained (Rodriguez et al., 2000). This illustrates the importance of autocyclic controls (e.g. channel avulsion), particularity in deltaic environments. Overall, in terms of geometry, facies distribution, and size the Brazos Delta forms a reasonable modern analog for the asymmetrical wave-dominated delta located along the ancient Falher "D" coastline.

Generalized Sedimentology: Wave-dominated Deltas vs. Strandplains

Both wave-dominated deltas and strandplains form in wave- and storm-dominated systems and therefore produce similar successions. However, wave-dominated deltas contain distributary channels and are thereby affected by fluvial processes. Higher sedimentation rates, river-flood events, and fluvially induced environmental stresses all affect the downdrift regions of wave-dominated deltas. These processes produce

distinctive characteristics that can be used to differentiate deltas and typical shorefaces. Fluvial characteristics are most evident within the prodelta and distal delta-front regions where fair-weather deposits are preserved. Increased storm amalgamation within the upper distal delta-front results in the erosion of fair-weather deposits and subsequent loss of fluvial indicators. Intensely storm-dominated delta-fronts are nearly impossible to differentiate from storm-dominated shorefaces since they both produce coarsening-upward storm amalgamated sandstone successions (Moslow and Pemberton, 1988). Common sedimentological characteristics present in the prodelta, delta-front, and delta-plain of wave-dominated deltas will be discussed and contrasted with laterally equivalent strandplain environments in the following section.

Prodelta

The subaqueous portion of deltas is subdivided into the prodelta, distal delta-front, and proximal delta-front. These facies form the platform over which subaerial deposits prograde as the delta advances seaward. The prodelta region is the least variable subenvironment between the three delta types and the most different from typical shoreface environments (MacEachern, 2000). Muddy deposits dominate the succession with thin hummocky cross-stratified very-fine sandstones interbedded within the upper portion of the prodelta (MacEachern and Pemberton, 1992). These muddier intervals within wave-dominated deltas tend to have lenticular to wavy bedding. Other less common sedimentary structures include combined flow and current ripples also within the upper portion of the prodelta. Distinctive features of the prodelta environment include the presence of convoluted mudstones, increased siderite, organic-rich muds, and syneresis cracks (MacEachern, 1994; Gingras et al., 1998, Coates and MacEachern, 1999; MacEachern, 2000; MacEachern et al., 2005; Coates and MacEachern, in press). This is indicative of the higher sedimentation rates and fluctuating salinities associated with deltas. Hyperpycnal flows created during river flood events could permit the transport of freshwater into the prodelta resulting in the formation of syneresis cracks (Coates and MacEachern, in press) and greatly suppressing the ichnological signature (discussed below). Also associated with river flood events would be increased concentrations of organic material. Increased sideritic intervals could be produced by the degradation of

increased quantities of organic-material by bacteria (Coleman, 1993). However, these features are less common in wave-dominated systems due to the increased wave activity that mediates environmental stresses and reduced sedimentation rates compared to more river-dominated systems (MacEachern et al., 2005). This environment is not common within cored intervals of the Falher "D" due to reduced core control in the northern half of the study area and therefore will not be examined further. Prodelta and laterally adjacent offshore deposits would be of great assistance in the differentiation of deltaic and shoreface environments.

Delta-Front

Delta-front successions are generally sand-dominated and have moderate to high biogenic activity. Overall, the delta-front is dominated by wave processes and shows little evidence for discrete point sources of sediment input. Intense wave activity keeps silts and clays in suspension and transports most into the prodelta region. However, during and after river-flood events wave energy can be subdued (Rodriguez and Mehta, 1998). The distal delta-front is strongly affected by storms in wave-dominated successions. Thick hummocky cross-stratified units interbedded with rare dark organic-rich shales and massive silty mudstones dominate the lower portion of the distal delta-front. These dark organic-rich mudstones are interpreted to represent "phytodetrital pulses" associated with river-flood events following prolonged storms (Leithold, 1989; Raychaudhuri and Pemberton, 1992). Also associated with river-flood discharge is the mantling of storm beds with increased concentrations of plant debris washed seaward from the delta-plain. As in the prodelta, convolute bedded mudstones are another distinctive feature of delta-fronts, however they tend to be less common in wave-dominated deltas. Upward through the distal delta-front, interbedded HCS sandstones and weakly to non-bioturbated mudstones transition into erosionally amalgamated SCS sandstones with mudstone rip-up clasts (Saunders et al., 1992; Moslow and Pemberton, 1988; Vossler and Pemberton, 1988). Current and fair-weather wave rippled structures are largely absent. This storm imprinting largely eliminates fair-weather deposits and hence eliminates most distinctive deltaic characteristics.

The proximal delta-front is very similar to and shares a number of characteristics with the upper shoreface and foreshore of strandplain settings. This is the result of the fact that similar nearshore processes occur in both environments including breaking waves, surf zone conditions, and swash-backwash (Reading and Collinson, 1996). These processes result in sedimentary structures including trough cross-stratification, current ripples, and finally low angle planar laminations. However, distributary channels frequently crosscut proximal delta-front deposits. Proximal delta-front deposits tend to be thicker, more poorly sorted, and contain a much greater proportion of coarse material (see FA3). These characteristics are a direct result of the close proximity to distributary channels. However, strong wave action and longshore drift can redistribute this sediment along-strike and reduce the expected deltaic signature.

Delta-Plain

The subaerial portion of deltas is subdivided into the lower delta-plain and the upper delta-plain. The lower delta-plain includes the intertidal portion of the delta and consists mainly of abandoned beach-ridges separated by weakly bioturbated sandy mudstones (Dominguez, 1996). Other associated environments include lagoons, minor tidal flats, rare tidal inlets and tidal deltas, rare distributary channels, and interdistributary bays. Lagoons and interdistributary bays are characterized by brackish-water conditions. These environments are dominated by heterolithic successions of mudstone interbedded with planar laminated and current rippled sandstone and siltstone (MacEachern, 2000). Washover sandstones associated with storms are also common. Lagoons may also contain tidal rhythmites if the tidal range is sufficient. These environments would not be expected with strandplain environments and are typically found within the downdrift portion of deltas, especially within strongly asymmetrical deltas (see FA4). The updrift portion of asymmetrical deltas will be composed of amalgamated beach-ridges nearly identical to typical strandplains and can only be differentiated based on its close proximity with distributary channels (Bhattacharya and Giosan, 2003). Adding to the complexity, large wave-dominated deltaic systems can therefore contain a number of associated strandplains along-strike.

The upper delta-plain occurs above the tidal range and is not affected by marine processes (MacEachern, 2000). Environments present are similar to those of typical coastal plains. These environments include fluvial channels, floodplains, swamps, lakes, and marshes. Marshes and swamps tend to be large in size and lead to peat accumulation (Diessel et al., 2000). Wave-dominated settings typically have small lagoons and extensive swamps and marshes. During progradation marine influence is very limited due to active beach-ridge formation (Reading and Collinson, 1996). Under these conditions extensive freshwater swamps can form extremely close to the coast. In ancient successions this can translate into coal formation directly above delta-front deposits and freshwater deposits dominating the delta-plain (Pemberton et al., 2001).

Generalized Ichnology: Wave-dominated deltas vs. Strandplains

Wave-dominated deltaic successions generally show a decrease in bioturbation upward as well as an increase in grain size and bedding thickness upwards (MacEachern and Pemberton, 1992). This upward decrease in trace fossil abundance is due to increased sedimentation rates, higher depositional energies, and increased erosional amalgamation of beds (MacEachern et al., 2005). Strandplains have a similar vertical succession and contain characteristics comparable to those described above. However, the lack of direct fluvial influences in strandplains result in lower sedimentation rates, dramatically less environmental stress, and considerably less mud, silt, and other fluvially derived material (e.g. organic material, mudstone rip-up clasts, and wood fragments). These differences form the framework for differentiating wave-dominated deltas and adjacent strandplains. Deltaic settings are constantly submitted to direct freshwater input and a number of other environmental stresses and strandplains are not (Moslow and Pemberton, 1988). Deltaic settings tend to have impoverished diversities, lower abundances, and sporadic distribution of trace fossils owing to these stresses. Turbidity stresses generally suppress filter-feeding structures, while substrate instabilities and rapid sedimentation rates tend to suppress more complex and deposit-feeding structures (Gingras et al., 1998; MacEachern et al., 2005). However, wave-dominated deltas generally have reduced sedimentation rates as compared to river-dominated deltas. Therefore, wave-dominated deltas tend to be dominated by grazing and deposit-feeding

structures (MacEachern et al., 2005). Strong wave action within wave-dominated deltas will lessen the impact of most of these environmental stresses but will not completely eliminate them. Therefore, organisms existing within river-dominated deltas will be affected to a much greater degree than organisms within wave-dominated deltas (Coates and MacEachern, 1999). Nonetheless, ichnology plays an important role in differentiating wave-dominated deltas and strandplains.

Prodelta

Ichnological characteristics differentiating deltaic/strandplain environments are most noticeable in more distal settings. This is especially true in strongly storm-influenced settings. Distal fair-weather deposits contain the most distinct characteristics, as they are most affected by fair-weather river-induced environmental stresses. Storm-deposition on the other hand, produces similar successions within a number of different environments. However, storm-influence with the prodelta is relatively minor compared to the delta-front and consequently will demonstrate the greatest biological differences from equivalent offshore environments. Prodelta deposits within wave-dominated systems are typically represented by a stressed *Cruziana* assemblage (e.g., Coates and MacEachern, 1999; MacEachern et al., 2005). Ichnogenera commonly found within this environment include *Phycosiphon, Helminthopsis, Zoophycos, Planolites, Teichichnus, Terebellina, Chondrites, Cylindrichnus, Asterosoma*, and fugichnia. Rare suspension feeding structure including *Skolithos* and *Arenicolites* are also present. The prodelta environment represents the most diverse suite of trace fossils in wave-dominated successions, however most ichnogenera are typically diminutive in size, sporadically distributed, and low in number (MacEachern, 2000). This moderate to high diversity is in contrast to river-dominated deltas, which have very low diversities.

The moderate to high diversities seen within the prodelta and delta-front is due to wave actions ability to mediate various stresses. Wave agitation will result in decreased water stratification, well-oxygenated waters, and normal fully marine salinities (MacEachern et al., 2005). Some wave-dominated fair-weather prodelta and delta-front deposits have even contained up to 21 ichnogenera (Raycjaudhuri and Pemberton, 1992). However, strongly storm influenced systems will result in a strong storm overprinting of

the high diversity fair-weather deposits. Post-storm opportunistic organisms that would typically colonize the upper portions of storm beds are very similar in both deltaic and shoreface environments and therefore will be of little use in differentiating them. This is the case in many wave-dominated systems including the Falher "D". Under these conditions ichnological deltaic signatures are best identified in more distal environments where storm amalgamation is less abundant. Unfortunately cored intervals within the prodelta region of the Falher "D" are lacking and consequently distinctive deltaic signatures are also lacking.

Distal Delta-Front

The distal delta-front contains a greater proportion of storm-amalgamated sandstone than the prodelta, however rare fair-weather mudstones are still preserved. These mudstones tend to be either weakly bioturbated with low diversities or non-bioturbated. Non-bioturbated mudstones are not present within typical shoreface succession and are distinctive of deltaic environments. Interpreted to be the result of increased river discharge following heavy rains associated with storm events, these intervals are referred to as "phytodetrital pulses". Increased concentrations of terrestrial organic material may produce dysaerobic conditions and inhibit colonization. Weakly bioturbated horizons with low diversities are the product of fluvial stresses including variations in salinity, oxygen level, sedimentation rate, water turbidity and energy, and substrate consistency.

A number of wave-dominated distal delta-front deposits from the modern and ancient have been interpreted as a moderately diverse and locally abundant, mixed *Skolithos-Cruziana* assemblage (ex: Dunvegan and Belly River formations; Gingras et al., 1998; Coates and MacEachern, 1999). Typical ichnogenera of wave-dominated distal delta-front deposits include *Helminthopsis, Zoophycos, Phycosiphon, Cylindrichnus, Planolites, Teichichnus, Palaeophycus, Thalassinoides, Terebellina,* fugichnia, and very rare *Diplocraterion* and *Skolithos* occurring in storm beds (Coates and MacEachern, 1999). This trace fossil assemblage represents an equilibrium community generated during fair-weather deposition. The relatively high abundances compared to river-dominated deltas are a result of heightened wave action that mediates the stresses listed

above. However, diversities still tend to be lower than in typical shoreface successions. There is also a low diversity *Skolithos* assemblage present that occurs at the top of storm beds. This trace fossil assemblage is characterized by relatively low numbers of *Ophiomorpha*, *Diplocraterion* and *Skolithos*, which represent suspension-feeding organisms. This will produce an interesting contradiction with sandy substrates with very few suspension-feeders (MacEachern et al., 2005). This low abundance of suspension-feeding structures is due to higher mud concentrations in suspension (Gingras et al., 1998). This is in contrast with shoreface successions which tend to have much a greater abundance and diversity of suspension-feeders.

Interbedded fair-weather highly bioturbated zones and nearly non-bioturbated HCS sandstones results in a bedding fabric referred to as "lam-scram" (Pemberton et al., 2001) within shoreface successions. This does not generally occur within wave-dominated deltaic succession due to the reduced bioturbation intensities. Within the Falher "D", the greatest intensities of bioturbation are found within the shoreface are the "burrowed zone" described within Chapter Two. The "burrowed zone" is characteristic of typical shoreface successions within the study area. In contrast, this bioturbated horizon is generally not present within the immediate vicinity of distributary channels or on the downdrift flanks of deltas. This may be the result of environmental stresses associated with fluvial deposition or a preservational issue related to delta formation and/or progradation.

Proximal Delta-Front

In general the proximal delta-front within wave-dominated systems is non- to weakly-bioturbated with only rare trace fossils present. Typical ichnogenera of wave-dominated proximal delta-front include rare *Ophiomorpha, Rosselia, Cylindrichnus, Skolithos, and Diplocraterion*. There are also local intervals of abundant *Macaronichnus* near the top of the proximal delta-front. The lack of biogenic structures is due to the masking of most fair-weather ichnological characteristics by storm bed amalgamation. In this environment wave action may remove all mud from the substrate. However, the water column will still contain significant amounts of mud, which will result in decreased suspension feeding structures. This will occur primarily downdrift from the fluvial

source (MacEachern et al., 2005). Overall, the proximal delta-front and upper shoreface, biologically speaking, are very similar. The proximal delta-front within the Falher "D" tends to be dominantly non-bioturbated while the upper shoreface contains sporadic concentrations of *Palaeophycus*, para-*Macaronichnus*, *Macaronichnus simplicatus*, and *Diplocraterion*. The overall decrease in bioturbation within the proximal delta-front may also be related to increased grain sizes and salinity variations associated with proximity to fluvial point sources.

Asymmetrical Delta Model: Effects on Bioturbation

The asymmetrical nature of wave-dominated deltas dramatically affects the intensities and diversities of bioturbation along the coast. Within these systems, fluvially-induced stresses, in the form of turbid mud plumes and salinity variations, are deflected downdrift and are nearly absent updrift (MacEachern et al., 2005). Therefore, deltaic signatures, such as non-bioturbated mudstones and syneresis cracks, will be confined to the downdrift regions. These settings contain decreased diversity and abundances of trace fossils as well as a noticeable lacking of suspension-feeding traces (Gingras et al., 1998; MacEachern et al., 2005). Emergent barrier bars forming within the downdrift regions can permit sheltering and formation of extensive brackish water bays/lagoons (Bhattacharya and Giosan, 2003). These environments are characterized by heterolithic successions with very low diversity brackish-water trace fossil suites. *Teichichnus, Planolites, and Chondrites* dominate these suites with common horizons thoroughly reworked by one ichnogenera (Pemberton and Wightman, 1992). In contrast, updrift regions would be expected to contain ichnological suites very similar to typical shorefaces. More pervasive bioturbation, increased diversity and the presence of vertical dwelling and suspension-feeding traces highlight the differences in the ichnological signature between the updrift and downdrift flanks of wave-dominated deltas. The spatial distribution of relative bioturbation is mapped and discussed further within Chapter Four.

Summary

The lateral variability of sedimentological and ichnological characteristics in the Falher "D" succession highlight the along-strike transition in from wave-dominated delta to strandplain. Deltas and strandplains are commonly found along wave-/storm-dominated coastlines and are often closely associated. The Falher "D" is interpreted to contain an asymmetrical wave-dominated delta. Asymmetrical delta models have recently been constructed for a number of wave-dominated deltas with "classical" sand-dominated strandplains on the updrift portions and more complex heterolithic environments on the downdrift. Most criteria used to differentiate these two environments are focused around the presence of fluvial input. Strong wave energies serve to mediate a number of fluvial effects in wave-dominated deltas and therefore will have a much greater degree of similarity to strandplains than river-dominated deltas. Sedimentological and ichnological differences include the presence of convolute bedding, syneresis cracks, non-bioturbated mudstone beds, organic-rich mantling of storm beds, and an overall increase in mud content. More proximal settings will contain thicker successions, more poorly sorted sandstones and conglomerates, and possible lagoonal deposits. Biological differences include an overall reduction in the diversity and abundance of trace fossils and suspension feeding structures. This is a direct result of fluvially induced stresses associated with freshwater input from rivers. However, wave-dominated deltas tend to have much greater diversities than other delta types due to the increased wave activity. Overall, differentiating wave-dominated deltas and strandplains is difficult. However this process is extremely valuable and will significantly impact any facies interpretations or paleogeographic reconstructions. The following chapter will focus on the spatial distribution of a number of important characteristics, facies associations, and stratigraphic units. This section is designed to further our understanding of the Falher "D" succession and strengthen the interpretations formed within this chapter.

Chapter 4: Stratigraphic cross-section analysis, depositional mapping, and sequence stratigraphic modeling

The previous chapters have provided detailed descriptions of the sedimentology, ichnology, and interpreted depositional environments of the fifteen facies and five facies associations observed in core (Table 4.1). This chapter builds upon this foundation through analysis of facies distributions of the environmentally-significant units, which is exemplified in cross-sections, isopach maps, lithological maps, biogenic maps, and paleogeographical maps. The Falher "D" succession will be separated into two stratigraphic intervals, D1 and D2, utilizing a number of important stratigraphic surfaces. The first step is to determine/define the important bounding surfaces (ex: TSE1 and TSE3) for the Falher "D" and within the succession itself (ex: TSE2 and SB).

(4.1) Important Stratigraphic Surfaces and Sequence Stratigraphic Model

The Falher "D" succession contains a number of regionally and locally significant stratigraphic surfaces, which are allocyclic and autocyclic in origin, respectively. Allocyclic surfaces are the result of processes that occur outside the depositional basin and result in changes to the supply of energy or sediment into the system (Emery and Myers, 1996). According, these surfaces tend to be regionally extensive and separate genetically-unrelated depositional systems. Eustatic sea level fluctuations, tectonic activity (i.e. uplift), subsidence, and climatic variations are processes that are attributed to the formation of allocyclic surfaces (Bhattacharya and Walker, 1992). These regional stratigraphic surfaces separate the Falher Member into five separate sub-members (Cant, 1984). The processes that produce these surfaces play an important role in the overall formation of the depositional system and will be described/illustrated with paleogeographic maps.

In contrast to regionally extensive allocyclic surfaces, autocyclic surfaces are formed by processes that function within the depositional basin (Emery and Myers, 1996). Typically, these surfaces have limited stratigraphic continuity; however autocyclic processes can be important locally. Delta lobe switching, river meandering, and storms are examples of processes that can produce autocyclic surfaces (Bhattacharya

Facies Association	Description	Recurring Facies	Environments
FA1: Storm-Dominated Lower Shoreface /Distal Delta Front	Interbedded laminated mudstone and very fine-grained sandstone; HCS/SCS; rare conglomerate; rare to moderately bioturbated (Mixed Skolithos-Cruziana Ichnofacies)	F3a, F3b, F4a	Offshore Transition, Lower Shoreface, Middle Shoreface, Prodelta, Distal Delta-Front
FA2: Wave-Dominated Upper Shoreface and Foreshore	Fine- to very coarse-grained sandstone and very well-sorted granule and pebble conglomerate; trough cross-stratification and horizontal planar parallel stratification; rare bioturbation (Skolithos Ichnofacies)	F4b, F4c, F6, F7, F8a, F8b	Upper Shoreface, Foreshore, Proximal Delta-Front
FA3: Wave-Dominated Proximal Delta-Front	Fine- to very coarse-grained sandstone and poorly-sorted granule and pebble conglomerate; trough cross-stratification, planar tabular cross-stratification, and horizontal planar parallel stratification; very rare bioturbation (Low diversity Skolithos Ichnofacies)	F4b, F7, 8c (Delta Front) F5 (Channel)	Proximal Delta-Front, Distributary Channels
FA4: Lower Delta-Plain/Marginal-Marine Brackish-Water Environments	Interbedded laminated mudstone, siltstone, and very fine-grained sandstone; current ripples, oscillation ripples, combined flow ripples, planar parallel lamination, lenticular bedding; syneresis cracks (Low diversity mixed Skolithos-Cruziana Ichnofacies)	F1a, F1b, F3a, F3b	Lagoon, Bay-fill, Intertidal Flat, Lower Delta Plain (Distributary Channels, Interdistributary Bay, interstrandplain Lagoon)
FA5: Upper Delta-Plain/Coastal Plain	Organic-rich rooted interbedded coal, mudstone, siltstone, and very fine-grained sandstone; massively bedded, planar parallel lamination; cross-bedded fining-upward sandstone; pedogenic alteration; No bioturbation	F1b, F9 (Coastal Plain) F4c, F5, F7, F8c (Channel)	Coastal Plain, Floodplain, Overbank, Swamps, Lakes, Fluvial Channel, Upper Delta Plain (Floodplain, Distributary Channel, Overbank, Swamp)

Table 4.1 – Summary of the facies associations listed in the approximate depositional order. Facies include: F1a - bioturbated silt-rich mudstone, F1b - unburrowed silty mudstone and massive shale, F2 - sandy siltstone, F3a - bioturbated interbedded mudstone and fine-grained sandstone, F3b - non-bioturbated interbedded mudstone and fine-grained sandstone, F4a - very fine-grained hummocky cross-stratified sandstone, F4b - sporadically bioturbated very fine-grained to fine-grained trough cross-bedded sandstone, F4c - very fine-grained planar laminated sandstone, F5 - fine- to coarse-grained trough cross-bedded and planar laminated sandstone, F6 - very coarse-grained sandstone, F7 - interbedded sandstone and conglomerate, F8a - unimodal chert granule conglomerate, F8b - bimodal chert conglomerate, F8c - polymodal chert conglomerate, F9 - organic-rich shale with interbedded coal.

and Walker, 1992). Erosional surfaces at the base of distributary channels within the proximal delta-front and/or delta-plain are the most common form of autocyclic surface found within the Falher "D". Despite the localized effects of autocyclicity, many autocyclic processes tend to be influenced or directly produced by external allocyclic controls (Emery and Myers, 1996).

Allocyclic Surfaces

Each of the five Falher members is separated above and below by major discontinuities (Leckie and Walker, 1982; Cant, 1984; Smith et al., 1984; Leckie, 1986a; Cant, 1995). These discontinuities typically manifest themselves as organic-rich coastal plain mudstones and coals sharply overlain by marine sandstones and mudstones (Cant, 1984; Emery and Myers, 1996). The Falher "D" exemplifies this relationship as the marine sandstones sharply overly the coastal plain deposits of the underlying Falher "E" (Fig. 4.1). The top of the Falher "D" is also bounded by a major discontinuity: the uppermost coastal plain deposits are sharply overlain by marine sandstones of the overlying Falher "C" (Arnott, 1993; Casas and Walker, 1997; Armitage, 2002). Both discontinuities are characterized by distal facies overlying more proximal facies, which signify major relative sea level rises. In other words, these surfaces represent marine flooding surfaces that reflect allocyclic changes in sedimentation patterns (Van Wagoner et al., 1990). However, these surfaces exhibit significant erosion and demonstrate a landward shift of facies; therefore they are referred to as transgressive surfaces of erosion (TSE) (MacEachern et al., 1992). Transgressive surfaces of erosion in the Falher "D" are characterized by sharp, low relief surfaces commonly overlain by poorly-sorted conglomerate beds containing intraformational rip-up clasts (c.f. MacEachern et al., 1992). The sharp character of these surfaces is attributed to wave and current action associated with erosive shoreface retreat (Nummedal and Swift, 1987). These surfaces may be demarcated by substrate-controlled ichnological suites such as the *Glossifungites*, *Teredolites*, and/or *Trypanites* Ichnofacies depending on the nature of the substrate colonized during transgression (MacEachern and Pemberton, 1992; Pemberton and MacEachern, 1995; Pemberton et al., 2001).

Fig. 4.1 - Selected examples of important stratigraphic surfaces within the Falher "D" succession: (A) Very fine-grained planar to sub-planar laminated sandstone sharply overlying massive mudstone that contains common pyrite nodules and a high organic content. This surface represents a transgressive surface of erosion (TSE2) separating the D1 interval from the overlying D2 interval (10-31-68-10W6, 2171.1m); **(B)** Very fine-grained sandstone containing *Asterosoma* and *Palaeophycus* sharply overlying a massive to planar laminated mudstone containing *Teichichnus, Thalassinoides, Planolites*, and *Chondrites*. The underlying bioturbated mudstones represent preserved transgressive deposits (TSE1) from the basal Falher "D" and the overlying sandstones represent marine sandstones from the D1 interval (06-19-68-12, 2450.4m); **(C)** Poorly-sorted conglomerate lag deposit from the Falher "C". This surface represents a transgressive surface of erosion (TSE3), which separates the Falher "D" from the overlying Falher "C" (06-21-67-10W6, 2457.5m); **(D)** Irregular poorly sorted conglomeratic lag deposit encased in massive mudstone. This surface represents a transgressive surface of erosion (TSE1) separating the Falher "D" from the underlying Falher "E" (06-20-68-09W6, 2171.3m).


A
TSE 2
B
As
Te
Th
TSE 1
Pl
Ch
C
TSE 3
TSE 1

The Falher "D" is bound above and below by two major discontinuities. The surface separating the top of the Falher "E" from the base of the Falher "D" is hereafter referred to as TSE1 (Fig. 4.1d) and the contact delineating the top of the Falher "D" and the base of the Falher "C" will be referred to as TSE3 (Fig. 4.1c). In some localities, these surfaces are overlain by thin poorly-sorted conglomeratic deposits often sandwiched between coastal plain mudstones and marine sandstones. In rare cases, brackish water deposits are preserved between the Falher "E" coastal plain and the Falher "D" marine sandstones (Fig. 4.1b). This brackish strata represents preserved deposits formed during the transgression, which often have a very low preservation potential (Reading, 1989; Reinson, 1992). The conglomeratic lags are interpreted to have formed during the erosion of previously deposited nearshore complexes associated with the transgression of the shoreline (Posamentier and Allen, 1999). In other words, coarse clastic material that was originally deposited in underlying successions was eroded and re-deposited in more distal marine settings. These wave-cut surfaces are also referred to as wave ravinement surfaces (Nummedal and Swift, 1987; Walker, 1992).

Another transgressive surface of erosion, referred to as TSE2, is present within the Falher "D", however it is a higher order stratigraphic surface (Fig. 4.1a). Distal deposits overlying more proximal deposits also characterize this surface as they do with TSE1 and TSE3. However, the juxtaposition of facies along this surface is not as severe as those described above and generally comprises lower shoreface deposits overlying upper shoreface deposits (ex: 10-31-68-10W6). The presence of a TSE indicates that a rise in the relative sea level occurred during the deposition of the Falher "D" sandbody (c.f. Walker, 1992; Emery and Myers, 1996). This surface is utilized to separate the Falher "D" sandbody into two sub-members, termed D1 and D2 (Fig. 4.2). The D1 unit is situated between the TSE1 and TSE2 surfaces, while D2 occurs between TSE2 and SB (Fig. 4.3).

Another important stratigraphic surface is only observed in the northern (distal) regions of the study area. A sequence boundary (SB) occurs between the upper Falher "D" sandbody and the overlying coastal plain deposits (Van Wagoner et al., 1990; Walker, 1992). Marine mudstones and sandstones are overlain by coastal plain deposits, which indicates that transitional facies are absent (ex: 07-26-69-09w6). This surface

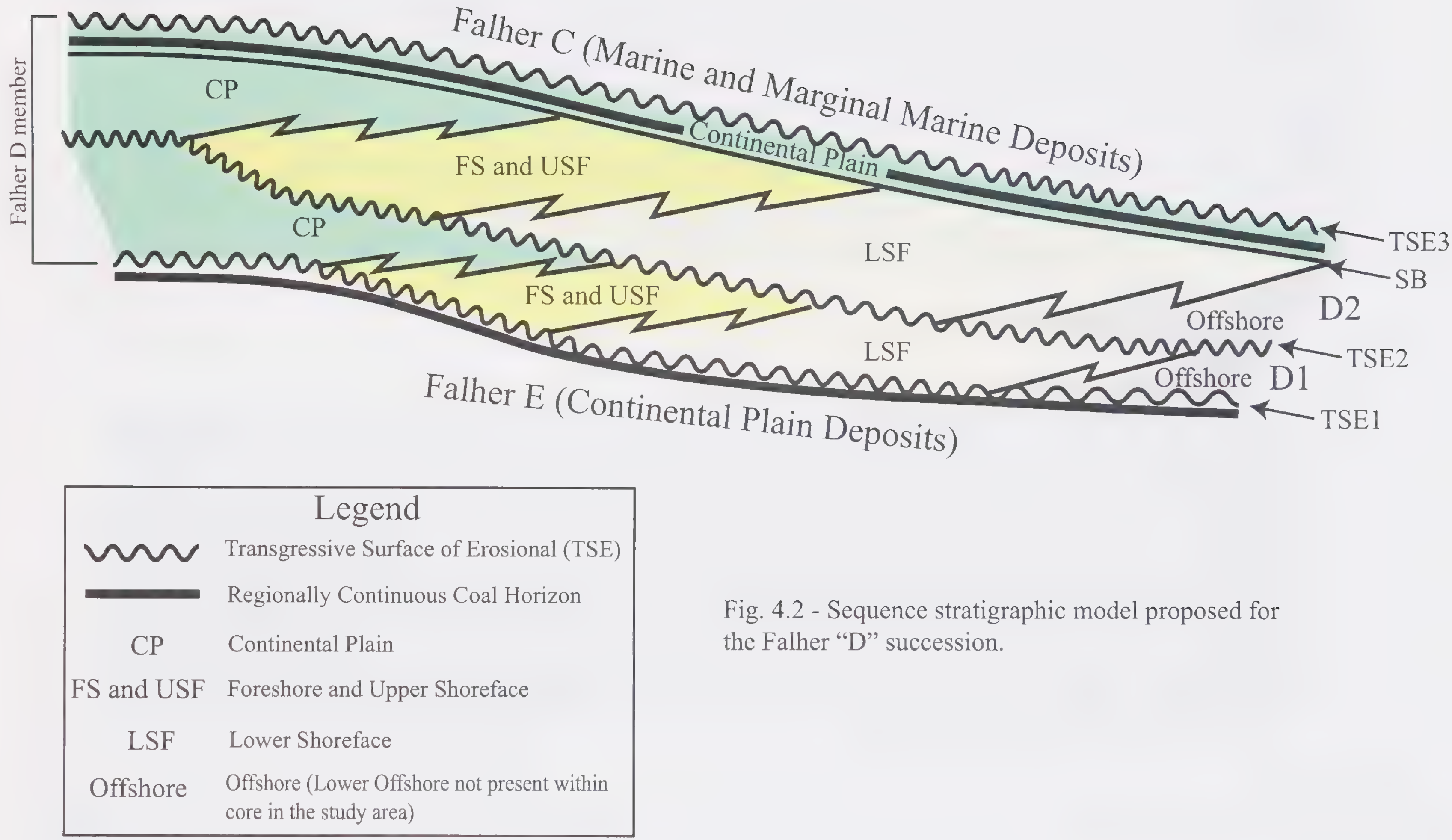

Fig. 4.2 - Sequence stratigraphic model proposed for the Falher "D" succession.

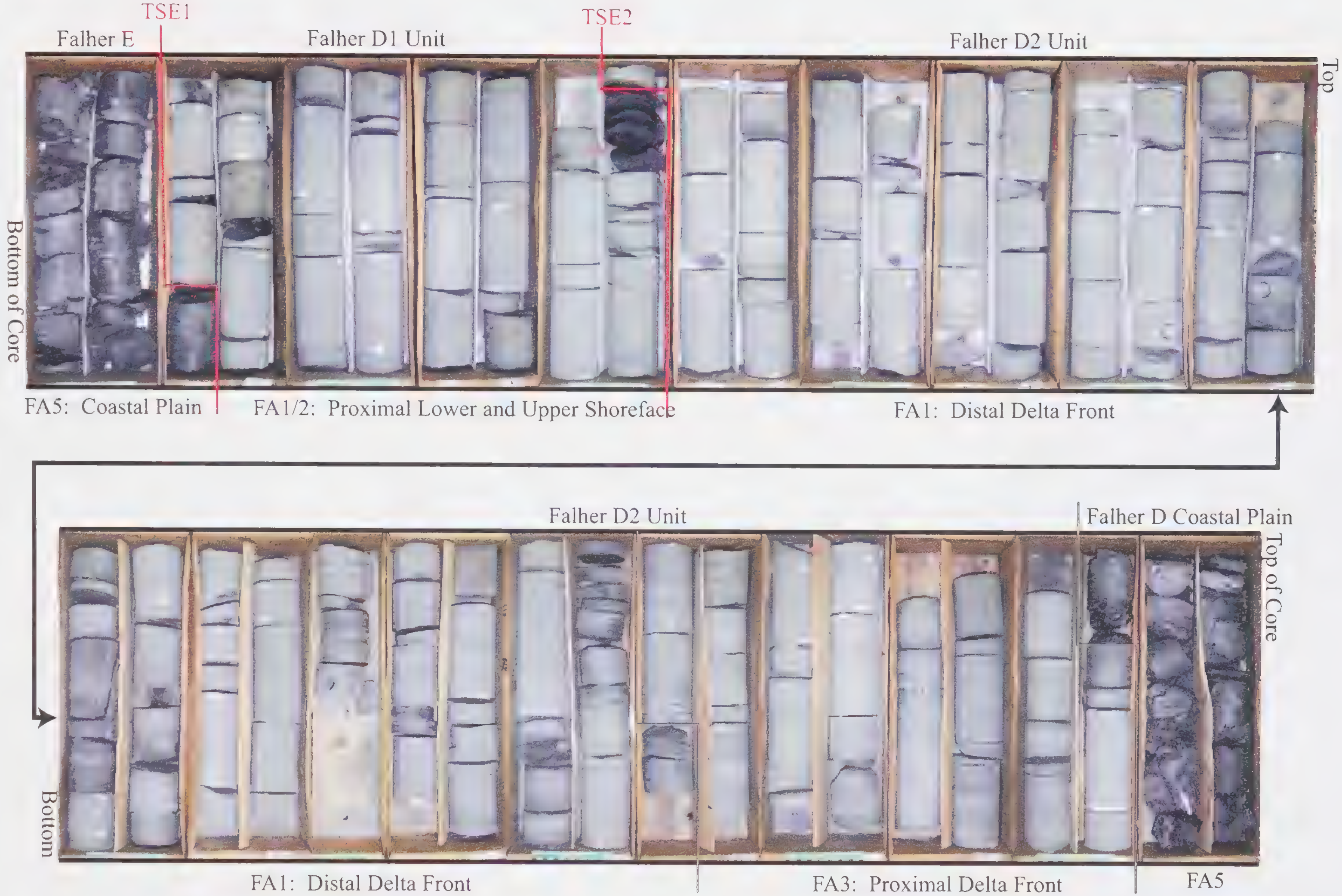

Fig. 4.3 - Deltaic succession from the Falher D member containing both the D1 and D2 intervals. The D2 unit contains a coarsening-upward succession from distal delta front to proximal delta front. The D1 interval contains proximal lower shoreface and upper shoreface deposits. Underlying interbedded coals and mudstones are from the Falher E member. Core photos taken from well located at 10-31-68-10W6, depth 2153.6-2175.7m.

would correspond too younger coastal plain strata overlying much older coastal plain deposits in the southern half of the study area and would be difficult to locate. A rapid northward shift in the shoreline position, following a forced regression, is interpreted to account for the missing facies (Posamentier et al., 1992; Arnott, 1993). This seaward shift in the shoreline is in response to a relative sea-level lowering (Van Wagoner et al., 1990; Bhattacharya and Walker, 1992; Posamentier et al., 1992). Significant erosion will occur along this surface as the higher energy environments located close to the shoreline move northward (Swift, 1975; Walker and Plint, 1992). This interpretation will be discussed and supported in the following sections.

Autocyclic Surfaces

The Falher “D” succession also contains a number of other internal surfaces, which are autocyclicly controlled. These surfaces are not as regionally extensive as those described above; however, they have important implications on a local scale. Autocyclic variations are commonly identified within deltaic regions, and are typically attributed to the activity of distributary channels (Bhattacharya and Walker, 1992). Delta lobe switching and river meandering within the delta plain can substantially influence the associated delta and adjacent strandplains. Within the Falher “D” autocyclic discontinuities can be found at the base of distributary channels in the upper and lower delta-plain. These discontinuities result in proximal channel-fill deposits sharply overlying delta-front successions.

Coupled with longshore drift, distributary channels are the primary source of most sediment supplied to the Falher “D”. At the same time, channel migration within the delta-plain results in erosion of older underlying delta-front and delta-plain deposits. Channel migration can also result in delta lobe switching and subsequent cut off of sediment supply to older delta lobes. Delta lobe abandonment corresponds to destructional processes (wave action) that prevail over previously constructive processes (fluvial) (Bhattacharya and Walker, 1992). The updrift very well sorted conglomerates of Facies 8a are interpreted (Chapter Three) to form this manner. Delta lobe abandonment within a number of modern asymmetrical wave-dominated deltas was illustrated in chapter three and demonstrates processes similar to those proposed for the Falher “D”. In

each case, lobe abandonment was an important mechanism in the redistribution of sediment. Accordingly, a wide range of deposits is expected within the deltaic system with very well sorted strandplain and more poorly sorted deltaic deposits as end members. This lateral variability is exemplified in the Falher "D" with very well sorted conglomerates in the west, poorly sorted conglomerates in the central portion of the study area, and interbedded sandstones and mudstones in the east (refer to the depositional model section of Chapter Three).

Summary

Within the study area the Falher Member consists of five cycles that represent a series of coarse clastic shoreface successions trending approximately NW-SE along depositional strike (Cant, 1984). Each Falher cycle is bound above and below by major discontinuities. These surfaces are allocyclic in origin, regionally extensive, and tend to manifest themselves as coastal plain mudstones and coals sharply overlain by marine sandstones and mudstones. Significant erosion, low relief, common conglomeratic lags, and a landward shift of facies along these surfaces indicate that they represent transgressive surfaces of erosion (TSE) (Posamentier and Allen, 1999). The surface separating the top of the Falher "E" from the base of the Falher "D" is referred to as TSE1 and the contact delineating the top of the Falher "D" and the base of the Falher "C" is referred to as TSE3 in this study. Another transgressive surface of erosion, referred to as TSE2, is present within the Falher "D" itself, however the juxtaposition of facies along this surface is not as severe. This surface is utilized to separate the Falher "D" sandbody into sub-members, termed D1 and D2. The following section focuses on the lateral distribution of facies and environmentally significant units within the stratigraphic framework established above.

(4.2) Cross-section Description and Interpretation

Fifteen cross-sections were constructed within the study area in order to gather additional information on the spatial distribution of the units described in Chapter Three, as well as the important stratigraphic surfaces discussed previously. Cross-sections use petrophysical well log suites including; gamma ray, resistivity, neutron-density, and sonic

logs. Facies associations and stratigraphically significant surfaces were correlated using log signatures and detailed core descriptions. For simplicity, only gamma ray signatures are displayed on the cross-sections. A series of 8 equally spaced (~6 km apart) north-south oriented dip-sections were constructed roughly perpendicular to the Falher D paleoshoreline (Fig. 4.4). As well, 7 equally spaced (~3 km apart) east-west strike-sections were constructed roughly parallel to the Falher D paleoshoreline (Fig. 4.4). Cross-sections do not extend into Township 67 as the Falher "D", in this region, contains entirely non-marine strata that does not contribute to this particular study.

For practical reasons, all 15 cross-sections are not included and described in this thesis. Three key north-south cross-sections and one east-west cross-section is included and described in the following section (Fig. 4.4). The north-south cross-sections are located such that the stratigraphic relationships of distinct depositional environments are displayed. The first cross-section, A-A', is located in the western portion of the study area and displays the facies distributions within the updrift strandplain environment. The next cross-section, B-B', is located in the central portion of the study area and transects deposits corresponding to the delta-plain and proximal delta-front settings. The final dip-section, C-C`, is located in the eastern portion of the study area and exhibits facies relationships within the downdrift lagoonal environments. These three sections coupled with the east-west strike-section, D-D', provide an improved understanding of the along-strike variations of the Falher "D" within the study area.

The stratigraphic succession exemplified within well logs from this study is generally consistent and encompass the following. Approximately 10m of the upper Falher "E", which primarily consists of coastal-plain deposits with numerous coal beds, is included at the base of the stratigraphic sections. The surface separating the top of the Falher "E" from the base of the D1 interval is referred to as TSE1. This surface typically manifests itself as upper to lower shoreface deposits of the D1 interval sharply overlying thick coals of the Falher "E". The D1 and D2 intervals are separated by TSE2, which typically manifest itself as lower shoreface sharply overlying upper shoreface deposits in the study area. Overlying the D2 interval are coastal plain mudstones and coals of the upper Falher "D". The surface separating the top of the Falher "D" and the base of the Falher "C" is referred to as TSE3. This surface is overlain by approximately 25m of

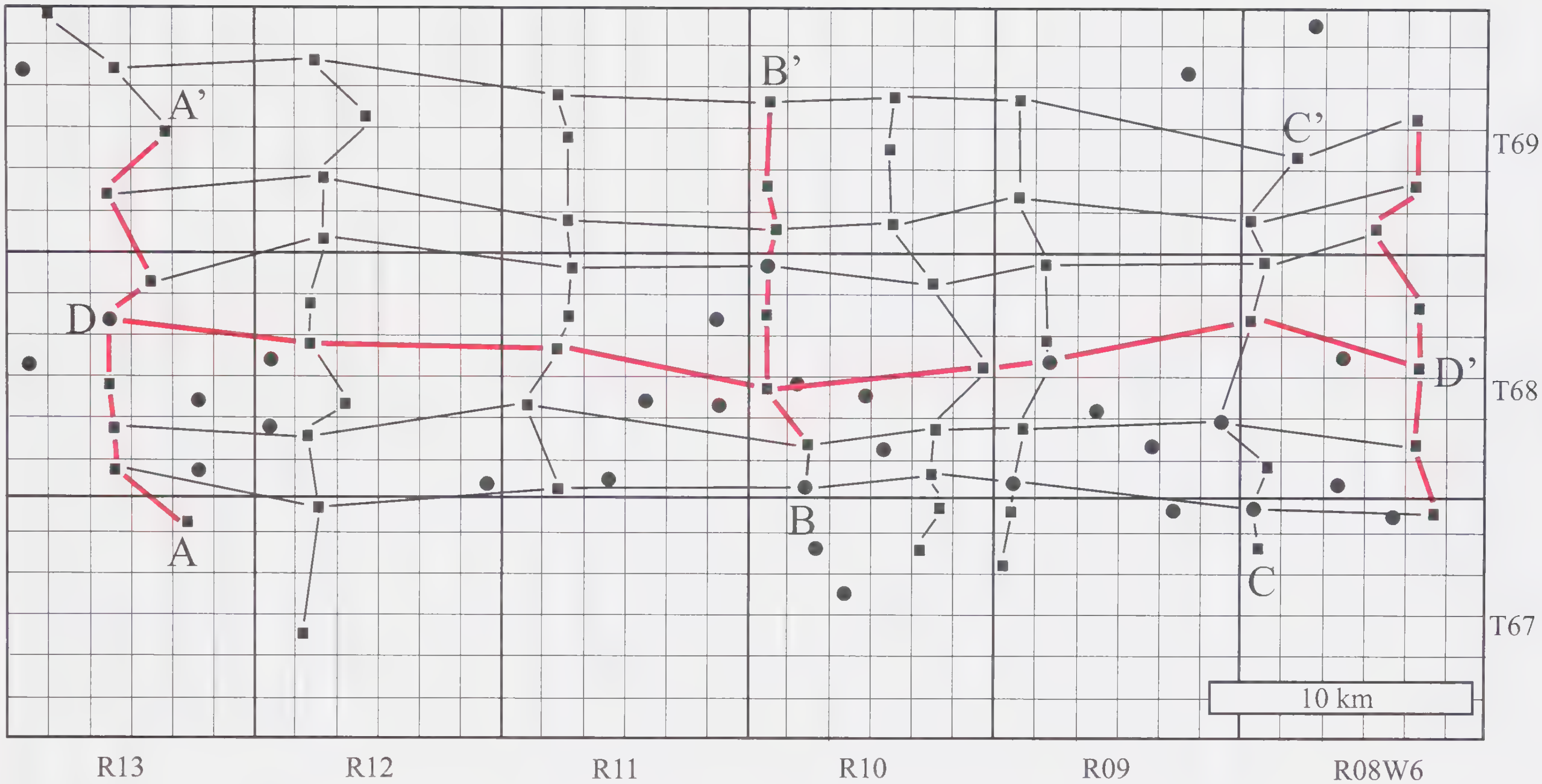

Fig. 4.4 - Location of cross-sections within the study area. Squares represent well logs used in cross-sections and circles represent cored wells. Red lines represent cross-sections included within this thesis. Three dip-sections, A - A', B - B', and C - C', are described in detail and one strike-section, D - D', is described in detail.

marine and non-marine strata of the Falher "C" and rarely 5-10 m of non-marine strata of the Falher "B". The underlying Falher "E" and overlying Falher "C" members are shown to view possible structural controls, significant depositional patterns, and illustrate of validity of the datum selected.

Stratigraphic Datum

A datum is an extensive surface that is roughly horizontal and can be used as a reference to construct reliable cross-sections and correlate important surfaces and units (Emery and Myers, 1996). The principle datum used in this study is the contact between the top of the Falher "D" sandbody and the base of the first regionally extensive coal. One advantage of using this contact is that it reflects an interval of time that falls within the unit of interest. Also, this datum is easily picked within a large number of cores and well logs in the study area. The disadvantage of using this datum is the uncertainly of the extent of erosion and potential stratigraphic discontinuity associated with the coal bed. The top of the Falher "D" sandbody is a less desirable datum due to inconsistent thickness and common localized erosion of the upper portions. A datum commonly use in Lower Cretaceous studies is the Harmon Maximum Flooding Surface (e.g., Hayes, 1988; MacEachern, 1994). This surface is a regional marine flooding surface in the Harmon Formation and is distinctly visible on a number of different petrophysical well logs. However, this surface is located a significant stratigraphic distance above the interval in question; therefore, this surface was judged to be a poor choice for a datum in this study.

Cross-section A-A' – Updrift Strandplain

Cross-section A-A' is a dip-oriented section (Fig. 4.5) that is approximately perpendicular to the Falher "D" paleoshoreline (Fig. 4.4). This cross-section is located west or updrift of inferred wave-dominated deltaic deposits. The section contains a northward predictable proximal to distal transition in facies in the D1 and D2 intervals. However, proximal foreshore and upper shoreface deposits predominate the cross-section south of Township 69. In other words, this section does not contain distal deposits south of Township 69. This is in contrast to the remainder of the study area, which commonly

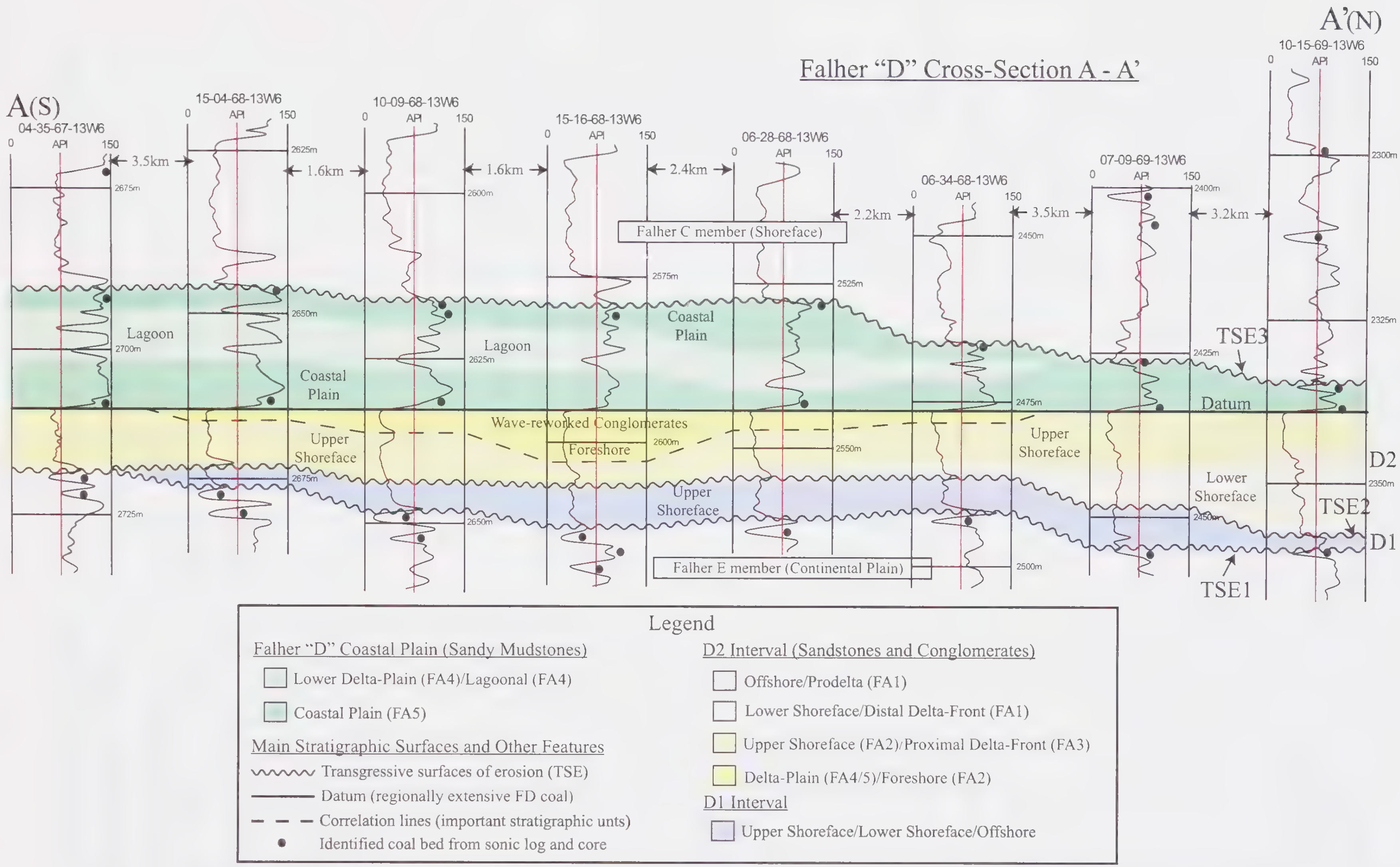

Fig. 4.5 - North-south trending, dip-oriented cross-section located within Range 13W6 (Fig. 4.4). This is the cross-section that characterizes the western (strandplain) portion of the study area.

contains distal lower shoreface deposits throughout Township 68. This distribution of facies is a function of the proximity to source areas, which are thought to be located west and southwest of the study area (Cant, 1984; Jackson, 1984; Smith, 1984; Leckie, 1986a; Pate, 1988; Smith, 1994; Caddal, 2000). However, the Falher "D" is clearly thinner along this section as compared to sections B-B' and C-C'. The facies relationships observed within the D1 and D2 intervals in A-A' are discussed below

D1 Interval

The most southerly occurrence of the D1 shoreface is near the boundary between Townships 67 and 68 (Fig. 4.5). This package thickens basinward to approximately 6 m; however, significant erosion of the upper D1 likely occurred during deposition of the overlying D2 shoreface. Along this section, the D1 sandbody predominantly consists of coarse-grained deposits interpreted to reflect foreshore and upper shoreface deposition. However, the paucity of core control within this interval severely limits any interpretation. The D1 shoreface extends northward to the lower half of Township 69 where it pinches out. The D1 interval is more consistent in terms of occurrence, thickness, and grain-size within this cross-section as compared to other dip- and strike-sections. The consistency of D1 in A-A' is a function of its westerly position and more consistent input of sediment from the west (Leckie, 1986; Caddel, 2000; Caddel and Moslow, 2004). Other regions encountered eastward, along-strike, may receive reduced sediment input and thereby did not form significant thicknesses.

D2 Interval

The D2 shoreface is generally comprised of foreshore and proximal upper shoreface deposits from FA2. This interval extends southward to the northern half of Township 67, and thickens in the basinward direction (Fig 4.5). The deposits of the D2 interval encompass interbedded sandstones and conglomerates sharply overlain by well to very well sorted conglomerates. These coarse clastics correspond to the proximal upper shoreface and foreshore beach environments, respectively (Pemberton and MacEachern, 1992; Caddel and Moslow, 2004). The very well sorted beach conglomerates thicken basinward to a maximum of 7m near the middle of Township 68, and subsequently thin

rapidly northward to pinchout in the northern portion of Township 68. The origin and characteristics of this well sorted conglomeratic body will be discussed further in the depositional map sections. Overall, the thickness and characteristics of the Falher "D" succession are consistent in this region and correspond to an updrift strandplain environment within the asymmetrical delta model (Bhattacharya and Giosan, 2003). The deposits observed in this section may also represent reworked deposits from an older abandoned delta lobe present along the Alberta-British Columbia boarder (Arnott, 1993; Caddel, 2000). Abandoned delta lobes are a common updrift source of sediment in a number of modern asymmetrical wave-dominated deltas (Bhattacharya and Giosan, 2003).

Distal lower shoreface deposits are not observed south of the Township 68-69 boundary within this cross-section. Beyond this boundary, the deposits consist of storm-amalgamated HCS sandstones from the proximal lower shoreface (c.f. Pemberton and MacEachern, 1992). In other words, muddy intervals in the form of distal lower shoreface or offshore strata are not observed. This occurrence is in direct contrast to the remainder of the study area in which distal lower shoreface and offshore environments predominate the succession north of the northern half of Township 68. The paucity of muddy strata in the D2 interval of A-A', is interpreted to be partially associated with the proximity to the source area located in the southwest and the along-strike source of sediment in the west. The strong groyne effect produced by distributary channels within the wave-dominated delta located in Range 10W6 may also restrict alongshore movement of sediment towards the east (Bhattacharya and Giosan, 2003). Nevertheless, the pronounced muddying of the Falher D along Township 69 starting at Range 12W6 corresponds with the presence of a large asymmetrical wave-dominated delta. The change in grain size along strike may also be related to the paleoshoreline, which appears to change slightly from an east-west trend (most of the study area) to a more northwest-southeast trend near the western edge of the study area. This change in the shoreline trend likely plays an important role in the regional distribution of the Falher "D". Previous analysis of the Falher "D" shoreline west of the study area documents a continued change in the shoreline trend towards a northwest-southeast position (Caddel, 2000; Caddel and Moslow, 2004).

Cross-section B-B'– Delta-Front and Delta-Plain

Cross-section B-B' is a dip-oriented section that is approximately perpendicular to the Falher "D" paleoshoreline (Fig. 4.6) and lies within the middle of the study area (Fig. 4.4). This cross-section incorporates 7 gamma-ray well log signatures, many of which come from wells with significant cored intervals. This cross-section contains a proximal to distal transition in facies northward (i.e. basinward) in both the D1 and D2 intervals. As compared to the previous cross-section, B-B' displays a dramatically thicker D2 interval and a similar thickness in the D1 interval. This cross-section also exhibits the occurrence of distal lower shoreface/distal delta-front deposits northward of the Township 68-69 boundary, which contrasts the proximal lower shoreface strata observed to the west of B-B'.

D1 Interval

The proximal shoreline deposits of the D1 shoreface in this cross-section are present in the northern portion of Township 68 (Fig. 4.6). The proximal strata consist of medium- to very fine-grained moderately sorted sandstone, which is interpreted to represent the middle and upper shoreface settings. Basinward, these deposits transition into lower shoreface and offshore deposits. Overall, the D1 shoreface never exceeds 5m in thickness; however, as mentioned previously, this unit may have undergone significant erosion (TSE2). From cored intervals, it is apparent that within most of Township 68 the D1 interval is dominated by coastal plain and significant channel deposits. Comparison to the previous cross-sections, indicates the presence of a slightly thinner succession as well as a northward shift in the occurrence of this interval. The D1 deposits also tend to be finer grained with a dramatic decrease in the amount of conglomeratic material.

D2 Interval

In section B-B', the D2 shoreface extends farther southward than the D1 shoreface and is more pronounced than in other cross-sections (Fig. 4.6). Within this region of the study area, the D2 shoreface lies sharply above interbedded coastal plain mudstones and coals in the south and marine sandstones of the D1 shoreface in the north. The contact between the D1 and D2 intervals can be difficult to identify due to the

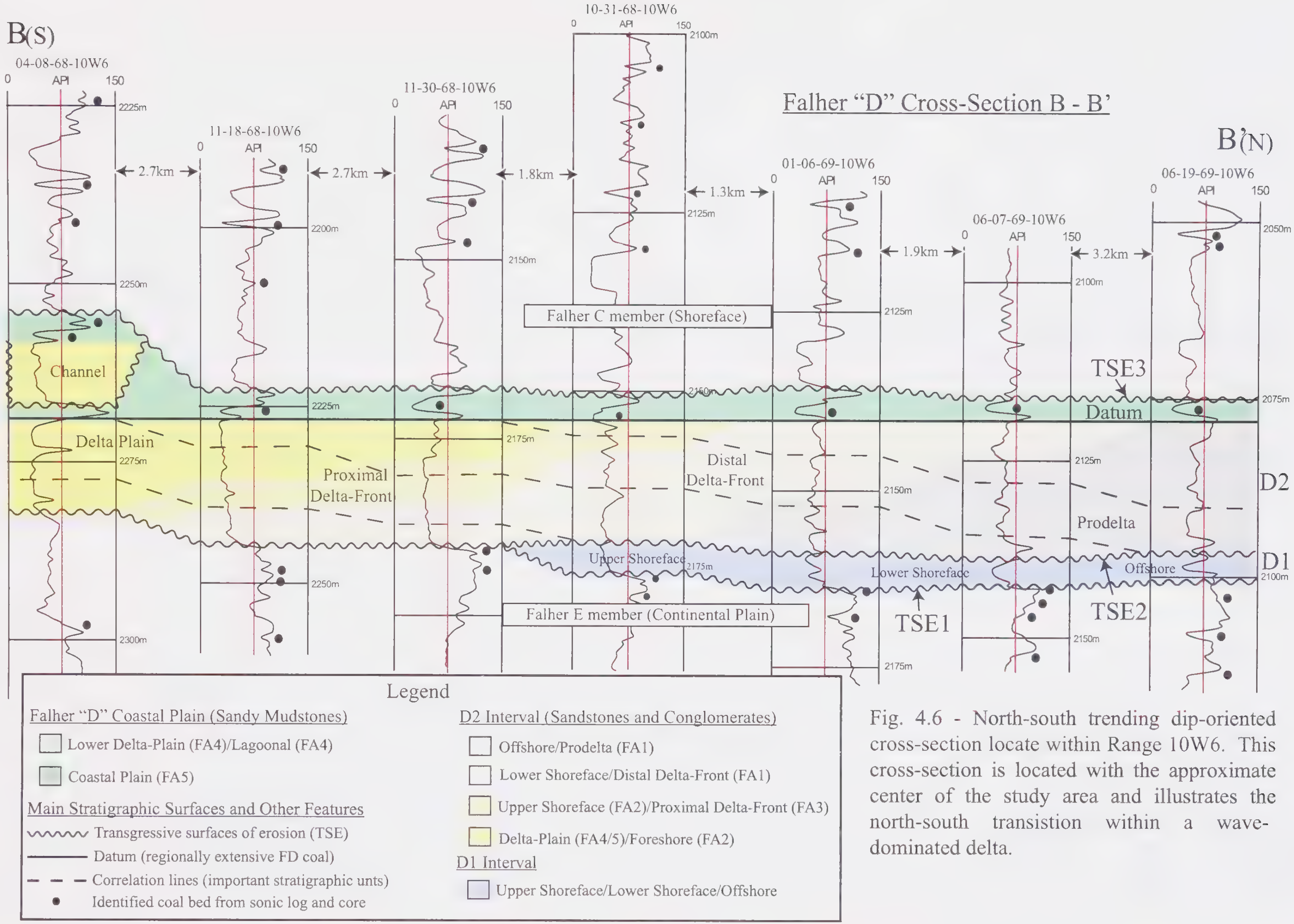

Fig. 4.6 - North-south trending dip-oriented cross-section locate within Range 10W6. This cross-section is located with the approximate center of the study area and illustrates the north-south transition within a wave-dominated delta.

similarity in grain size, lithology, and physical structures of the D1 and D2 successions. The intervals can be discerned based on the juxtaposition of more distal D2 strata above more proximal D1 strata.

The southern most wells in this cross-section are dominated by interbedded sandstone, poorly sorted clast-supported conglomerates and rare mudstones from FA3 (proximal delta-front) and FA4 (lower delta-plain). Basinward, these deposits transition into sandstone-dominated delta-front deposits from FA2/3. The most basinward wells in this cross-section are dominated by interbedded sandstone and mudstone from FA1, which are interpreted to reflect prodelta deposition (MacEachern et al., 2000). This is, however, difficult to ascertain with certainty due to a lack of core control within most of Township 69. Coastal plain deposits consisting of 2 – 5 m thick organic-rich mudstones and coals cap the D2 succession along the entire length of the study area. These mudstones and coals are erosionally overlain by lower shoreface deposits of the Falher "C". Cross-section B-B' transects north-south through an interpreted asymmetrical wave-dominated delta. This interpretation is supported by the increased thickness of D2 compared to the rest of the study area, the presence of distinctive deltaic signatures as discussed in chapter three, the presence of thick fluvial deposits landward, and the depositional/lithological maps within the following sections.

Cross-section C-C'– Downdrift deltaic

Cross-section C-C' is a dip-oriented section located in the eastern portion of the study area (Fig. 4.4) and is nearly perpendicular to the paleoshoreline (Fig. 4.7). Included within this cross-section are 7 gamma-ray well log signatures, which come from wells with significant cored intervals or are located close to cored wells. This dip-section displays a significant decrease in the thickness of the Falher "D" succession and a dramatic increase in the amount of mud in the form of heterolithic lagoonal mudstones and sandstones. The D1 interval however maintains a fairly consistent thickness and lithology throughout the section compared to the variable D2 interval.

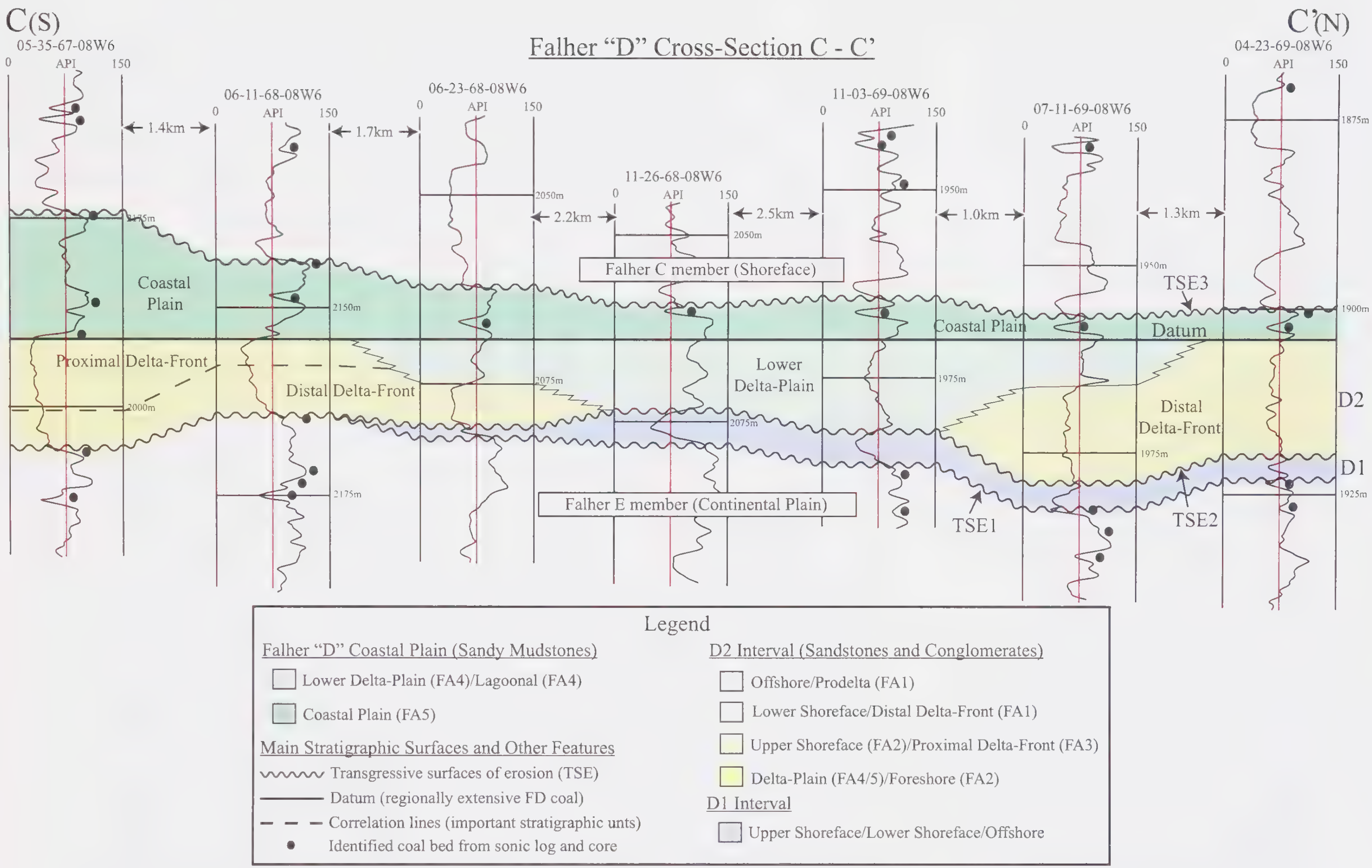

Fig. 4.7 - North-south trending dip-oriented cross-section located within Range 8W6. This is the eastern most cross-section in this study and illustrates downdrift deltaic deposits.

D1 Interval

The D1 shoreface displayed in C-C' appears to be more irregular and thinner than the D1 correlated in A-A'. This interval reaches a maximum thickness of approximately 4.5 m near the top half of Township 68 and decreases in thickness northward (Fig. 4.7). The overall irregularity of the D1 shoreface within this region is most likely the result of reduced sediment input due to the distance from sediment sources. Another important factor is the amount of erosion along the TSE2 surface. The D1 interval within this region has extremely poor core control, which reduces the certainty of any interpretations.

D2 Interval

The D2 shoreface in this region of the study area possesses a reduced thickness and finer-grained character in comparison to the rest of the study area. The most southerly wells in this cross-section contain trough cross-bedded fine-grained sandstones of the upper shoreface and hummocky cross-stratified very fine-grained sandstones of the proximal lower shoreface (c.f. Pemberton and MacEachern, 1992). Section C-C' is dominated by an east-west trending 5 m to 12 m thick heterolithic interval interpreted to be lagoonal (c.f. Pemberton and Wightman, 1992) (Fig. 4.7). In well 06-23-68-08W6 these heterolithic lagoonal deposits sharply overlie HCS sandstones from the proximal lower and middle shoreface of the lower D2 interval. The lagoonal deposits thicken northward into the northern half of Township 68 to comprise the entire D2 interval. North of Township 68, these deposits again overlie lower shoreface units of the lower D2. The most distal well within this cross-section contains interbedded sandstones and mudstones from the distal lower shoreface to upper offshore or corresponding prodelta. This cross-section highlights the downdrift portion of an asymmetrical wave-dominated delta (Bhattacharya and Giosan, 2003). The increased proportion of mudstone within facies is interpreted to be sourced from the distributary channels present within Range 10W6 (Cross-section B-B'). The decreased abundance of sandstone and complete absence of conglomerate is thought to be related to the delta hindering longshore drift from the west.

Cross-section D-D' – Along-strike

Cross-section D-D' is a stratigraphic strike-oriented section (Fig. 4.8) that is nearly parallel to the Falher "D" paleoshoreline (Fig. 4.4). The wells in the western portion of the cross-section are located marginally more proximal to the shoreline than those in the east. This strike-section corresponds to the area with prominent core control and is located roughly 6.5 km basinward from the southern-most position of the Falher "D" shoreline. Included within this section are 8 gamma-ray well log signatures that predominantly correspond wells with cored intervals. Section D-D' documents the numerous along-strike variations present in the Falher "D" and cross-cuts the dip-sections discussed previously.

D1 Interval

The D1 shoreface is present in this cross-section as interbedded sandstone- and conglomerate-rich foreshore and upper shoreface deposits. In general, the grain-size and thickness of the unit decreases eastward. The along-strike variation in depositional environments is associated to the irregular shoreline trend that persisted during early Falher "D" deposition. The shoreline in the central portion of the study area was farther north than in the west due to possible deltaic protrusion, erosion associated with the TSE2 surface, and/or reduced sediment supply. Lack of good core control and poor preservation of the D1 interval limits the possible information gathered from this cross-section. Overall, D-D' illustrates the irregular nature of the D1 interval in terms of thickness and paleoshoreline trend (Fig. 4.8).

D2 Interval

This cross-section demonstrates the along-strike variability of the D2 sandbody across the study area (Fig. 4.8). The thickness of the D2 interval generally thins towards the east, with the exception of the extreme western portion of the study area. This corresponds with the asymmetrical delta model including, east to west, updrift strandplain, central delta complexes, and downdrift lagoonal environments (Bhattacharya and Giosan, 2003). The western portion of the study area consists of well to very well sorted conglomerates (Facies 8a, FA2) and interbedded sandstone and conglomerate

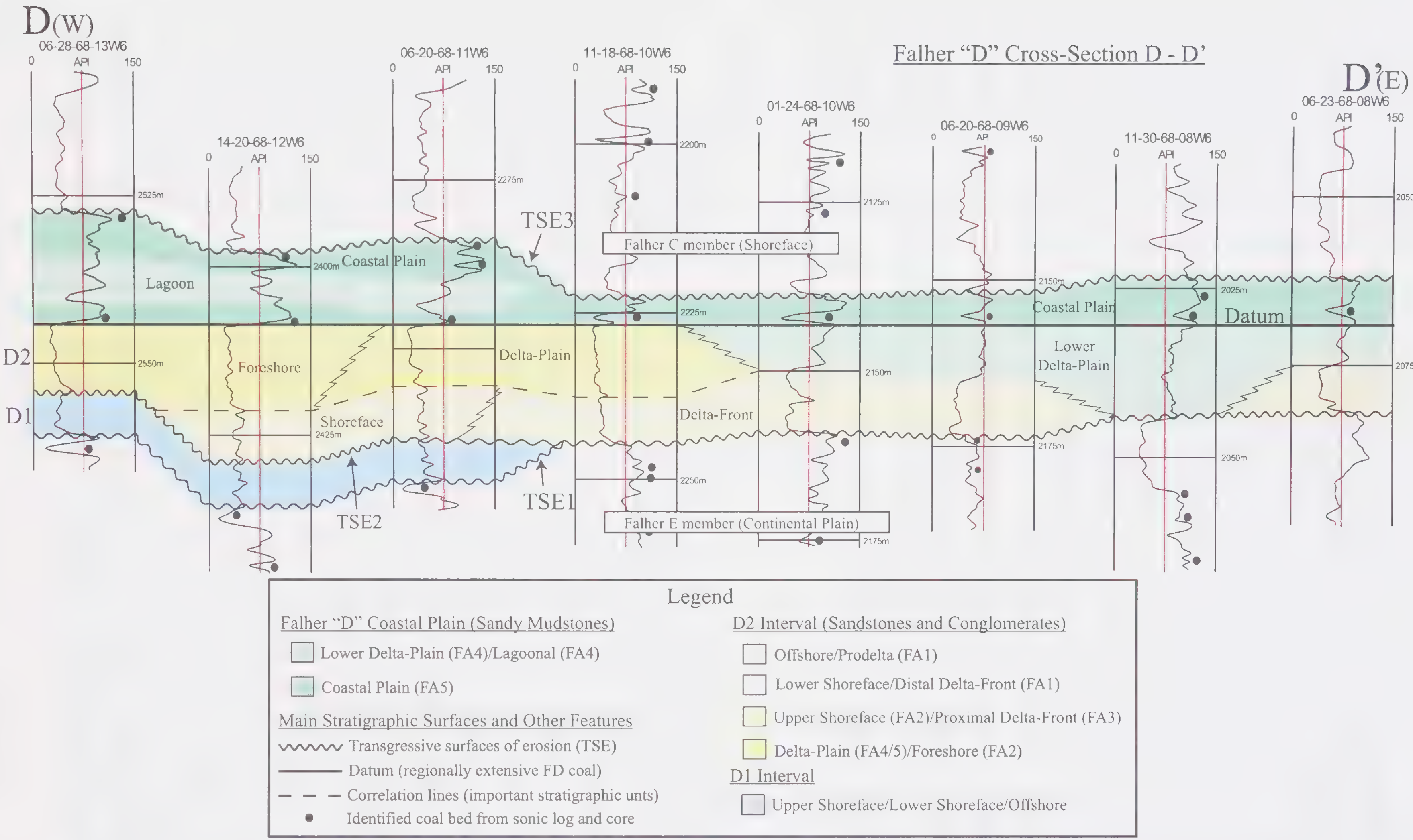

Fig. 4.8 - East-west trending strike-oriented cross-section locate within Range 10W6. This cross-section is located with the approximate center of the study area and illustrates an along strike transistion within a wave-dominated delta.

(Facies 7, FA2/3). These deposits are interpreted to represent a foreshore beach environment consisting of reworked deltaic deposits (Pemberton and MacEachern, 1992; Arnott, 1993; Caddel, 2000). The central portion of the study area is composed of interbedded sandstone, poorly sorted clast-supported conglomerates, and rare massive mudstones interpreted to represent delta-front and delta-plain deposits (FA3/4) (Bhattacharya and Walker, 1992; MacEachern, 2000). The eastern half of this cross-section contains interbedded sandstone and bioturbated silty mudstone (FA4) sharply overlying HCS very fine-grained sandstones of the lower shoreface (FA1). These deposits correspond to the downdrift lagoonal and delta-front environments (Bhattacharya and Walker, 1992; Pemberton and Wightman, 1992; MacEachern, 2000; Bhattacharya and Giosan, 2003). This illustrates the complex nature of along-strike variations in the Falher "D" member. However, in this instance all three depositional environments are interpreted to be subenvironments of one large asymmetrical wave-dominated delta (Bhattacharya and Giosan, 2003).

Summary

The spatial distribution of important stratigraphic surfaces and environmentally significant units was illustrated with three north-south oriented dip-sections and one east-west oriented strike-section. The western most dip-section, A-A', is characteristic of an updrift strandplain environment within a large asymmetrical wave-dominated deltaic system. The section consists of predominantly interbedded sandstone and conglomerate overlain by very well sorted conglomerate interpreted to represent a proximal upper shoreface and foreshore environment, respectively. The sediment source for these deposits is interpreted to be reworked abandoned delta lobes or other active deltas farther westward. The dip-section located in the middle of the study area, B-B', is characteristic of central deltaic complexes. This section is comprises a proximal to distal transition from sandstone and conglomerate dominated delta-plain and delta-front deposits to sparsely bioturbated interbedded sandstones and mudstones of the prodelta. The eastern most dip-section, C-C', contains a substantially thinner Falher "D" succession and displays a dramatic increase in the amount of mud in the form of heterolithic lagoonal mudstones and sandstones. These deposits correspond to the downdrift portion of an

asymmetrical wave-dominated delta. The east-west trending strike-oriented section, D-D', cross-cuts these dip-sections at their mid-point. This section illustrates the significant lateral variability present within the Falher "D" and encompasses elements from the three dip-sections described above. This corresponds with the asymmetrical delta model including, east to west, updrift strandplain, central delta complexes, and downdrift lagoonal environments (Bhattacharya and Giosan, 2003). The following section will examine these lateral variations in greater detail with the mapping of important lithological, sedimentological, and ichnological characteristics.

(4.3) Lithological and Ichnological Mapping

A number of lithological and biological maps were created in order to exemplify along-strike variations associated with changes in the depositional environment, more specifically the presence of an asymmetrical wave-dominated delta. Isopach maps display the overall thickness of the marine succession over the study area (Boggs, 2001). Variations in the thickness of the Falher "D" sandbody are common and illustrate changes in the depositional system. Likewise, the distribution and characteristics of conglomeratic intervals within the study area identify along-strike trends. The grain size, sorting, and general occurrence of conglomerate offers vital information on the processes affecting the Falher "D" shoreline at the time of deposition.

The diversity and abundance of trace fossils across the study area was mapped in order to identify changes in environmental stresses, such as salinity, water turbidity, water energy, sedimentation rate, oxygen level, and substrate coherence (MacEachern and Pemberton, 1992). Many of these parameters can only be assessed through the identification of biological structures, which are dependant upon the depositional conditions (Pemberton et al., 2001). Environmental parameters are particularly important in deltas where fluvial input results in physico-chemical stresses that dramatically affect infaunal organisms (MacEachern et al., 2005).

Isopach Maps

The total thickness of sandstone and conglomerate from the Falher "D" succession, D1 interval, and D2 interval are displayed in three separate isopach maps

(Fig. 4.9, 4.10, and 4.11). Core and well log data from the study area was utilized to construct these maps. Thickness variations can be useful in identifying depositional point sources, such as deltas, which generally have pronounced thicknesses compared to adjacent strandplains (Bhattacharya and Walker, 1992). However, extensive wave activity within wave-dominated deltas can effectively redistributed sediment such that a noticeable protuberance may be absent (Bhattacharya and Walker, 1992).

The overall thickness of the marine coarse clastics of the Falher "D" exemplifies a number of important trends (Fig. 4.9). In general, the thickness of the Falher "D" decreases towards the east. Although a maximum thickness of approximately 35 m occurs near the center of the study area. This region also contains rapid changes in thickness over relatively short distances. Variable thicknesses in the central portion of the study area are attributed to increased sedimentation rates and internal complexities attributed to deltaic deposition. The overall thickness of the Falher "D" decreases rapidly east of Range 10W6. The eastern region contains a noticeably thinner succession and, dramatic variations in thickness are common. The average thickness near the eastern edge of the study area is around 10 m and represents the thinnest occurrence of the Falher "D" succession in the study area. The western portion of the study area comprises uniformly distributed coarse clastics that are on average 17 m thick. The southern edge of coarse clastics along the Township 67-68 boundary corresponds to the southern limit of marine deposition within the D2 interval. The general orientation of thickness variations changes from an east-west trend in the east (Ranges 10W6 to 8W6) to a northwest-southeast trend in the west (Ranges 12W6 and 13W6). This corresponds to the change in the Falher "D" paleoshoreline trend discussed above.

The D1 isopach map was calculated from the base of Falher "D" (TSE1) to the base of the D2 interval (TSE2). The D1 interval varies in thickness from zero to just over 10 m (Fig. 4.10). The southern boundary of the sandbody is very irregular with an approximate east to west trend. The three thicker zones (located in or near T68) form strike-elongated bodies roughly 4.5 km wide and 12-19 km long. The preserved record of the D1 interval within the study area is most likely incomplete due to significant erosion that incurred prior to deposition of the D2 shoreface. In addition, the lack of cored intervals within the D1 has made interpretations on the D1 shoreface very difficult.

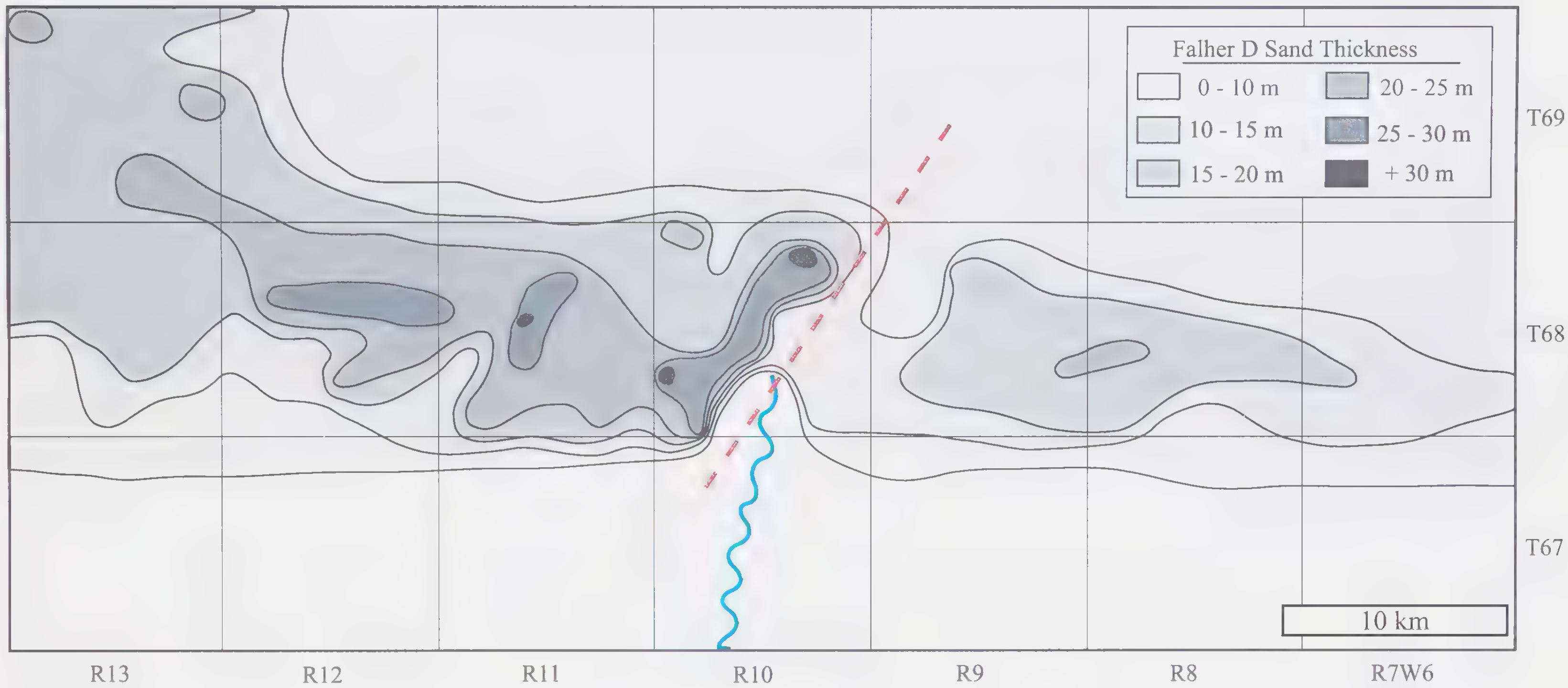

Fig. 4.9 - Isopach map of the Falher "D" sandbody within the study area. Fluvial deposits observed in core and well logs are shown in blue (up to 10m thick). The red dashed line represents a dramatic change in the lithology, vertical succession, and thickness of the Falher "D" succession.

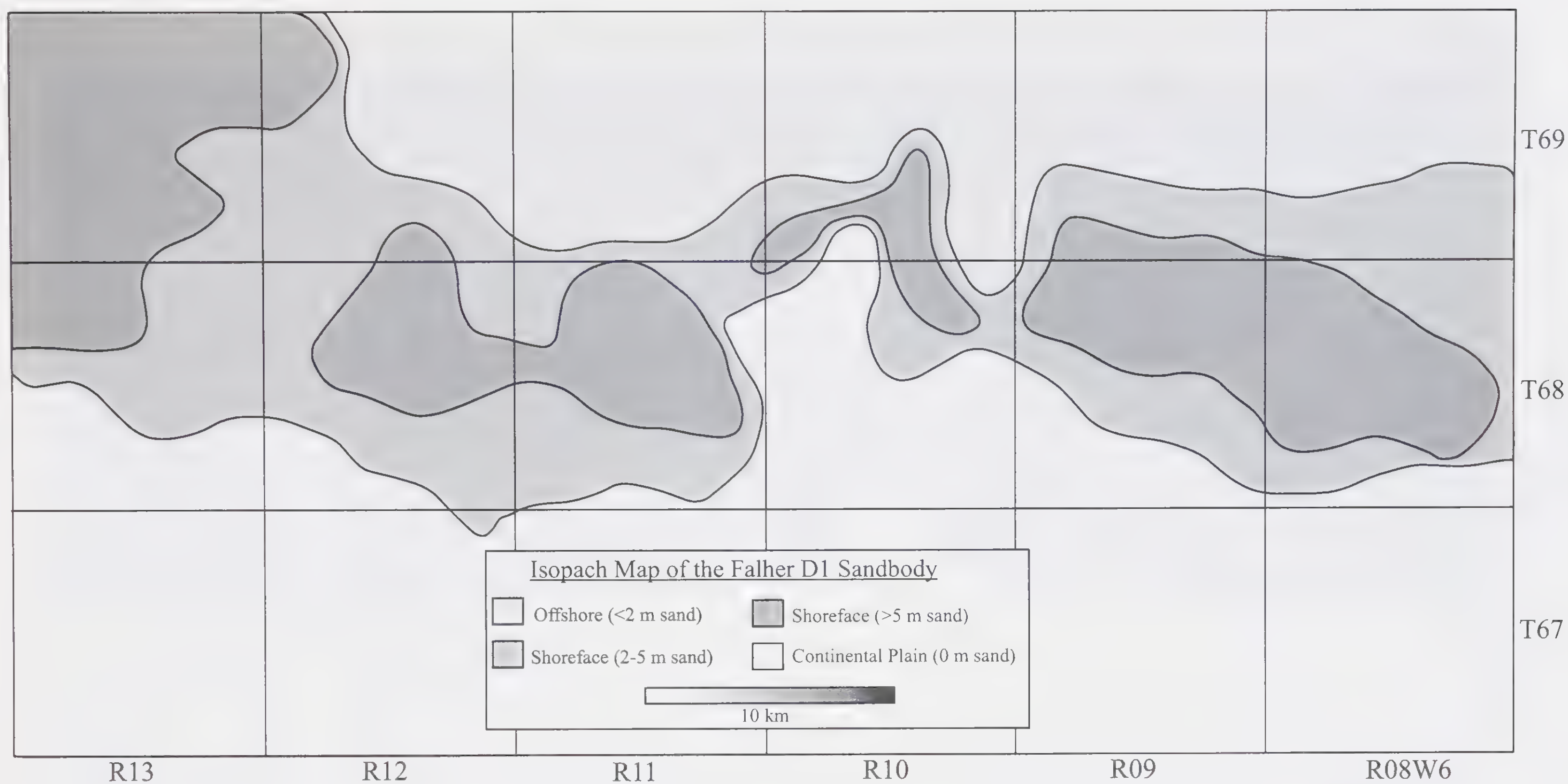

Fig. 4.10 - Isopach map of the Falher D1 sandbody within the study area. The preserved record of the D1 sandbody is most likely incomplete due to significant erosion incurred prior to deposition of the overlying D2 shoreface. Erosion, coupled with the lack of cored intervals, makes interpretations of the D1 shoreface very difficult.

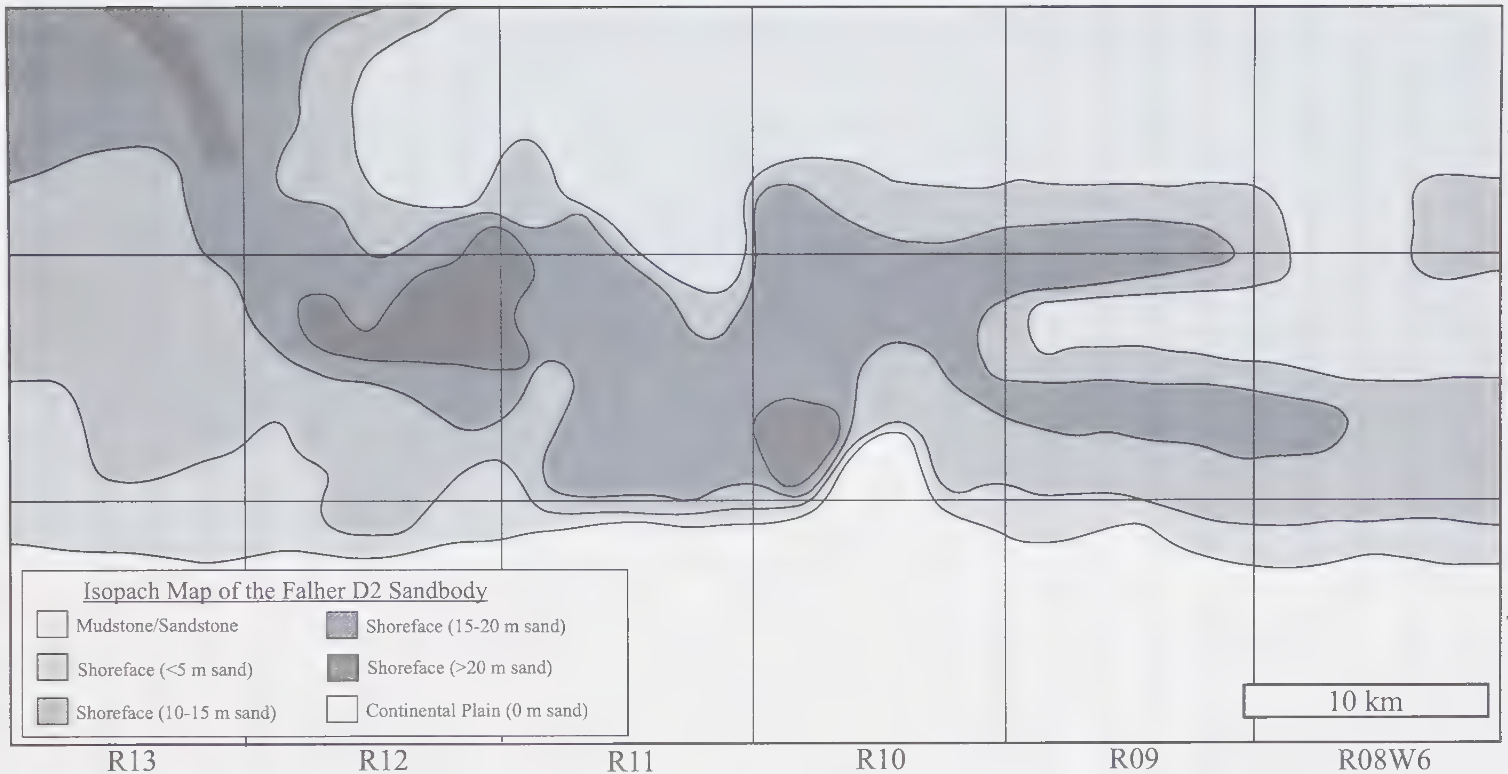

Fig. 4.11 - Isopach map of the Falher D2 sandbody within the study area. Note the overall decrease in thickness towards the east and the east-west paleoshoreline trend.

The D2 isopach map was calculated from the top of the D1 interval (TSE2) to the top of the sandstone or conglomeratic units (usually FA2/3). The D2 thickness is fairly consistent across the study area; however, large thickness variations are still present (Fig. 4.11). The coarse clastics range from less than 5 m to greater than 20 m in thickness, with the thickest deposits located in the west-central region. Similar to the overall Falher "D" there is a sharp decline in the thickness of the D2 interval from the middle of Range 10W6 towards the east. This decrease in thickness corresponds to the presence of fluvial channels and recognized deltaic deposits. The eastern half of the study area contains an increased proportion of mud than its central and western along-strike equivalents. This observation is explained with the downdrift heterolithic lagoonal deposits that are visible on the isopach map in the east-west trending 3 km wide low in thickness (Ranges 9W6 and 8W6). Immediately south of this trend, sandstone thicknesses resemble those of the western portion of the study area. This indicates that initially, the eastern half of the study areas consisted of typical strandplain deposition and that changes in the system resulted in lagoonal deposition. This corresponds with delta lobe abandonment in the west and delta reestablishment near the center of the study area. In this case, the eastern portion of the study would undergo dramatic paleoenvironmental changes and shift to downdrift lower delta-plain and delta-front deposition. This will be exemplified within the paleogeographical mapping section located at the end of this chapter.

Conglomerate Thickness, Characteristics, and Distribution

The distribution of conglomerate throughout the study area provides important information on the depositional processes that occurred within a given region (Fig. 4.12). Generally, significant accumulations of conglomerate are limited to the D2 interval, with only minor conglomeratic lags and thin interbeds present within D1. Previous studies have indicated that very little conglomerate is present within the Falher "D" north of the study area (Cant, 1984; Smith et al., 1984; Cant, 1995; Casas and Walker, 1997). The distribution of conglomerate within the D2 shoreface is generally restricted to Ranges 13W6 to 10W6 along Township 68, with insignificant accumulations of conglomerate present in the eastern region (Fig. 4.12). The sharp decline in thickness of the conglomeratic intervals corresponds to the sudden decrease in the overall thickness of the

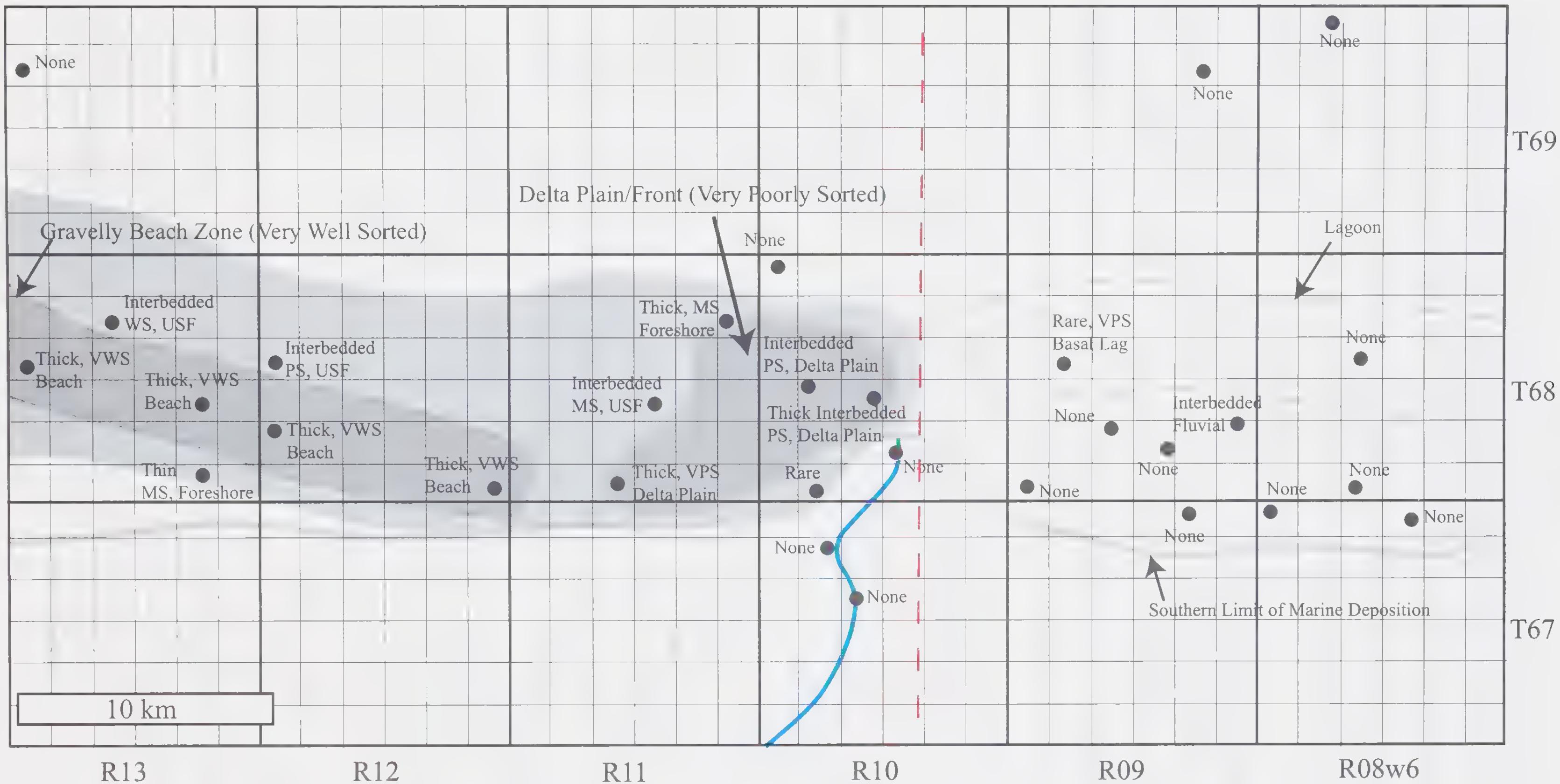

Fig. 4.12 - Relative thickness, sorting, and interpreted environment of deposition for conglomeratic intervals within individual core across the study area. Overall sorting characteristics are shown as: (VWS) - very well sorted, (WS) - well sorted, (MS) - moderately sorted, (PS) - poorly sorted, and (VPS) - very poorly sorted. Shaded light grey regions represent moderate thickeness of conglomerate, while the shaded dark grey regions represent very thick conglomeratic intervals. The blue line represents fluvial channel deposits identified in core. Note the lack of conglomerate on the eastern side of the red dashed line. Also note the well-sorted nature of the conglomeratic intervals in the extreme west of the study area as compared to the poorly-sorted conglomerate in the central portion.

D2 interval. One of the thickest accumulations of continuous conglomerate is present within Ranges 13W6 and 12W6, which forms a 3.2 km wide by 18 km long coarse clastic body. This conglomeratic body varies in thickness from approximately 7 meters along its western edge to less than 4 meters at its eastern termination (Fig. 4.12). The other thick accumulation of interbedded sandstone and conglomerate occurs within Range 10W6 and varies from 6 to 10 meters in thickness (Fig. 4.12).

Another important feature of the Falher "D" conglomerates is the degree of sorting, which ranges from very well sorted to very poorly sorted. The distribution of grain size sorting is an important indicator of the depositional processes that were required to physical sort sediment over various periods of time (Reading, 1989; Orton and Reading, 1993). Prominent intervals of very well-sorted, clast-supported conglomerates (Facies 8a), ranging from 0.5 to 5 m in thickness, are restricted to a WNW-ESE trending 3.2 km wide body present in the middle of Ranges 13W6 and 12W6 (Fig. 4.12). Within this conglomeratic body, the overall grain size generally decreases in an eastward direction, with Facies 6 (coarse sand and granules) replacing Facies 8a (small pebbles) along-strike. This conglomeratic feature has been interpreted in previous chapters as a result of delta lobe abandonment and along-strike reworking by longshore drift within an updrift strandplain setting. This will be discussed in the following section that deals with the depositional history of the Falher "D". Poorly to very poorly sorted conglomerates are found in the greatest concentration within the central section of the study area. These coarse clastics are generally interbedded with pebble-rich sandstones and less commonly with massive mudstones. This corresponds with the central deltaic complexes discussed previously. East of 10W6, conglomerate is generally absent and sandstones are typically well sorted with very low abundances of pebble-sized clasts as compared to laterally equivalent deposits in the west.

Bioturbation Mapping (Diversity/Abundance)

The diversity and intensity of bioturbation can present important information on the environment of deposition (Ekdale et al., 1984; Frey and Pemberton, 1984; MacEachern and Pemberton, 1992). Trace fossil distribution can be especially important in strata where physical sedimentary structures are not preserved. In general, cored

intervals of the Falher "D" possess very low levels of bioturbation. This is partly associated to the core control in which cores are often from the coarser-grained proximal regions where very little bioturbation would be expected (ex: proximal upper shoreface, foreshore, and delta-plain). The paucity of ichnofossils can also be explained by the storm dominance exhibited in distal deposits whereby extensive storm amalgamation occurred in the lower shoreface. In this cases, the preservation potential of fair-weather, most likely bioturbated intervals, is low. The exception to the lack of bioturbation is the "burrowed zone" discussed in the previous chapter (Saunders et al., 1994). However, this zone is either not present or not preserved in the eastern half of the study area.

The sporadic distribution of core control and paucity of core within the northern half of study area lead to difficulties discerning detailed ichnological variations. Notwithstanding, broad trends in the abundance of bioturbation within the lower and upper shoreface (or delta-front) exist (Fig. 4.13). This is illustrated in a sharp decrease in the amount of bioturbation at the Range 11W6-10W6 border, which occurs in conjunction with the abrupt decrease in the thickness of the Falher "D" sandbody and abundance of conglomerate. West of this region, thin 5-10 cm thick, sporadically to abundantly burrowed zones are common within the uppermost lower shoreface and distal upper shoreface. The ichnological suite generally consists of only 2-4 distinct traces, however up to 12 are present overall. This suite is characteristic of a low diversity, mixed *Skolithos-Cruziana* ichnofacies present within the upper shoreface and proximal lower shoreface (c.f. MacEachern and Pemberton, 1992). This presence of bioturbation is in stark contrast to the eastern half of the study area in which the lower and upper shoreface are nearly unburrowed. However, the lagoonal strata within the eastern region consists of abundant and very low diversity trace fossil suites that are typical to brackish water environments (Pemberton and Wightman, 1992). The most diverse and abundant trace fossil suites are found north of the Township 68-69 boundary. Within this region, deposits are characterized by a proximal *Cruziana* Ichnofacies found within interbedded sandstones and mudstones of the distal lower shoreface to upper offshore and corresponding prodelta (MacEachern and Pemberton, 1992). The northern portion of the study area also contains common intervals with little to no bioturbation (ex: 07-26-69-

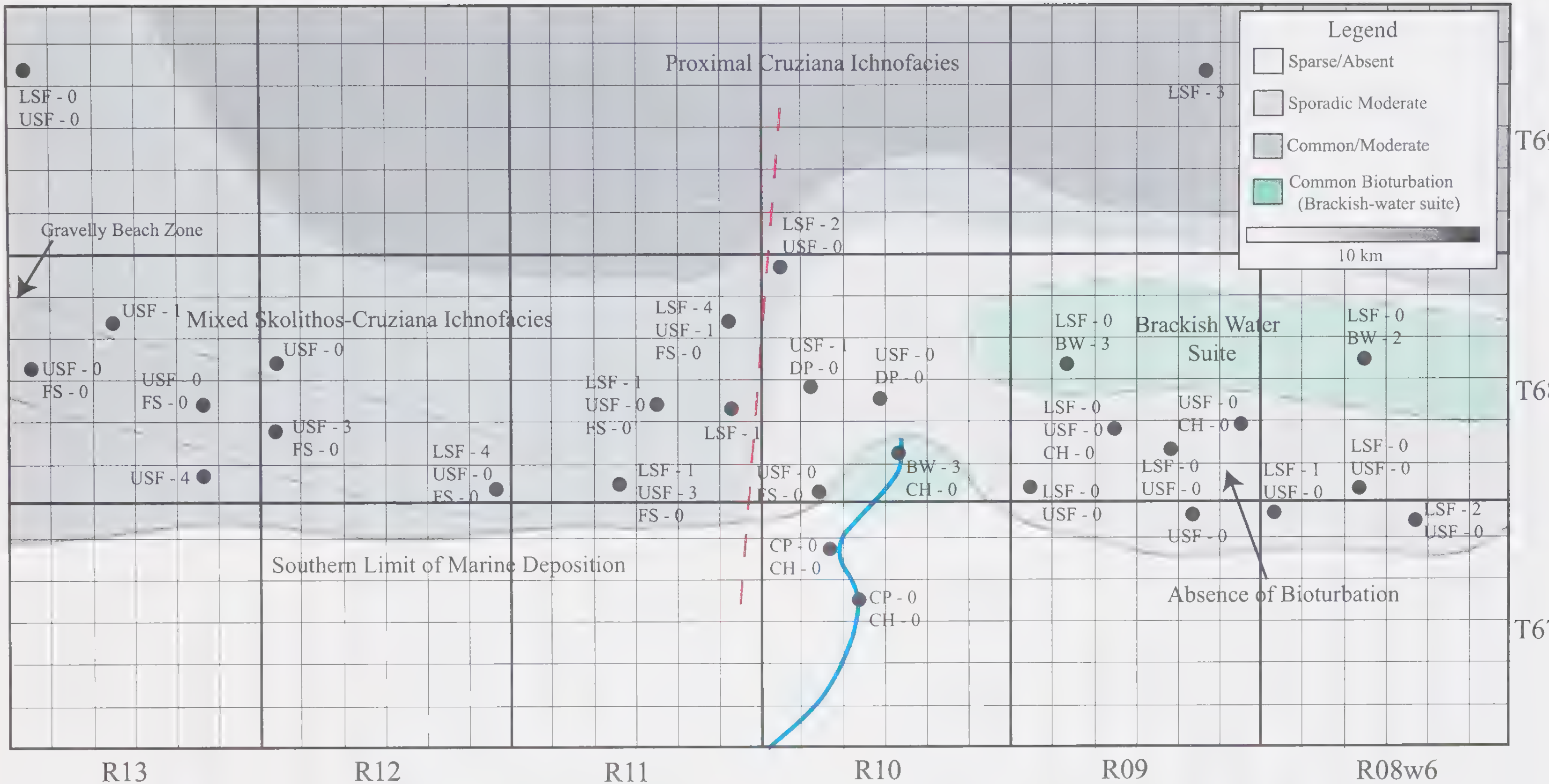

Fig. 4.13 - Relative overall bioturbation intensities in core from across the study area. Bioturbation intensities for each environment present within individual core are shown as: (0) - Absent, (1) - Sparse, (2) - Uncommon, (3) - Moderate, (4) - Common, (5) - Abundant, and (6) - Complete. Environments desribed include: (LSF) - Lower Shoreface/Distal Delta Front, (USF) - Upper Shoreface/Proximal Delta Front, (FS) Well-sorted conglomeratic foreshore beach, (DP) - Delta plain, (BW) - Brackish water lagoon, (CH) - Fluvial Channel, (CP) - Coastal Plain. Note the relative increase in bioturbation on the west side of the dashed line as compared to the east side of the study area.

09W6). The paucity of bioturbation is related to fluvially induced stresses within the prodelta as discussed in chapter three (MacEachern et al., 2005).

The abrupt lateral decrease in the abundance and diversity of bioturbation is a function of increased environmental stresses, including salinity fluctuations, water turbidity, and sedimentation rates, associated with fluvial input within regions of delta-influence. In this case, environmental stresses associated with deltaic deposition will be deflected downdrift. Therefore, updrift regions will exhibit ichnological characteristics typical of strandplain settings, while downdrift regions will reflect deltaic deposition. In addition, heterolithic strata consisting of very low diversity trace fossil suites typical to brackish water environments are also present within the downdrift region. This corresponds to deposition within the lower delta-plain. The spatial distribution of ichnological characteristics for the Falher "D" supports the presence of an asymmetrical wave-dominated delta. A detailed discussion of the sedimentological and ichnological characteristics of wave-dominated deltas is presented within chapter three and will not be repeated here.

Summary

The lithological and biological distribution maps discussed above all identify distinctive along-strike variations that predominantly occur within Range 10W6. This locality divides the study area into two distinct regions. The western half contains thick accumulations of very-well to very-poorly sorted conglomerate; relatively diverse and abundant ichnological suites; and an overall thick succession of sandstone and conglomerate. Conversely, the eastern portion of the study area contains virtually no conglomerate, sparse bioturbation, and a dramatically thinner shoreface succession. This region also contains abundant interbedded mudstone and sandstone that reflect brackish water lagoonal deposition. Accordingly, the eastern region contains pronounced mud and silt contents compared to the predominance of coarse clastics in the west.

The data described within this section is consistent with the interpreted presence of an asymmetrical wave-dominated delta centered within Range 10W6. The well-sorted, texturally mature sandstones and conglomerates of the western region are interpreted as the updrift strandplain deposits. The eastern, texturally less mature

sandstones and mudstone-rich lagoonal deposits are interpreted as the downdrift flank of the delta. The thicker, more poorly sorted interbedded sandstones, mudstones, and conglomerates within Range 10W6 are interpreted as delta-front and delta-plain deposits associated to landward distributary channels. The morphology of the Falher "D" deltaic complex is consistent with previously described modern and ancient asymmetrical deltas (ex: Giosan, 1998; Rodriguez et al., 2000; Bhattacharya and Giosan, 2003; Hansen and MacEachern, in press). The following section will illustrate the paleogeographical evolution of the Falher "D" succession within the study area utilizing the previously discussed lithological and biological maps, cross-sections, and depositional model.

(4.4) Paleogeographical Mapping

The depositional history and paleogeography of the Falher "D" succession is described below using a series of facies maps each representing a particular stratigraphic/time interval during deposition of the Falher "D". Six paleogeographical maps ranging from coastal plain-dominated intervals of the upper Falher "E" to the coastal plain-dominated intervals of the uppermost Falher "D" display the evolution of the Falher D within the study area. The intervals were selected in order to highlight particular depositional environments or stratigraphic events that are essential in he evolution of the Falher "D". Variations in relative sea-level and sediment supply are the primary factors that affects the paleogeographic evolution of the Falher D. The maps included in this section were created primarily using core descriptions along with well log profiles to fill in the considerable gaps in the study area. This information was combined with cross-section data in order to map the general environment at each well during each time interval. Using the paleogeographic maps, the depositional history of the Falher "D" is discussed below in a chronological order.

Time 1: Upper Falher "E"

A reasonable starting point for the discussion on the evolution of the Falher "D" is to begin with the end of Falher "E" deposition (Fig. 4.14). At this point, the Falher "E" shoreline was situated north of the study area (Smith et al., 1984). Deposits of the upper Falher "E" encompass organic-rich mudstones and coals with cross-cutting sandstone-

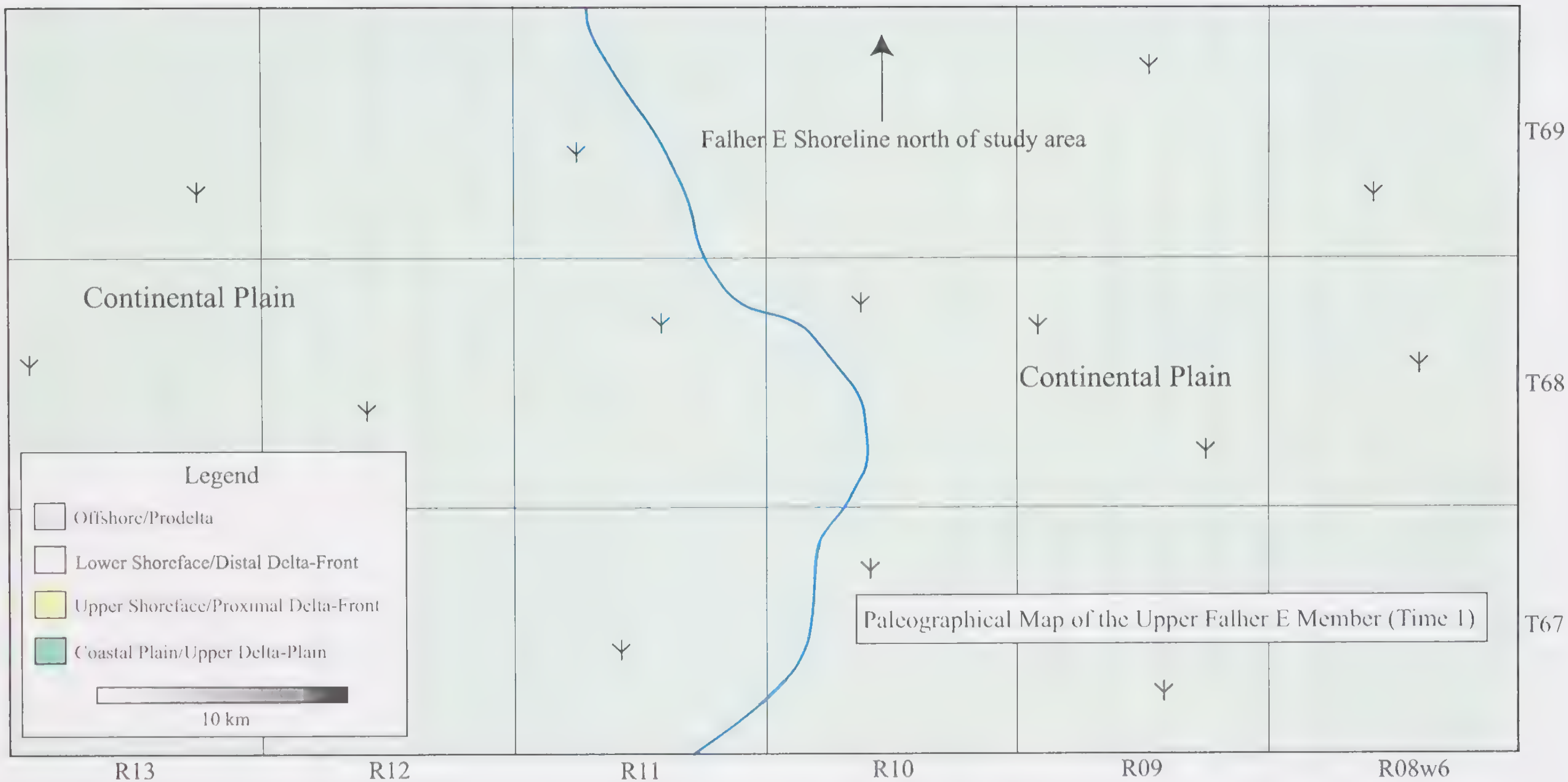

Fig. 4.14 - Paleogeographic reconstruction of the upper Falher "E". During this time, the Falher "E" shoreline has prograded northward out of the study area (Smith et al., 1984). Deposits within the study area are composed of organic-rich mudstones and coals with cross-cutting sandstone-rich fluvial channels (shown in blue) that feed the Falher "E" shorelines farther to the north.

rich fluvial channels that supplied sediment to the Falher "E" shorelines north of the study area. A prominent channel network is located in approximately the center of the study area (Range 10W6). This coastal plain strata of the upper Falher "E" is easily distinguished from the overlying marine deposits of the Falher "D", especially where the Falher "E" is characterized by thick coal beds. The Falher "E" stratigraphic interval ends with the introduction of the sharp-based sandstones and conglomerates of the Falher "D". The surface separating these two members, the TSE1, represents a large-scale increase in water depth, which resulted in submergence of the study area. This transgressive surface of erosion (TSE1) formed as the shoreline retreated southward resulting in the erosion of previously deposited marginal-marine and non-marine strata of the Falher "E". As in all other Falher cycles, these surfaces erode downward until the first major coal bed is reached (e.g. Leckie, 1982; Cant, 1984; Smith et al., 1984; Arnott, 1993; Casas and Walker, 1997; Rouble and Walker, 1997; Caddel, 2000; Armitage 2002; Hobbs, 2004). Erosion ends at the coal beds, as these coal-rich intervals tend to be harder and more resistant to erosion (Kalkreuth and Leckie, 1989). Accordingly, each Falher Member is separated above and below by a well developed coal-rich unit.

Time 2: Early Progradation of D1 Shoreface following Transgression (TSE1)

The southward transgression of the Falher "E" shoreline followed a relative rise in sea-level (Leckie, 1986). This resulted in the inundation of the coastal plain deposits and flooding of a vast proportion of the study area. The maximum landward position of the shoreline during this event was in the lower half of Township 68 (Fig. 4.15). Large brackish lagoonal environments possibly dominated the coast with potential wave-dominated estuaries forming at the mouths of fluvial channels. Physical evidence for transgression occurs in the presence of poorly sorted organic-rich conglomeratic lags, which occur along the TSE1 contact. Most transgressive deposits are not preserved and may be the result of a rapid transgression or lack of sediment input.

After transgression of the Falher "E", the shoreline was reestablished in the lower half of Township 68 (Fig. 4.15). During this time, the shoreline was extremely irregular with a roughly east-west trend. The most notable shoreline irregularity is the large 5 km wide protuberance within Range 10W6. This region contains large fluvial channels

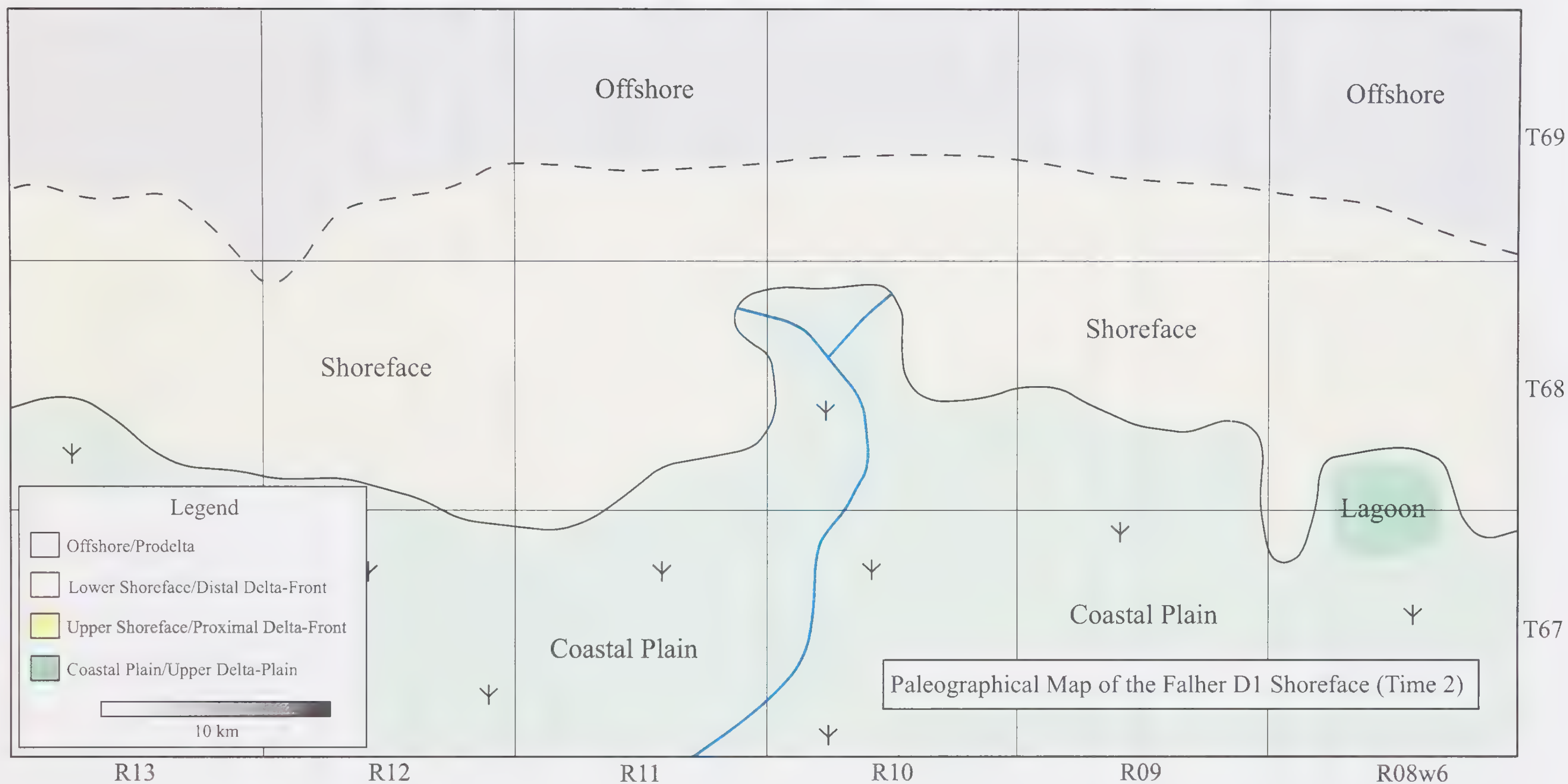

Fig. 4.15 - Paleogeographic reconstruction of the Falher D1 shoreline following the initial transgression of the Falher E Member and subsequent progradation of the D1 shoreface.

possibly feeding deltaic deposits farther north. East and west of this area, typical strandplain deposits predominate the early D1 interval. The D1 succession primarily consists of interbedded sandstone and conglomerate reflecting upper shoreface deposition. Northward there is a transition into interbedded sandstones and mudstones within the lower shoreface and offshore. Based on the available core data, distributions of environments within the D1 interval are difficult to ascertain, but appears similar to the successive D2 interval.

Time 3: Early progradation of the D2 shoreface following Transgression (TSE2)

Deposition of the D1 shoreface ends with a small rise in relative sea-level, which floods the nearshore coastal plain and leads to a southward retreat of the shoreline. The D2 shoreline is established in the top half of Township 67, which lies farther south than the previous D1 shorelines (Fig. 4.16). The only preserved deposits of this minor transgression are thin marginal-marine mudstones separating marine sandstones from D1 and D2 (ex: 06-28-68-13W6). A minor transgressive surface of erosion (TSE2) formed as the shoreline retreated southward again resulting in the erosion of previously deposited marine and marginal-marine strata of the D1 interval.

During early deposition of the D2 interval, the shoreline was linear as a result of effective redistribution of sediment supply. This is the most southerly position of the paleoshoreline at any time during Falher "D" deposition within the study area. As the rise in relative sea-level slowed and finally ended, sediment supply began to overcome available accommodation space and the D2 shoreline prograded northward. A wave-/storm-dominated strandplain environment dominated the central and eastern portions of the shoreline in the study area. The western edge of the shoreline comprised mainly interbedded sandstone and poorly sorted conglomerate interpreted to represent delta-front and delta-plain deposits (Fig. 4.16). This regions proximity to the British Columbia – Alberta boarder hampers interpretations, as there are few cored intervals west of the study area in British Columbia. Other deltaic deposits have been identified in outcrops west into British Columbia within stratigraphically equivalent deposits (Gates Formation; Leckie, 1986; Caddel, 2000; Caddel and Moslow, 2004).

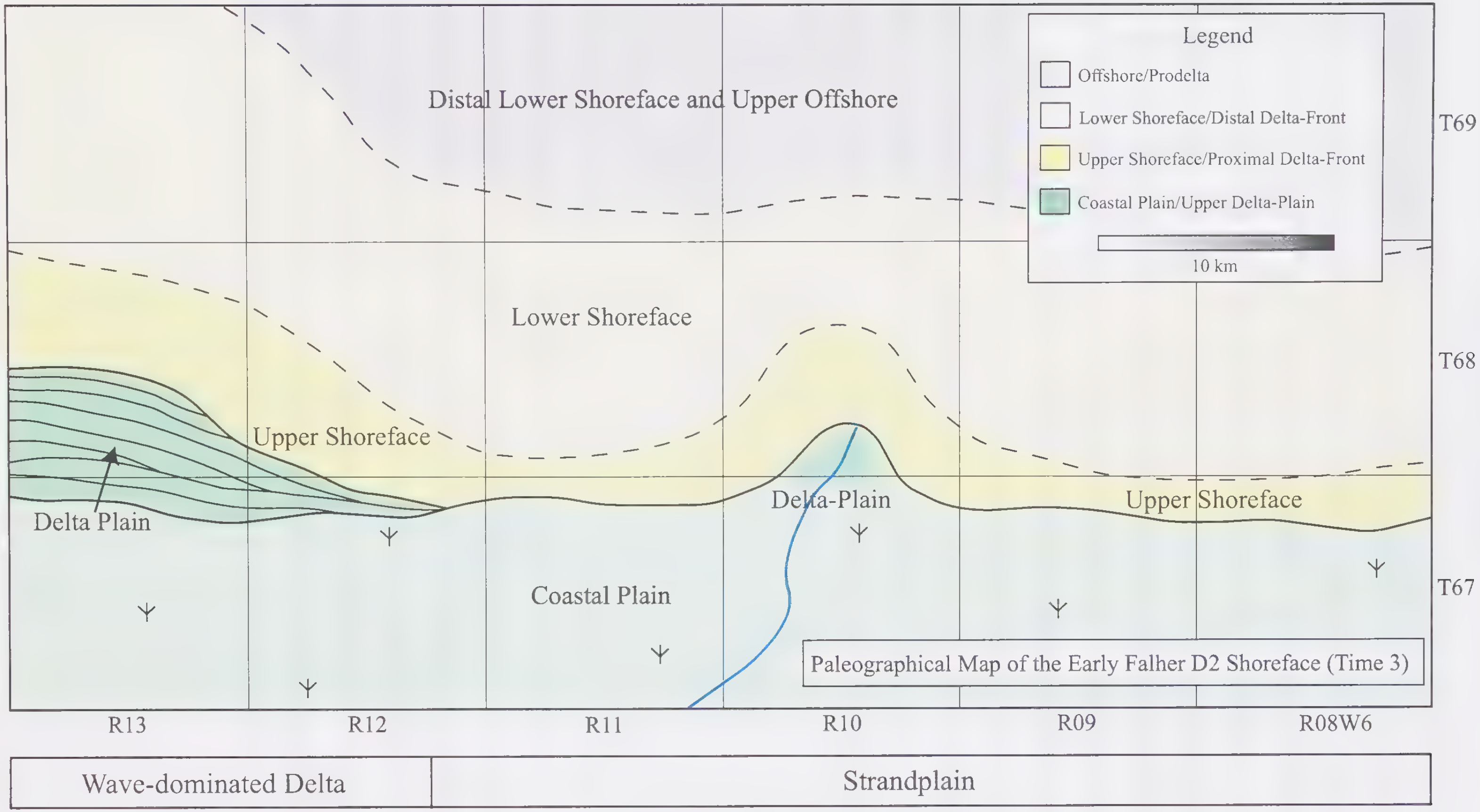

Fig. 4.16 - Paleogeographic reconstruction of the early Falher D2 shoreline following the transgression of the D1 unit and subsequent early progradation of the D2 unit. Formation of wave-dominated delta deposits along the western edge of the study area occurred at this time. However, most of the study area is dominated by a typical strandplain environment.

Time 4: Progradation of the middle D2 Shoreface

As progradation of the D2 shoreface continued, the complexity of the depositional systems increased. Progradation during this time resulted from an increase in sediment supply, which filled the available accommodation space leading to northward shoreline progression. A distinctive feature that appeared during progradation was a wave-dominated delta situated within Range 10W6 (Fig. 4.17). Evidence of deltaic deposition includes a slight shoreline protuberance consisting of interbedded sandstone, poorly sorted conglomerate, and mudstone; thick fining-upward sandstone packages interpreted as fluvial channels located south of the protuberance; an overall thickening of the Falher "D" within the area; and the sedimentological and ichnological trends mapped above and discussed in chapter three. West of the delta, there was also a 3.2 km wide, 22 km long, and 3-5 m thick very well-sorted clast-supported conglomerate unit present in Ranges 13W6 and 12W6. This linear body trends WNW-ESE and is interpreted to represents foreshore beach strata due to the extremely well sorted nature of the sediment (Fig. 4.17). This well sorted conglomerate body most likely formed from the destruction and redistribution of older delta-front and delta-plain deposits. Channel migration or aluvsion can terminate the sediment supply to particular delta lobes, which can leave it susceptible to erosion by destructional processes such as wave action (Arnott, 1993). Accordingly, sediment comprising the proximal delta-front and lower delta-plain is eroded and transported along strike by alongshore drift. In the case of the Falher "D", longshore drift could have transported reworked deltaic deposits from west of the study area and deposited it as the well-sorted conglomerates. It is feasible that the abandoned delta lobe (west of Range 13W6) and the preserved delta lobe (Range 10W6) were fed from the same fluvial channel network. This illustrates the importance of autocyclic processes within deltaic settings and demonstrates that large paleoenvironmental shifts are not necessarily related to allocyclic processes (ex: sea-level fluctuations).

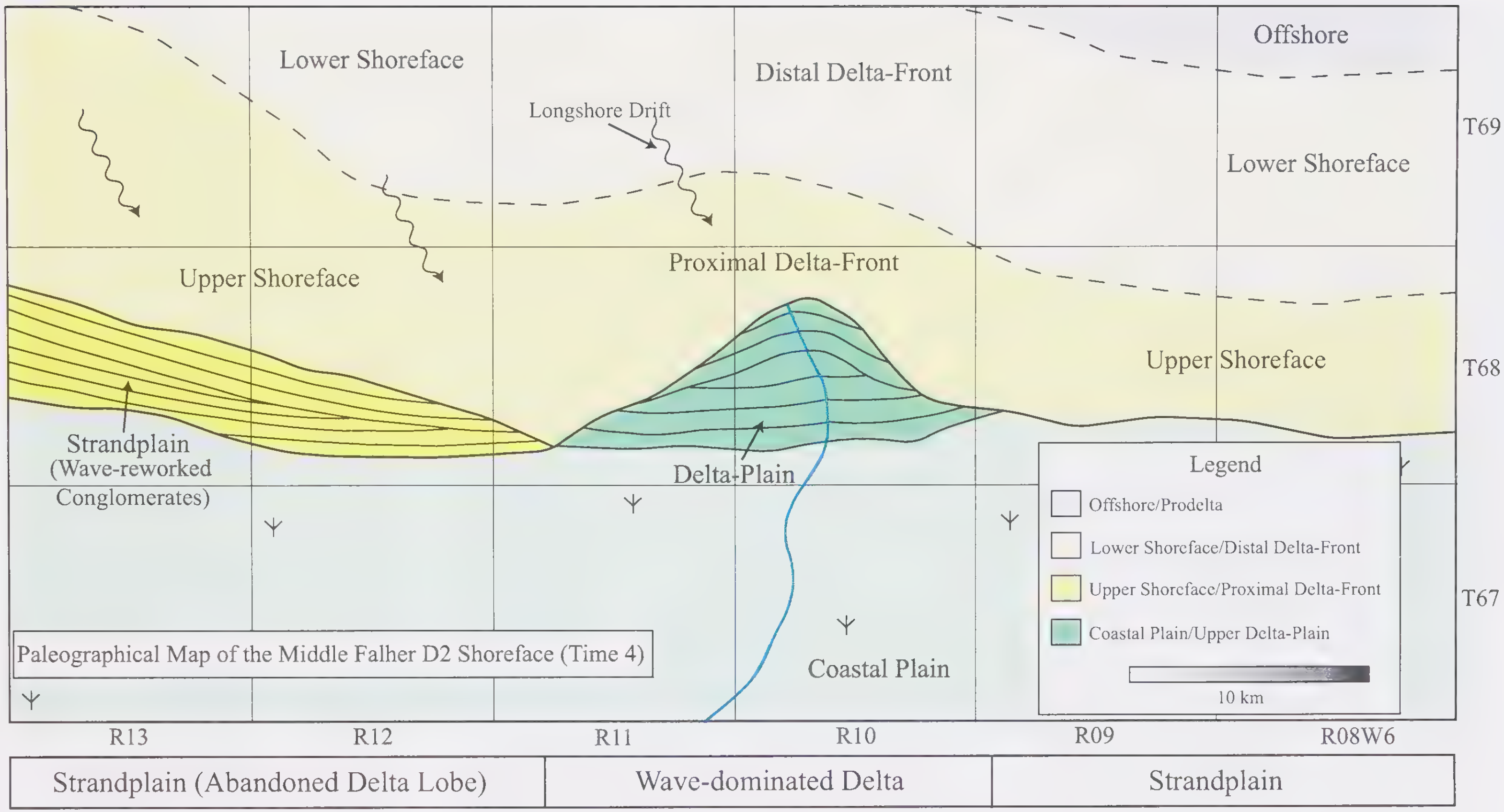

Fig. 4.17 - Paleogeographic reconstruction of the middle Falher D2 shoreline following delta lobe abandonment and along-shore reworking of sediment eastward. The delta lobe is re-established in the center of the study area and the D2 shoreface continues to prograde. The eastern and western portions of the study area are dominated by strandplain environments while the central region is strongly influenced by a wave-dominated delta.

Time 5: Progradation of the Late D2 Shoreface

Approaching the end of D2 progradation, the most basinward position of the D2 shoreline is located in the northern half of Township 68 (Fig. 4.18). During this time, the eastern portion of the study area is dominated by interbedded sandstones and bioturbated mudstones sharply overlying HCS very fine-grained sandstones interpreted to have formed in the lower shoreface. Based on detailed core descriptions and depositional mapping, these heterolithic deposits are interpreted as lagoonal strata sandwiched between abandoned beach ridges present in the downdrift portion of an asymmetrical wave-dominated delta (Fig. 4.18). These downdrift environments formed primarily due to the disruption of longshore drift from the west by the distributary channels present within Range 10W6. The lack of coarse-grained sediment supplied from the west and abundance of finer sediment within the downdrift deposits supports this idea. The delta provides protection from wave activity and is a source of mud for the downdrift region (Bhattacharya and Gisoan, 2003). Emergent barrier bars forming near the distributary mouth migrate downdrift to isolate small brackish water lagoons along the coastline. This deltaic system corresponds, more or less, with the asymmetrical delta model put forward by Bhattacharya and Giosan (2003) and discussed in detail within chapter three. This model predicts significant river-borne muds with lower quality reservoir facies in the downdrift areas, and higher quality sands in the updrift areas (Bhattacharya and Giosan, 2003). This model explains the decrease in thickness, lack of conglomerate, and decrease in intensity and diversity of bioturbation on the downdrift side of the wave-dominated delta.

Time 6: Forced Regression and Aggradation of the Uppermost Falher "D" Coastal Plain

Marine deposition within the study area ceases with a drop in the relative sea-level during forced regression (Posamentier et al., 1992). This event results in the sudden basinward movement of the shoreline north of the study area (e.g. Cant, 1984; Smith et al., 1984; Leckie, 1986; Casas and Walker, 1997). Accordingly, the study area experienced subaerial exposure and thus formed a sequence boundary (SB). Following

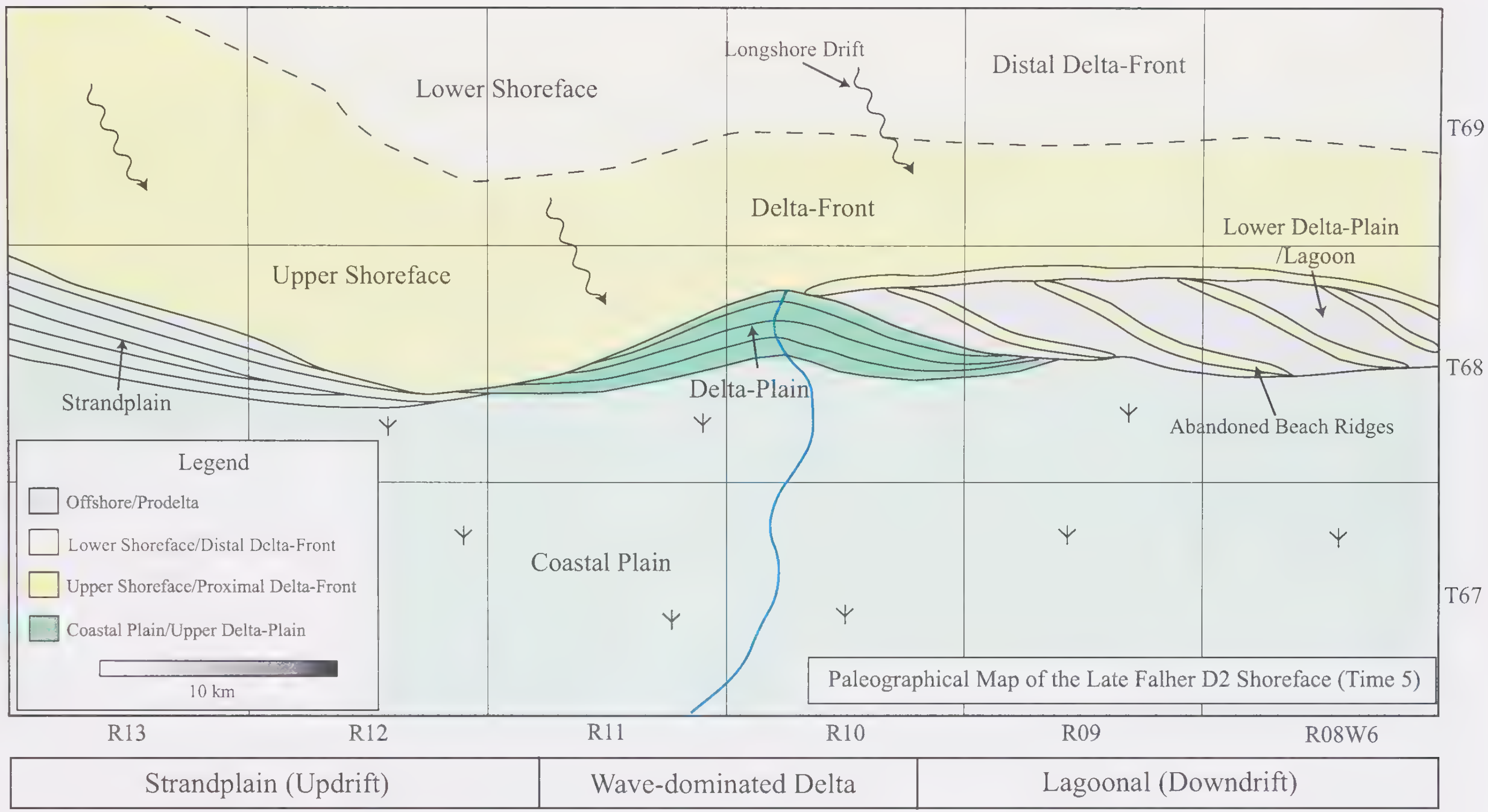

Fig. 4.18 - Paleogeographic reconstruction of the late Falher D2 shoreline at the most northward position of the D2 unit. Continued progradation of the wave-dominated delta within Range 10W6 produces downdrift lagoonal deposits in between beach ridges. The western portion of the study area is dominated by updrift strandplain deposits, while the central and eastern regions are dominated by deltaic complexes and downdrift lagoonal deposits, respectively. This is consistent with the asymmetrical delta model discussed in chapters three and four (Bhattacharya and Giosan, 2003).

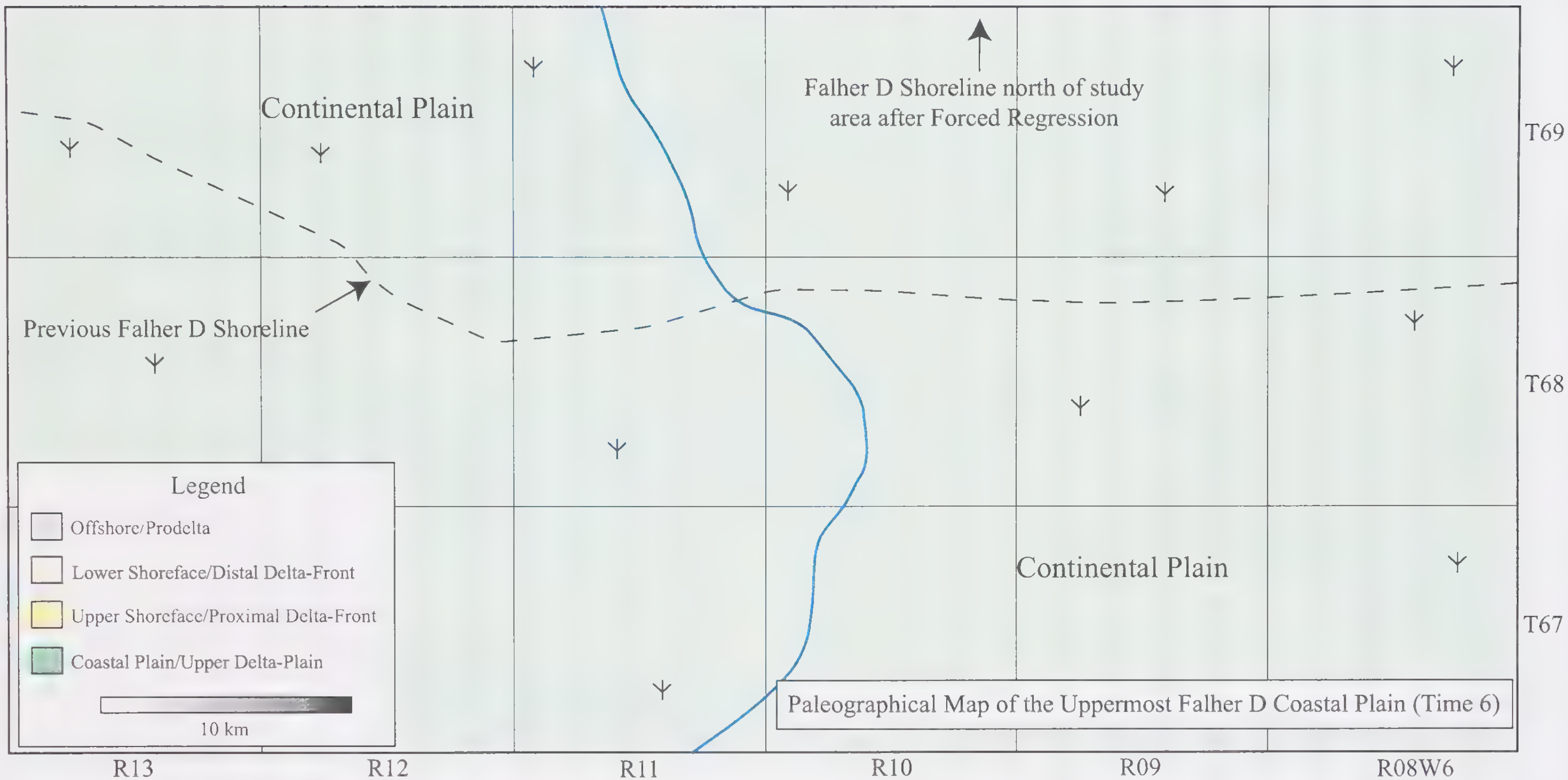

Fig. 4.19 - Paleogeographic reconstruction of the uppermost Falher "D" following a forced regression and re-establishment of the Falher "D" shoreline north of the study area. Aggradation of the coastal plain continued until transgression, associated to the deposition of the Falher "C" occurred.

forced regressive deposition, when the relative sea-level began to rise, coastal plain aggradation occurred during normal regression, which blanketed the study area (Fig. 4.19). This manifests itself in the form of a 1-5 m thick coastal plain unit overlying the northern half of the study area (ex: 07-26-69-09W6). Evidence of a minor forced regression and sequence boundary include the juxtaposition of coastal plain mudstones and coals sharply overlying more distal deposits (ex: lower shoreface). Core analysis north of the study area indicates that the Falher "D" underwent another minor transgression, which brought the shoreline south to the northern edge of the study area (Arnott, 1994; Casas and Walker, 1997). Evidence of this minor rise in relative sea-level is the presence of marginal-marine lagoonal mudstones encased in coastal plain strata of the uppermost Falher "D" in the northernmost part of the study area. However, in the remainder of the study area, this transgression would be represented in coastal plain overlying coastal plain deposits and would be difficult to discern. Deposition of the Falher "D" terminates with the major transgression associated to the deposition of the overlying Falher "C" (Casas and Walker, 1997; Armitage, 2002; Armitage et al., 2004).

(4.5) <u>Chapter Summary</u>

The previous chapters have provided detailed descriptions of the fifteen facies and five facies associations observed in core. This chapter built upon this foundation by establishing a stratigraphic framework for the Falher "D" and utilizing this framework in order to analyze the spatial distribution of environmentally-significant units identified in previous chapters. The Falher "D" is bound above and below by major discontinuities exhibiting significant erosion and poorly-sorted conglomeratic lags. The surface separating the top of the Falher "E" from the base of the Falher "D" is referred to as TSE1 and the contact delineating the top of the Falher "D" and the base of the Falher "C" is referred to as TSE3 in this study. Another transgressive surface of erosion, referred to as TSE2, is present within the Falher "D" itself, however the juxtaposition of facies along this surface is not as severe. This surface is utilized to separate the Falher "D" sandbody into sub-members, termed D1 and D2. Using this stratigraphic framework, the lateral distribution of facies was analyzed with three dip-sections, one strike-section, and a series of lithological and sedimentological maps. Each cross-section is located within a distinct

depositional environment corresponding with the depositional model established in chapter three. The western most dip-section, A-A', is characteristic of an updrift strandplain environment; the dip-section located in the middle of the study area, B-B', is characteristic of central deltaic complexes; and the eastern most dip-section, C-C', corresponds to the downdrift lagoonal environments within an asymmetrical wave-dominated delta.

A number of lithological and biological maps were created in order to exemplify along-strike variations associated with changes in the depositional environment, more specifically the presence of an asymmetrical wave-dominated delta. Isopach maps demonstrated that the D1 and D2 intervals thin eastward. This is exemplified by the dramatic eastward thinning of D2 across the Township 10W6-9W6 boundary. The spatial distribution of conglomerate illustrated that the western portion of the study area consisted of very well sorted small pebble conglomerates, while the central portion consisted of poorly sorted larger pebble conglomerates. Conversely, the eastern portion contains virtually no conglomerate. Trace fossil distributions illustrated similar trends with typical storm-dominated shoreface suites on the western half of the study area and very sparse bioturbation on the eastern half.

The depositional history and paleogeography of the Falher "D" is described using a series of facies maps each representing a particular stratigraphic/time interval during deposition of the Falher "D". Utilizing the depositional model established in chapter three, as well as the cross-section and mapping data described above, six paleogeographical maps illustrate the evolution of the Falher "D". These maps highlight the importance of lateral changes in the local depositional environment and demonstrate that all significant facies variations may not be allocyclicly controlled. The presence of an asymmetrical wave-dominated delta dominates the Falher "D" succession over most of the D2 unit and serves as an explanation for the numerous lateral variations observed across the study area.

Chapter 5: Conclusions

1. Fifteen facies (F1a to F9) are identified in core within the Falher "D" study area. Individual facies are differentiated based upon their lithological, sedimentological and ichnological characteristics. The fifteen facies are grouped into five facies associations corresponding to fully-marine (FA1 to FA3), marginal-marine (FA4) and non-marine (FA5) environments of deposition.

2. Analysis of the facies succession within the Falher "D" suggests a depositional system that varies considerably along-strike and includes elements of both shoreface and wave-dominated deltaic environments. Within wave-/storm-dominated settings, substantial overlap exists between facies that occur in shoreface and deltaic environments. Conversely, a number of facies associations will include both environments, while some will possess lateral equivalents. In typical strandplain settings, facies associations are as follows, lower shoreface (FA1), upper shoreface and foreshore (FA2), brackish-water environments (FA4), and coastal plain (FA5). While, in wave-dominated deltaic settings, facies associations are as follows, prodelta and distal delta-front (FA1), proximal delta-front (FA3), lower delta-plain (FA4), and upper delta-plain (FA5).

3. The interpreted depositional environments observed within the Falher "D" study area are consistent with asymmetrical wave-dominated delta models. The study area consists of well sorted sandstones and conglomerates from FA2 in the west, poorly sorted interbedded sandstones and conglomerates from FA3/4 in the center, and interbedded sandstones and mudstones from FA4 in the east. This is consistent with modern and ancient analogs and represents, updrift strandplain environments, central deltaic complexes, and downdrift lagoonal deposits respectively.

4. Wave-dominated deltas and strandplains are very difficult to differentiate within wave-/storm-dominated settings. However, detailed lithological, sedimentological and ichnological descriptions and mapping can provide important differences.

5. The Falher "D" is bound above, TSE1, and below, TSE3, by major transgressive surfaces of erosion. Another transgressive surface of erosion, TSE2, is utilized to separate the Falher "D" sandbody into two intervals, D1 and D2. These surfaces are allocyclic in origin, regionally extensive, and tend to manifest themselves as coastal plain mudstones and coals sharply overlain by marine sandstones and mudstones. This stratigraphic framework is utilized in order to analyze the spatial distribution of the facies associations listed above.

6. Six detailed paleogeographical maps (Time 1 to 6), each representing a particular stratigraphic/time interval during deposition, display the evolution of the Falher "D" within the study area. These maps highlight the importance of lateral changes in the local depositional environment and demonstrate that all significant facies variations may not be allocyclicly controlled. The presence of an asymmetrical wave-dominated delta dominates the Falher "D" succession over most of the D2 unit and serves as an explanation for the numerous lateral variations observed across the study area.

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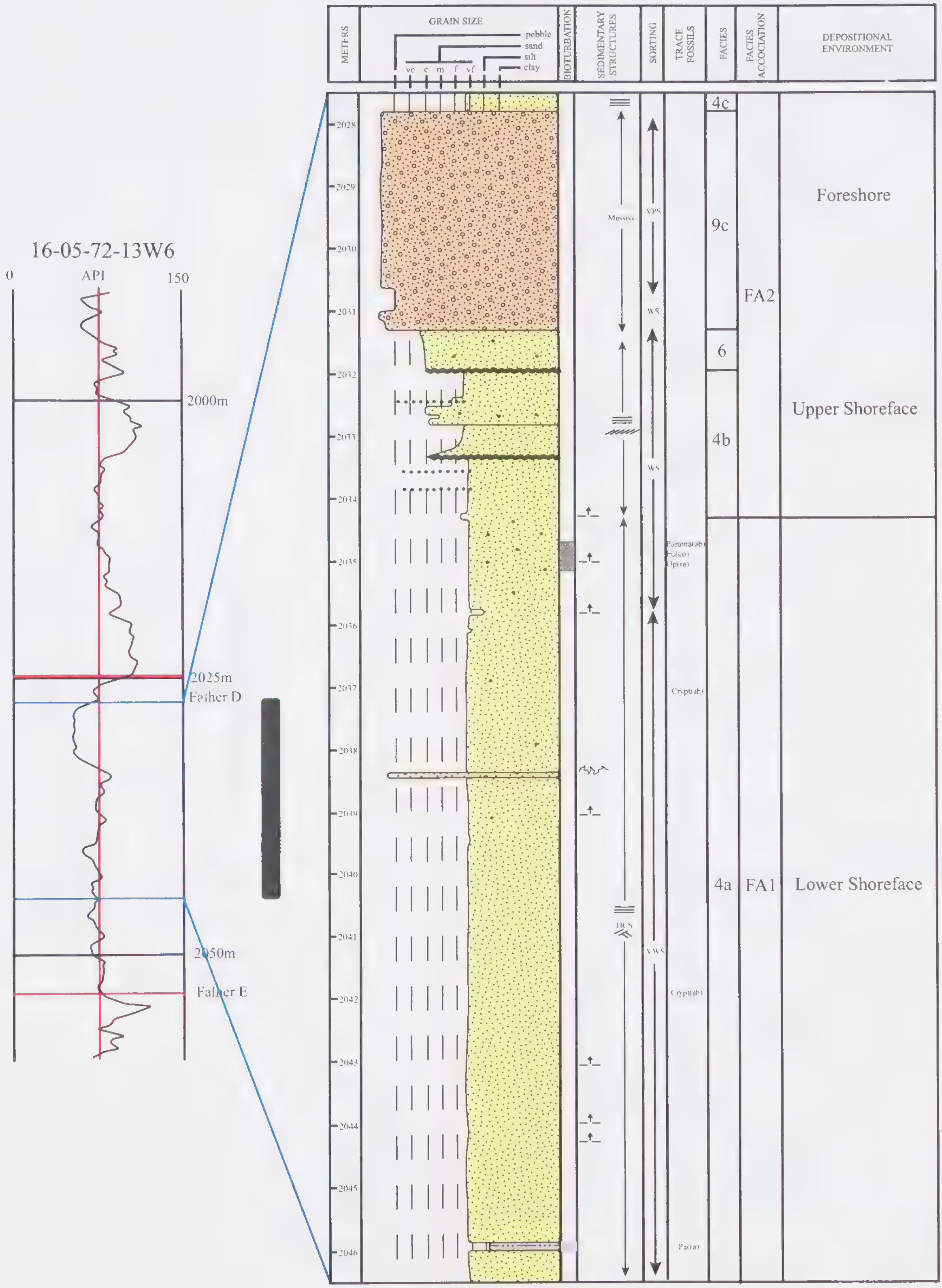
Appendix A: Core Logs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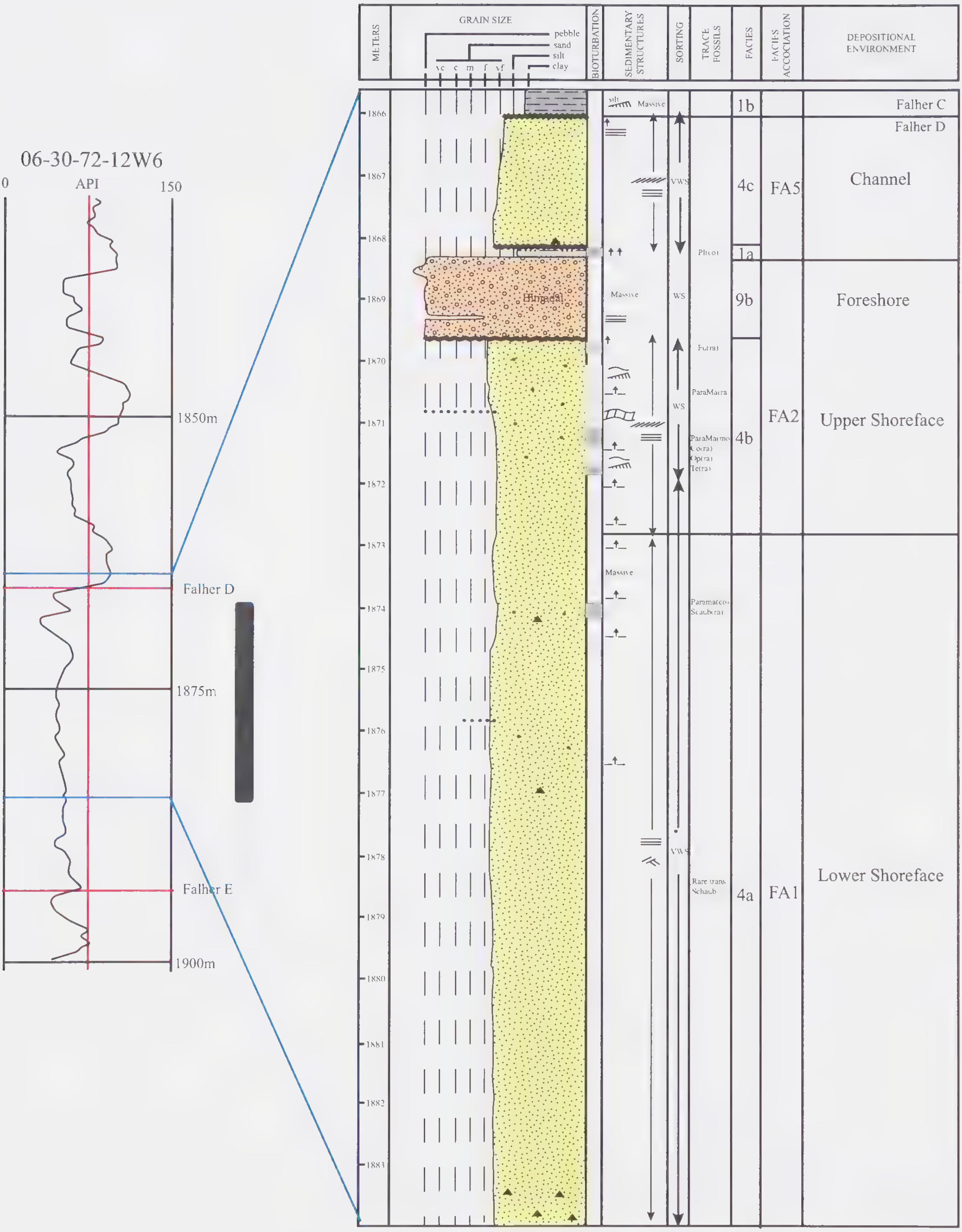
2000m
2025m
Father D
2050m
Falher E
METERS
GRAIN SIZE
pebble
sand
silt
clay
vc
c
m
f
vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ACCOCIATION
DEPOSITIONAL ENVIRONMENT
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040
2041
2042
2043
2044
2045
2046
Massive
VPS
WS
HCS
VWS
4c
9c
6
4b
4a
FA2
FA1
Foreshore
Upper Shoreface
Lower Shoreface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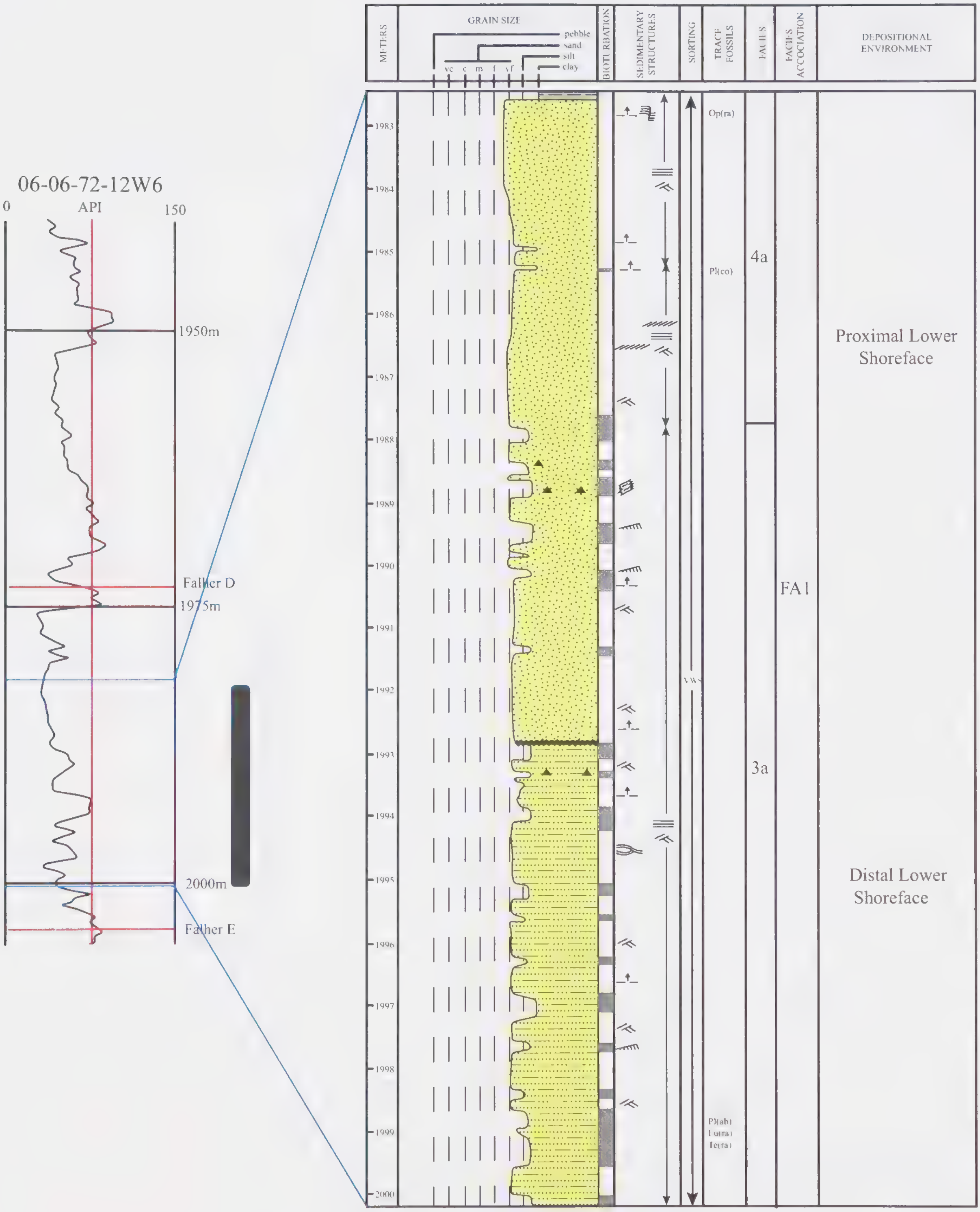
1850m
Falher D
1875m
Falher E
1900m
METERS
GRAIN SIZE
pebble
sand
silt
clay
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ACCOCIATION
DEPOSITIONAL ENVIRONMENT
1b
Falher C
Falher D
4c
FA5
Channel
1a
9b
Foreshore
4b
FA2
Upper Shoreface
4a
FA1
Lower Shoreface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1975m
2000m
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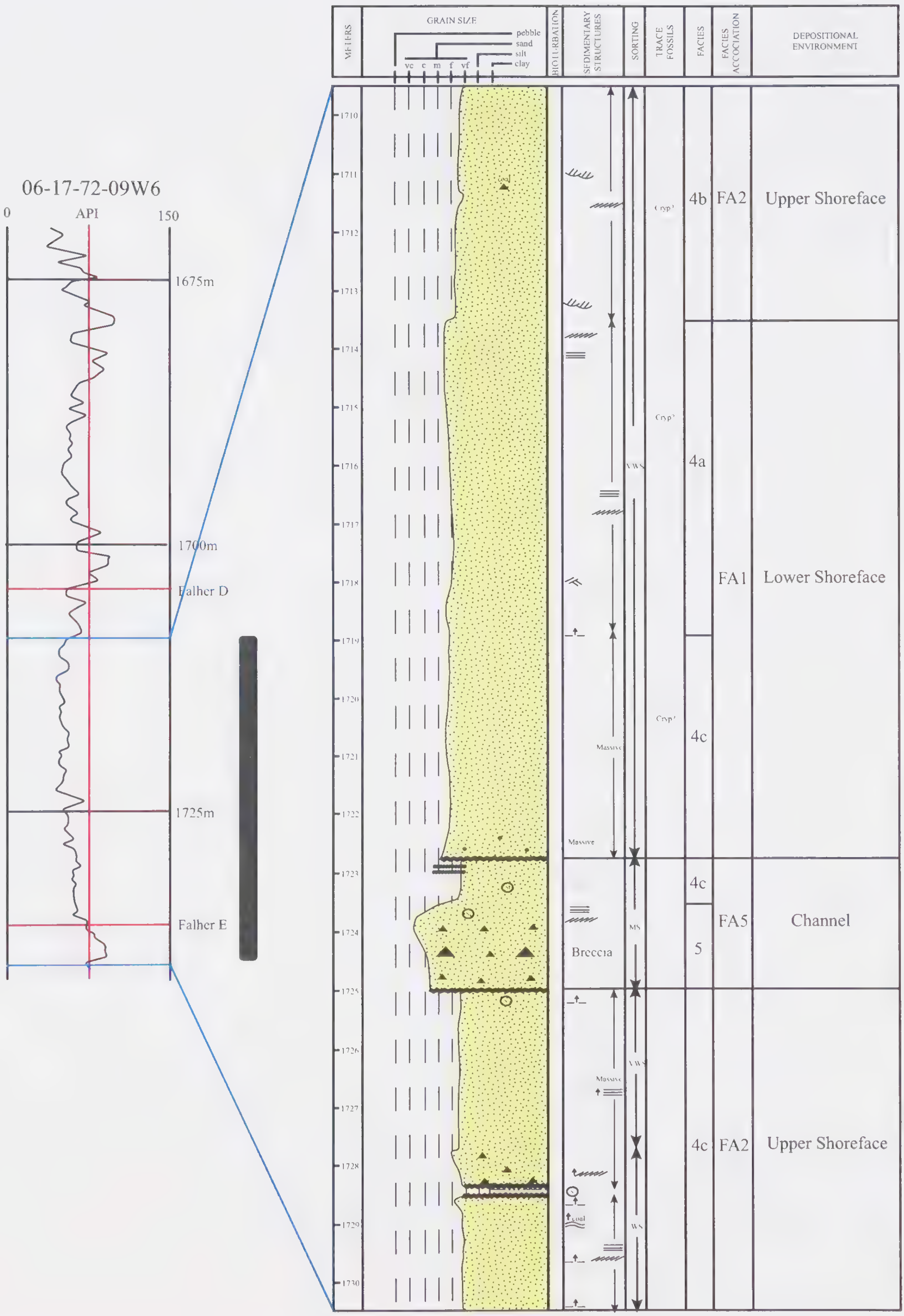
METERS
GRAIN SIZE
pebble
sand
silt
clay
vc
c
m
f
vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
Op(ra)
Pl(co)
4a
3a
FA1
Proximal Lower Shoreface
Distal Lower Shoreface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1700m
Falher D
1725m
Falher E
METERS
GRAIN SIZE
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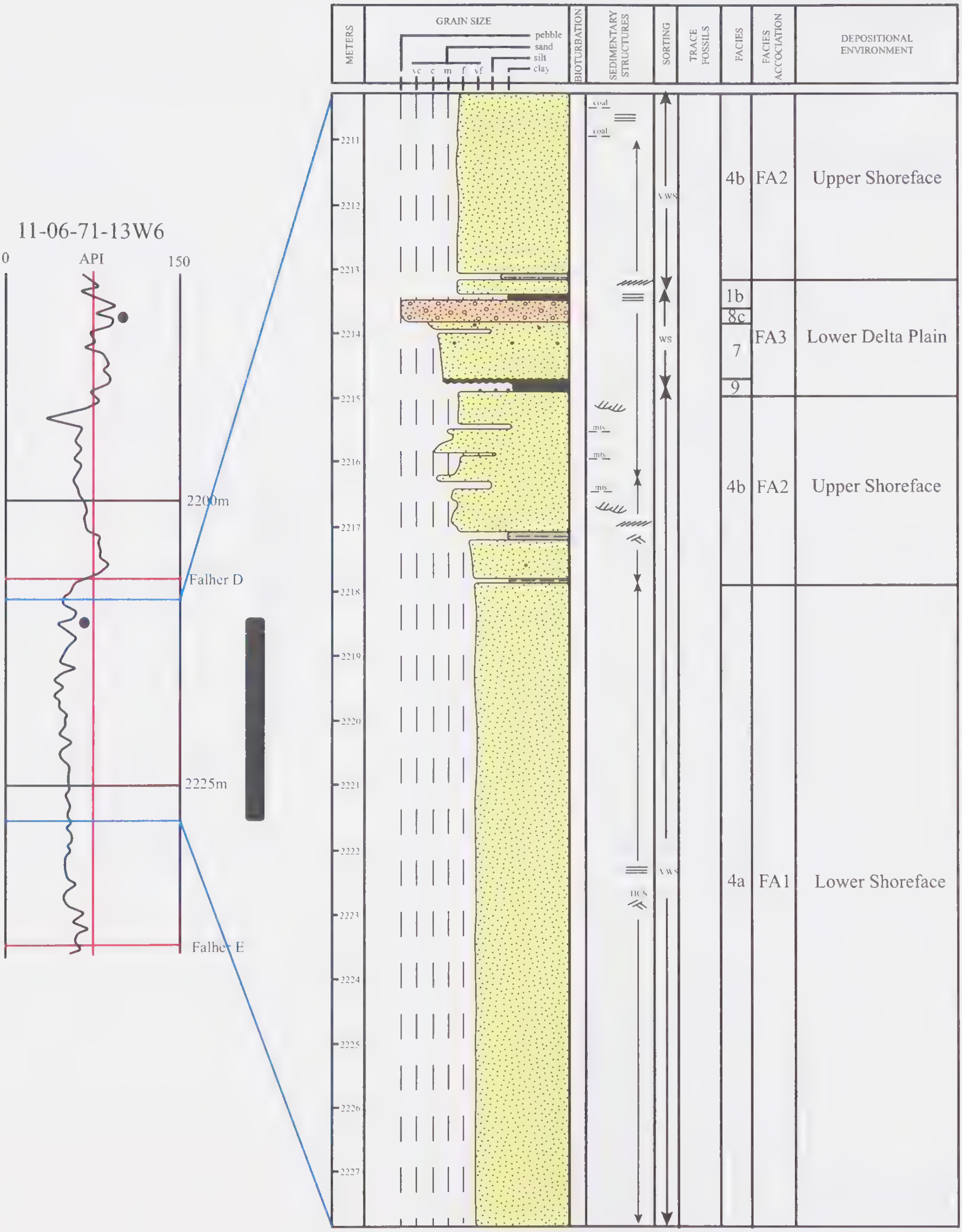
sand
silt
clay
vc c m f vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
Upper Shoreface
Lower Shoreface
Channel
Upper Shoreface
4b
4a
4c
4c
5
4c
FA2
FA1
FA5
FA2
Breccia
Massive



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Falher D
2225m
Falher E
METERS
GRAIN SIZE
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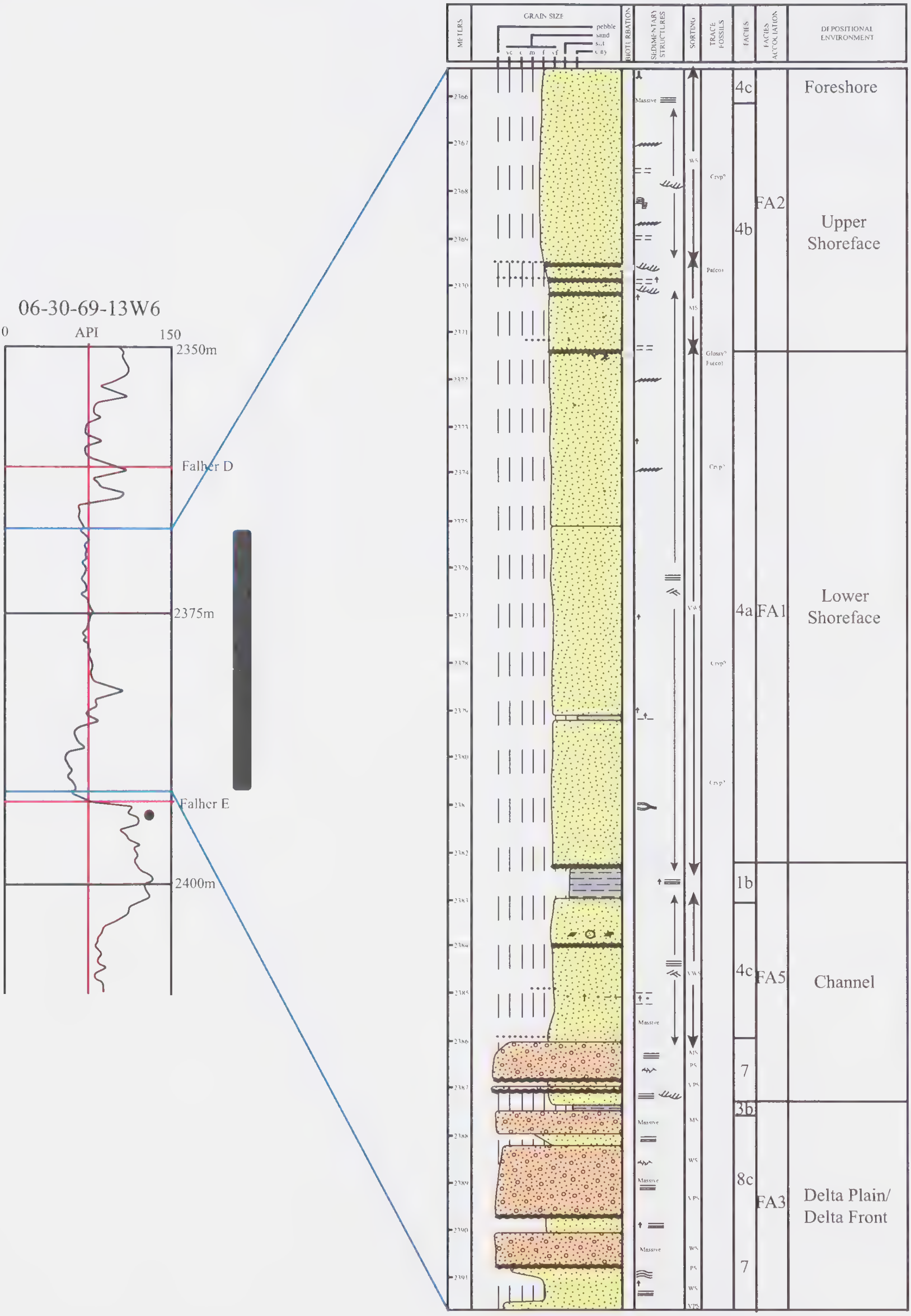
sand
silt
clay
vc c m f vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ACCOCIATION
DEPOSITIONAL ENVIRONMENT
coal
VWS
WS
HCS
4b FA2 Upper Shoreface
1b
8c
7
9
FA3 Lower Delta Plain
4b FA2 Upper Shoreface
4a FA1 Lower Shoreface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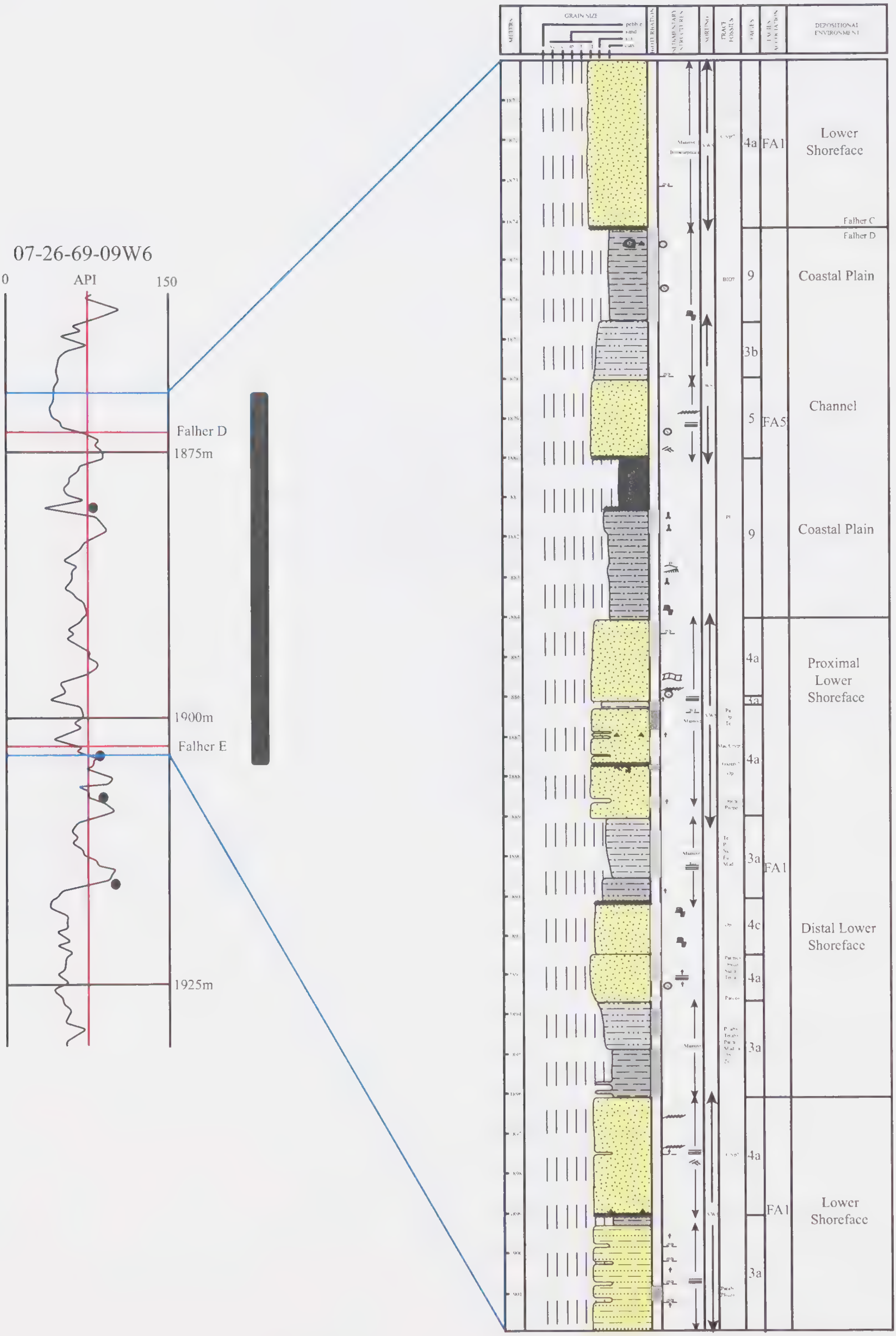
Falher D
2375m
Falher E
2400m
METERS
GRAIN SIZE
pebble
sand
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
4c
Foreshore
4b
FA2
Upper Shoreface
4a
FA1
Lower Shoreface
1b
4c
FA5
Channel
7
3b
8c
FA3
Delta Plain/ Delta Front
7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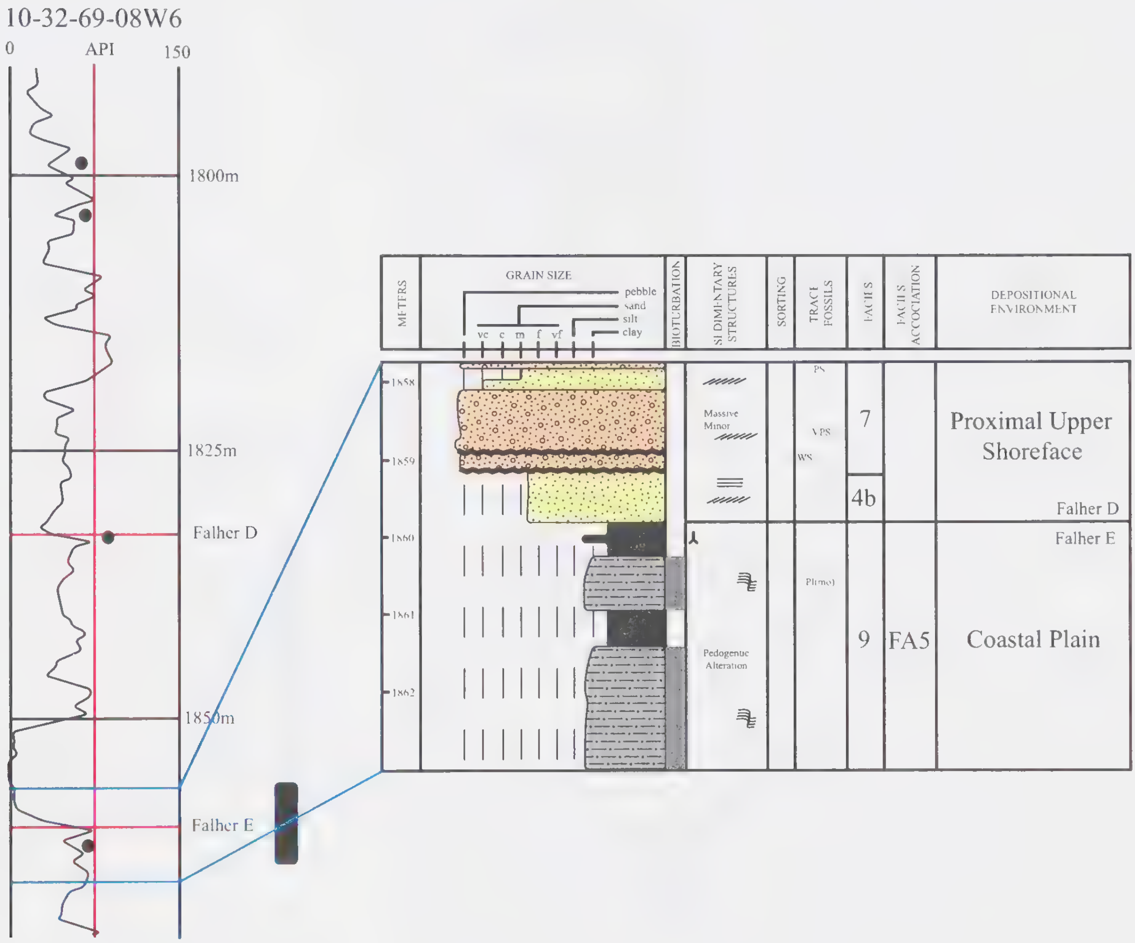
1900m
Falher E
1925m
GRAIN SIZE
DEPOSITIONAL ENVIRONMENT
Lower Shoreface
4a
FA1
Falher C
Falher D
Coastal Plain
9
3b
Channel
5
FA5
Coastal Plain
9
Proximal Lower Shoreface
4a
3a
4a
3a
FA1
Distal Lower Shoreface
4c
4a
3a
Lower Shoreface
4a
FA1
3a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Falher D
1850m
Falher E
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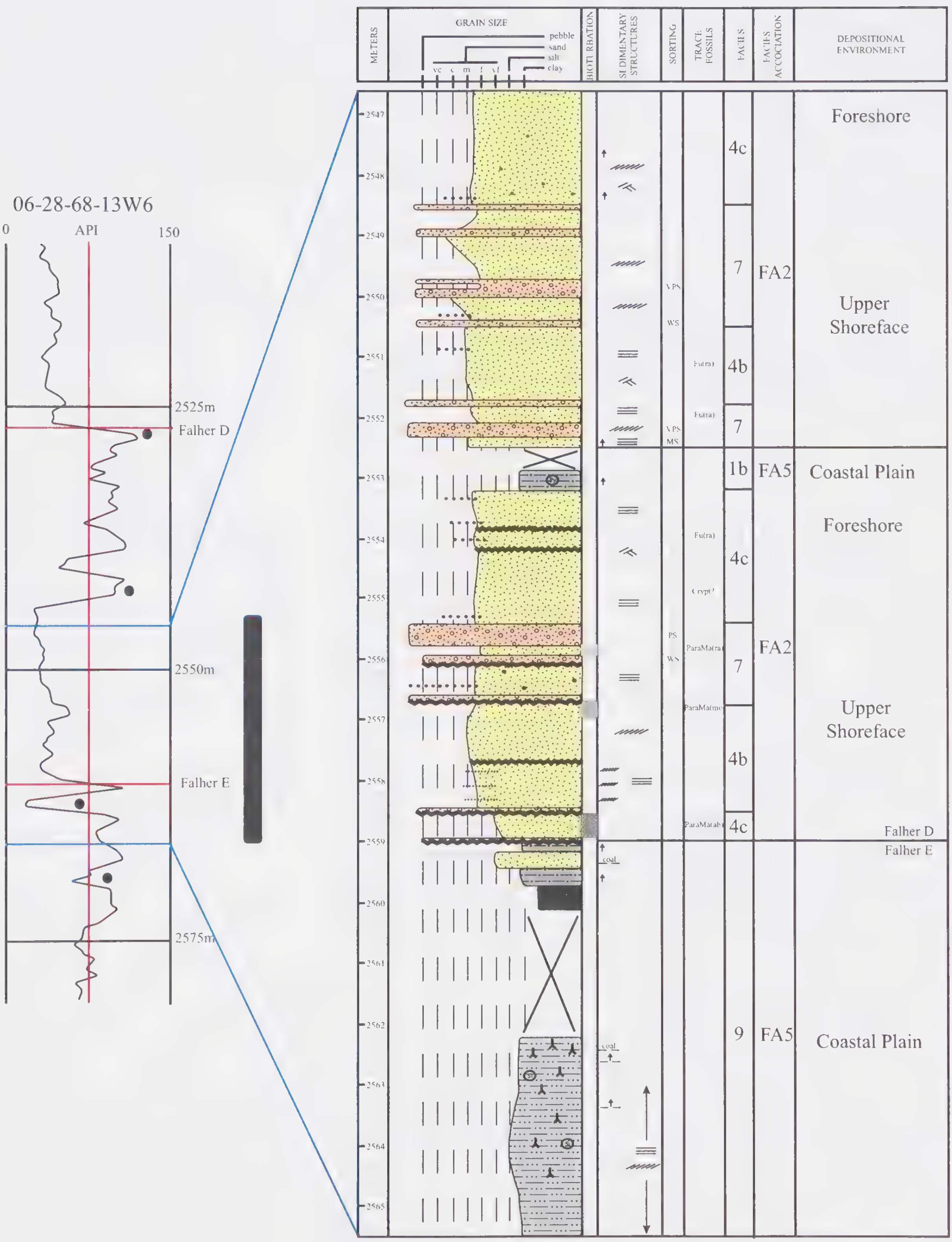
sand
silt
clay
vc
c
m
f
vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
1858
1859
1860
1861
1862
Massive
Minor
Pedogenic
Alteration
7
4b
9
FA5
Proximal Upper
Shoreface
Falher D
Falher E
Coastal Plain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sand
silt
clay
vc
c
m
f
vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
Foreshore
4c
7
FA2
Upper Shoreface
4b
7
1b
FA5
Coastal Plain
Foreshore
4c
FA2
7
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Falher E
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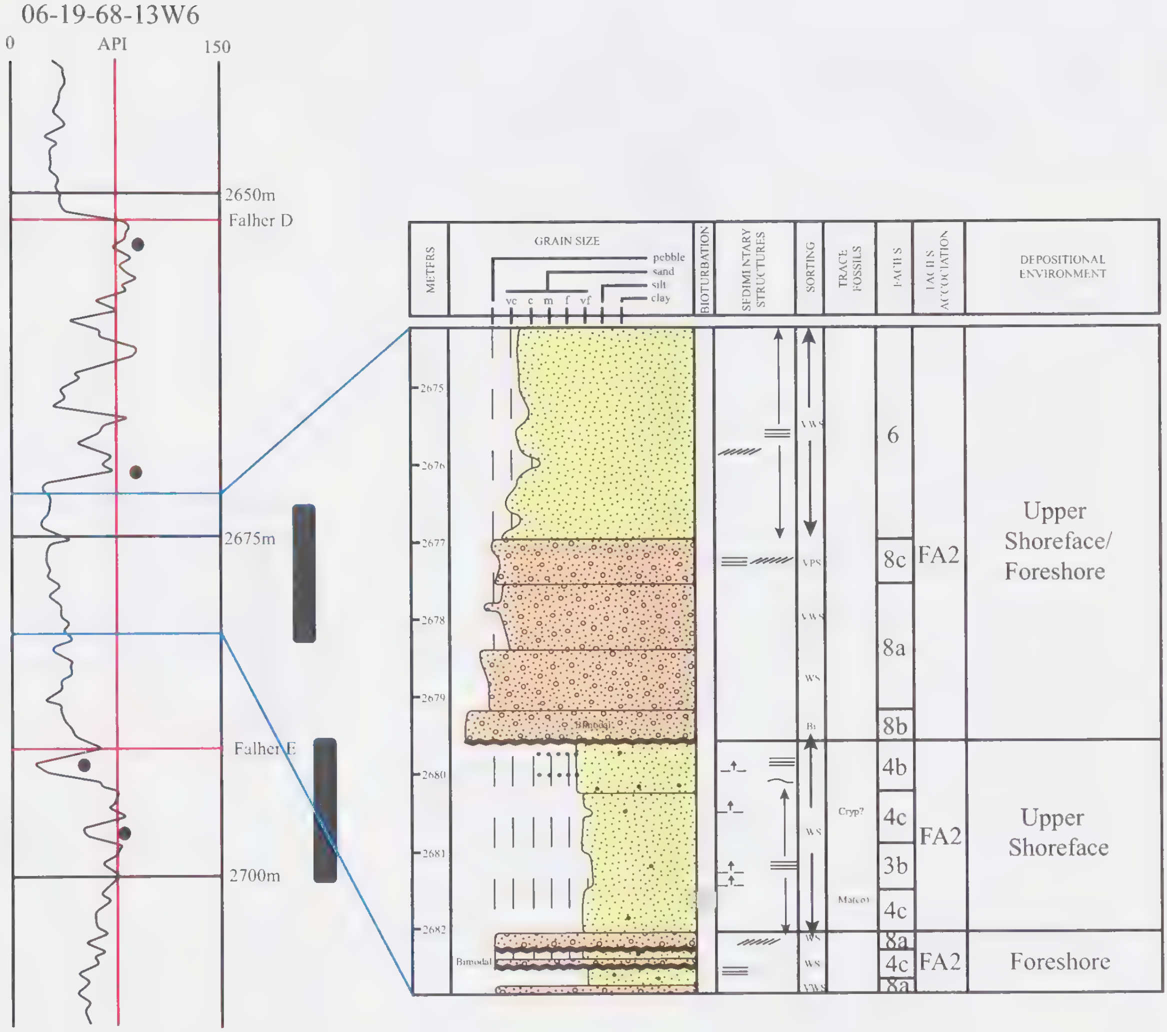
FA5
Coastal Plain
coal
coal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Falher E
2700m
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GRAIN SIZE
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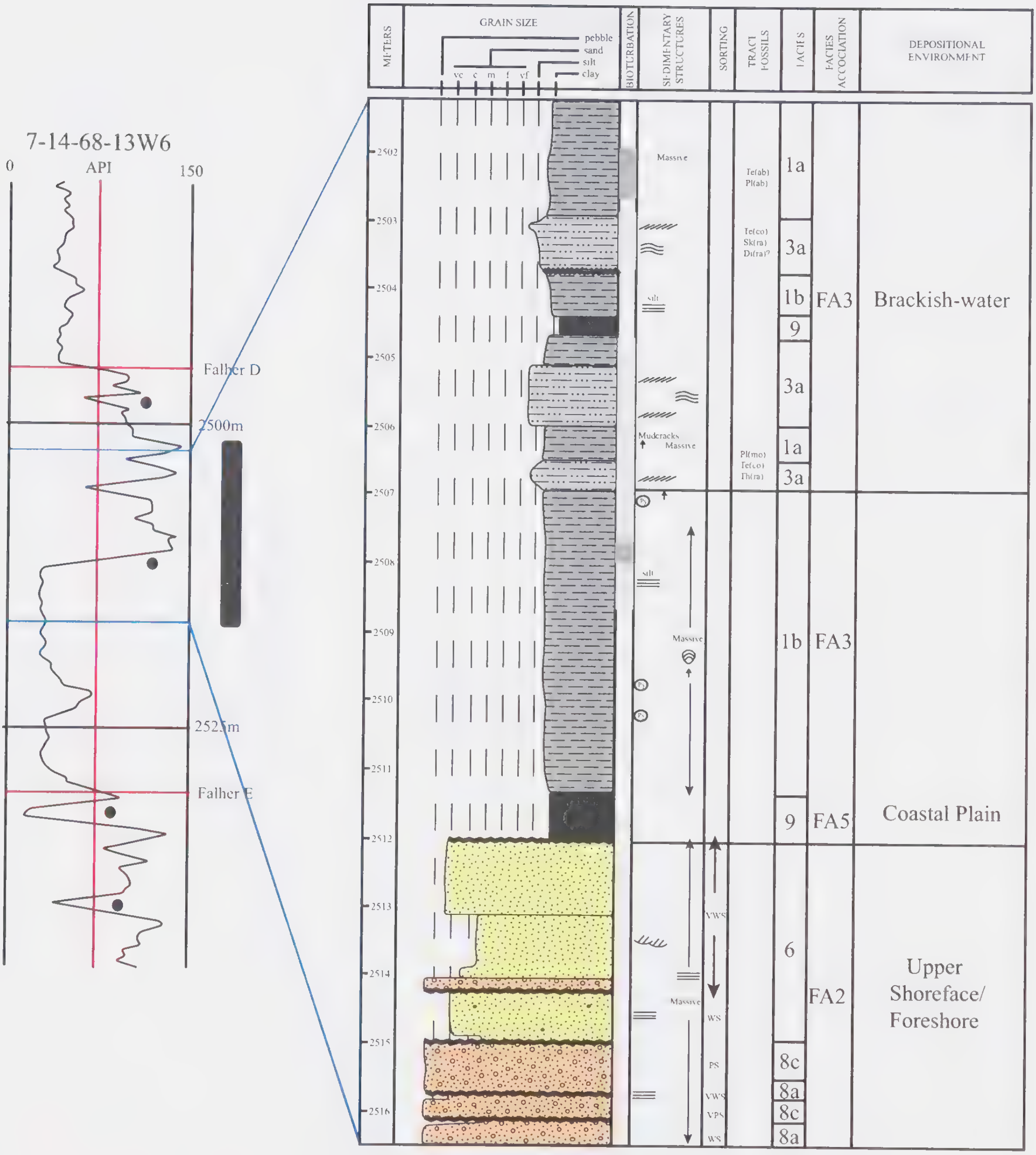
sand
silt
clay
vc
c
m
f
vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
2675
2676
2677
2678
2679
2680
2681
2682
Bimodal
6
8c
8a
8b
4b
4c
3b
4c
8a
4c
8a
FA2
FA2
FA2
Upper Shoreface/ Foreshore
Upper Shoreface
Foreshore
Cryp?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Falher E
METERS
GRAIN SIZE
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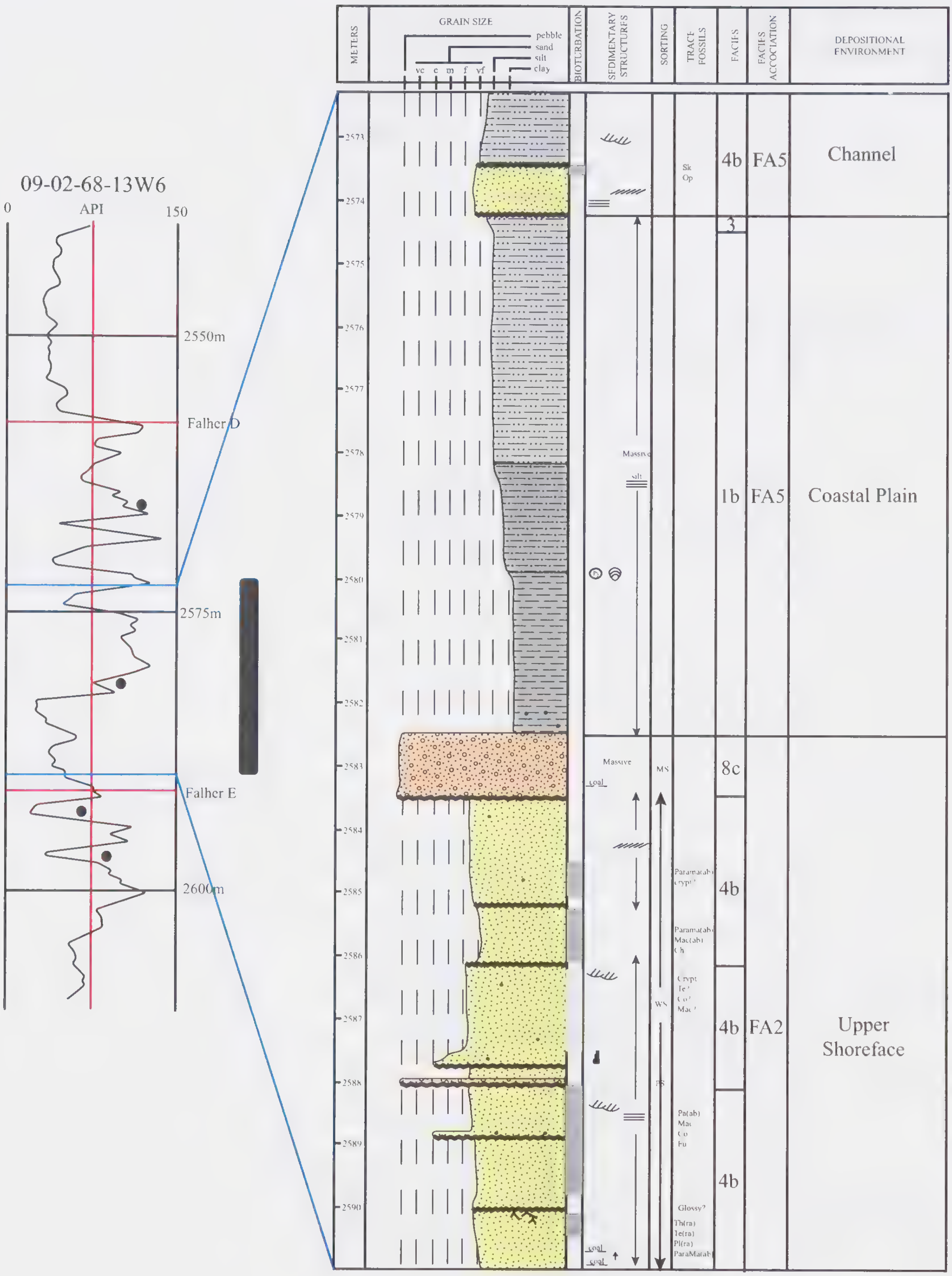
sand
silt
clay
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
Massive
Mudcracks
1a
3a
1b
9
3a
1a
3a
1b
9
6
8c
8a
8c
8a
FA3
FA3
FA5
FA2
Brackish-water
Coastal Plain
Upper Shoreface/ Foreshore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sand
silt
clay
vc c m f vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
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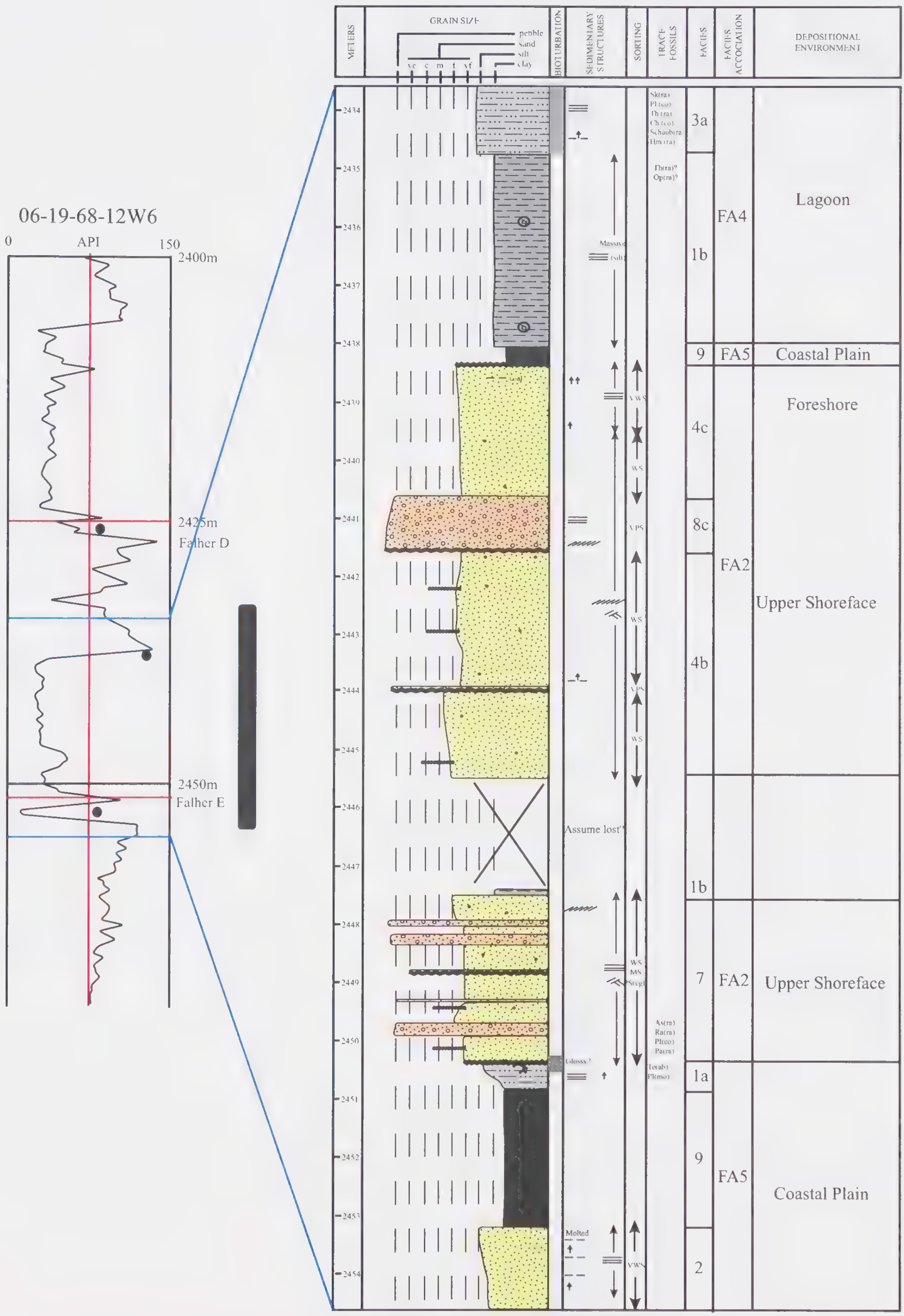
FA5
Channel
3
1b
FA5
Coastal Plain
Massive
8c
4b
4b
FA2
Upper Shoreface
4b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METERS
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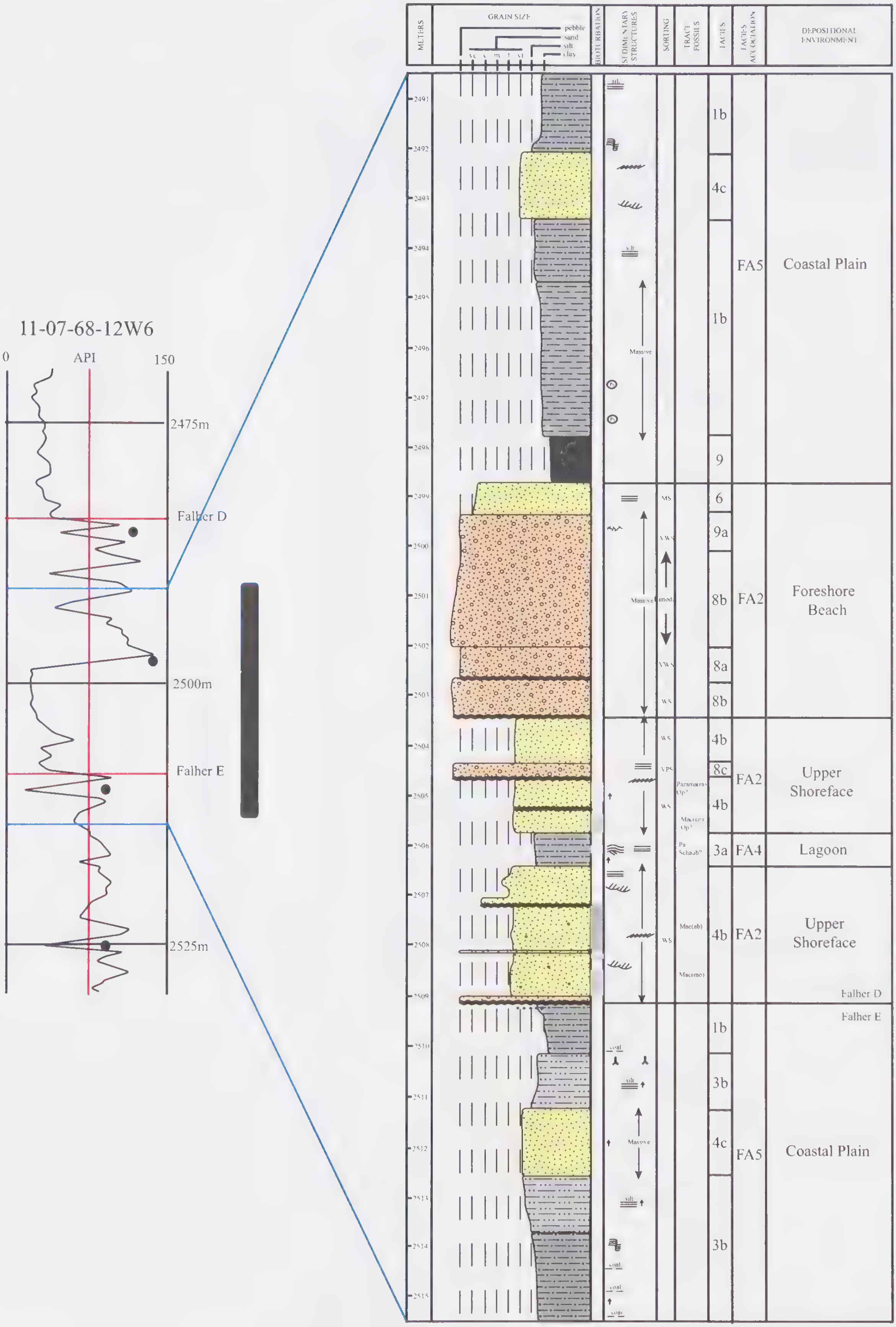
sand
silt
clay
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
3a
1b
FA4
Lagoon
9
FA5
Coastal Plain
Foreshore
4c
8c
FA2
Upper Shoreface
4b
Assume lost
1b
7
FA2
Upper Shoreface
1a
9
FA5
Coastal Plain
2
Massive
Molted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METERS
GRAIN SIZE
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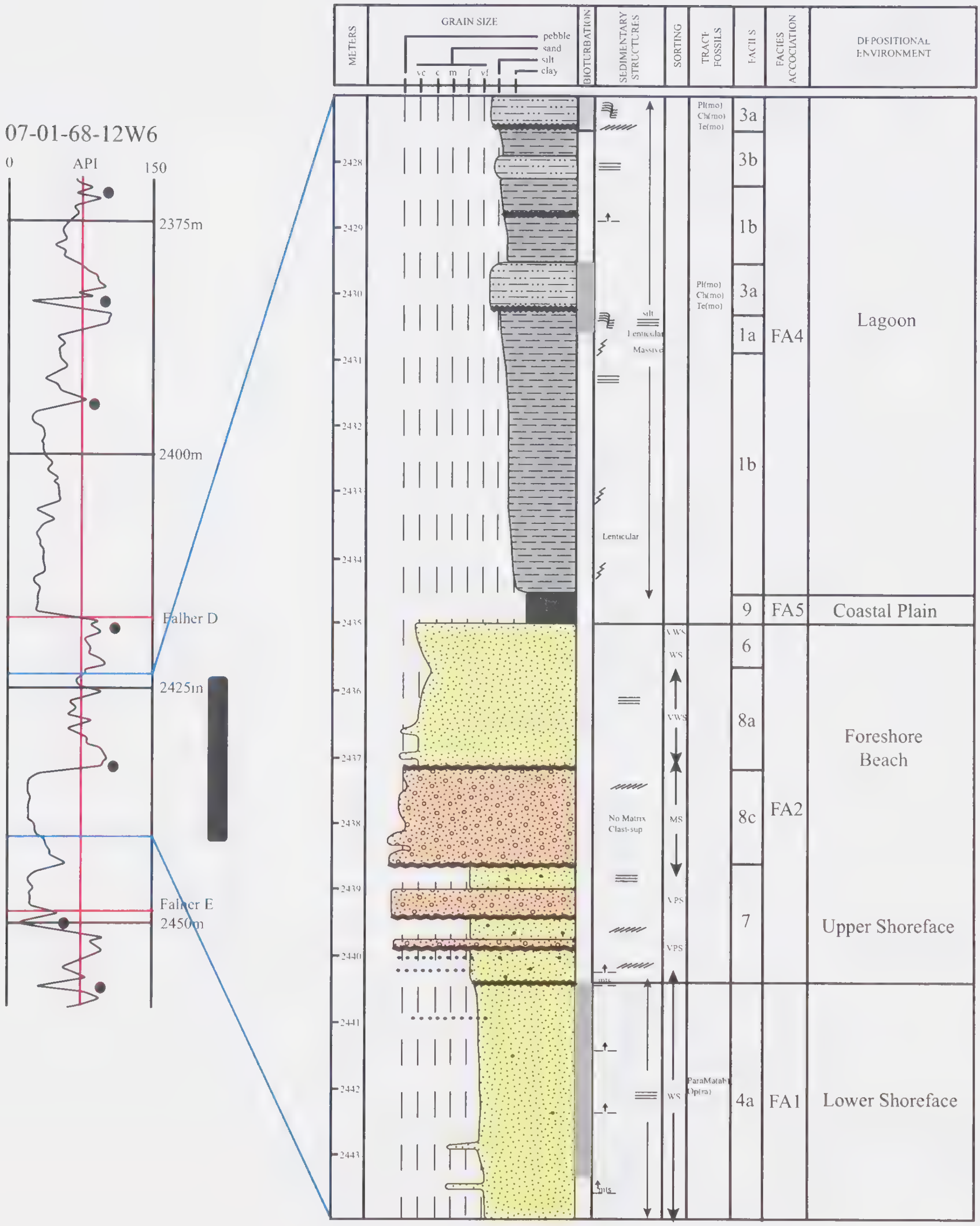
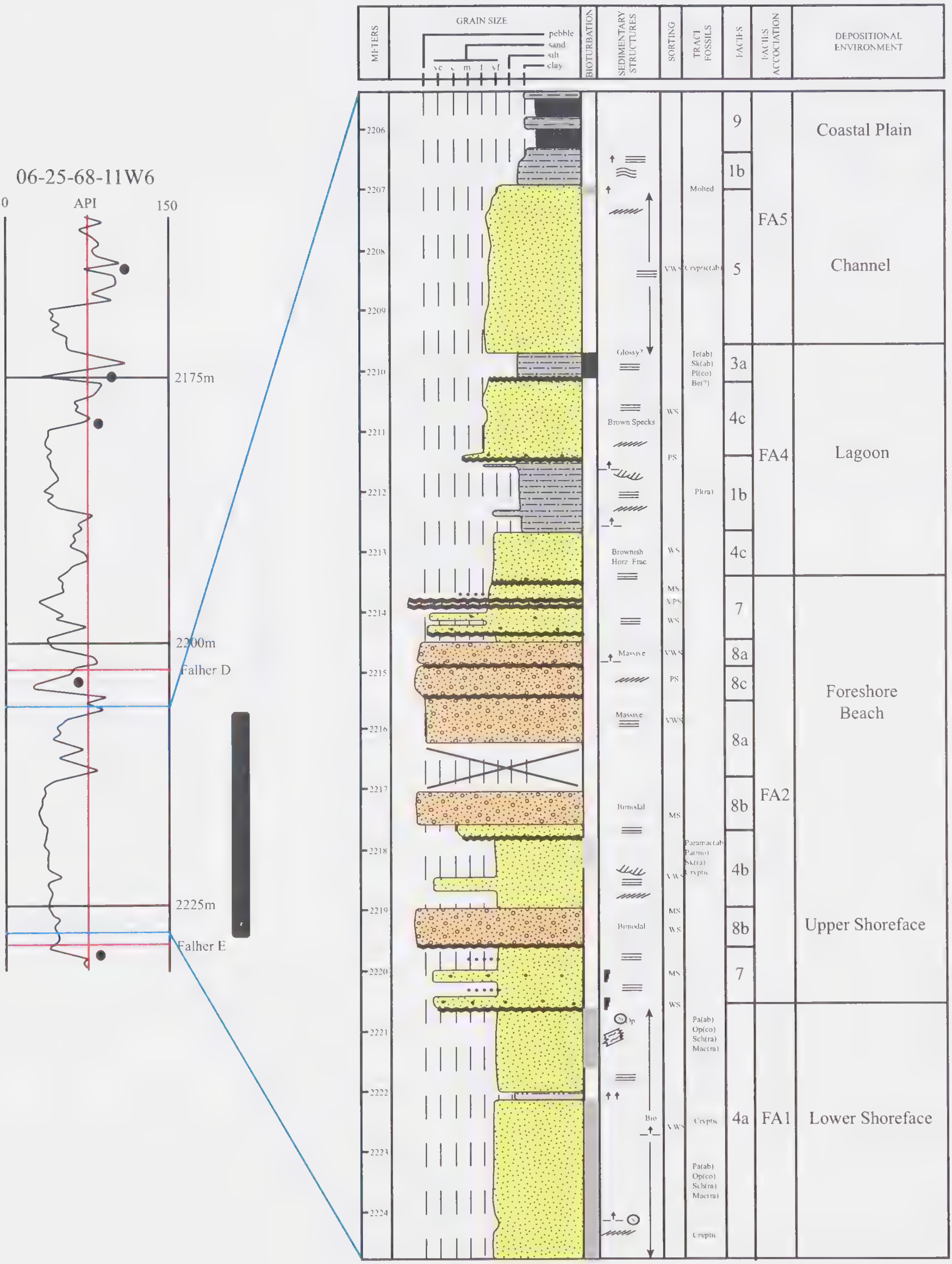
sand
silt
clay
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
Massive
1b
4c
1b
9
FA5
Coastal Plain
6
9a
8b
8a
8b
FA2
Foreshore Beach
4b
8c
4b
FA2
Upper Shoreface
3a
FA4
Lagoon
4b
FA2
Upper Shoreface
Falher D
Falher E
1b
3b
4c
3b
FA5
Coastal Plain


07-01-68-12W6
0
API
150
2375m
2400m
Falher D
2425m
Falher E
2450m
METERS
GRAIN SIZE
pebble
sand
silt
clay
vc c m f vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
No Matrix
Clast-sup
Lenticular
3a
3b
1b
3a
1a
1b
9
6
8a
8c
7
4a
FA4
FA5
FA2
FA1
Lagoon
Coastal Plain
Foreshore
Beach
Upper Shoreface
Lower Shoreface


06-25-68-11W6
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API
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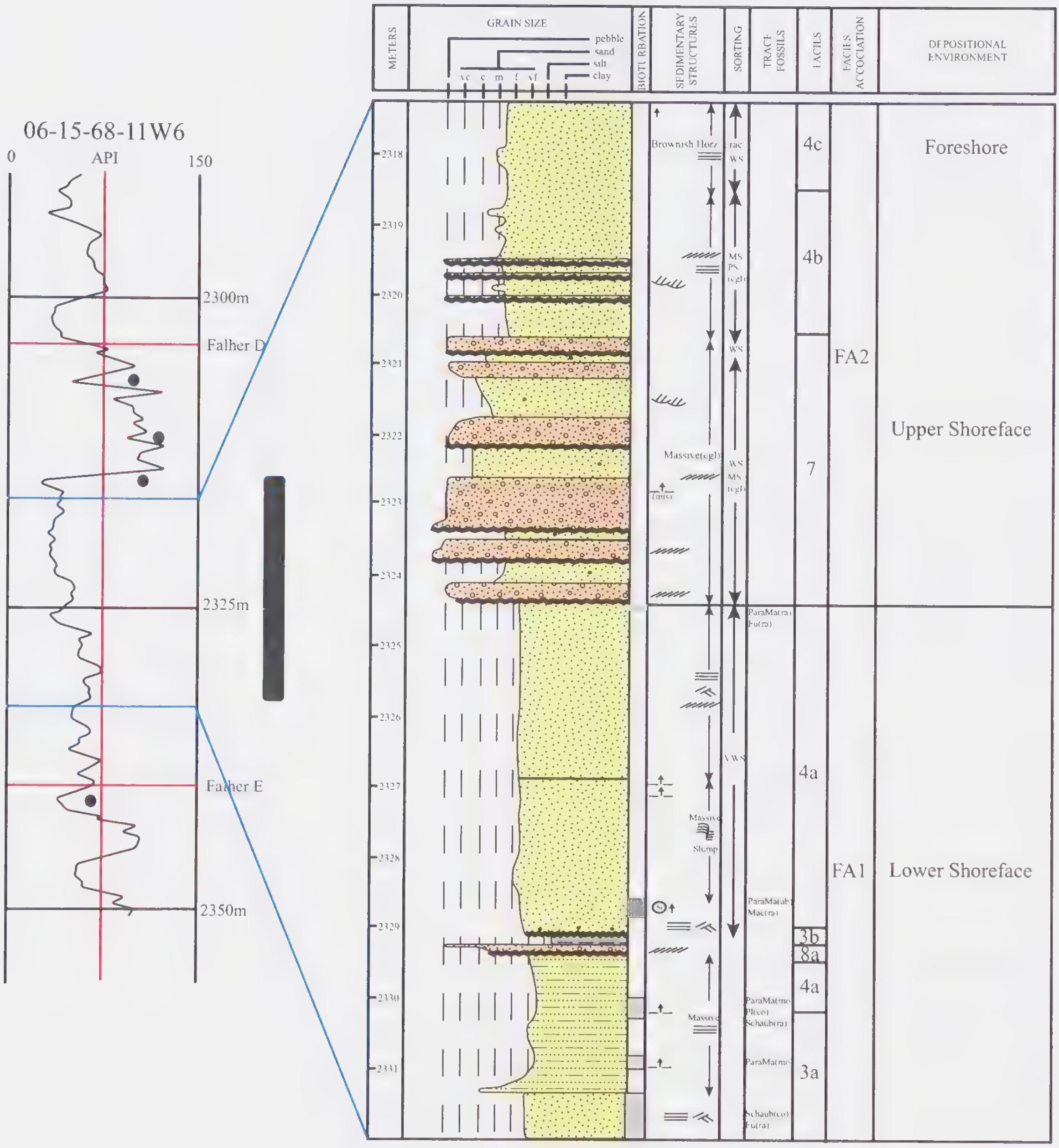
2175m
2200m
Falher D
2225m
Falher E
METERS
GRAIN SIZE
pebble
sand
silt
clay
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
2206
2207
2208
2209
2210
2211
2212
2213
2214
2215
2216
2217
2218
2219
2220
2221
2222
2223
2224
Molted
Glossy?
Brown Specks
Brownish Horz Frac
Massive
Massive
Bimodal
Bimodal
9
1b
5
3a
4c
1b
4c
7
8a
8c
8a
8b
4b
8b
7
4a
FA5
FA4
FA2
FA1
Coastal Plain
Channel
Lagoon
Foreshore Beach
Upper Shoreface
Lower Shoreface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API
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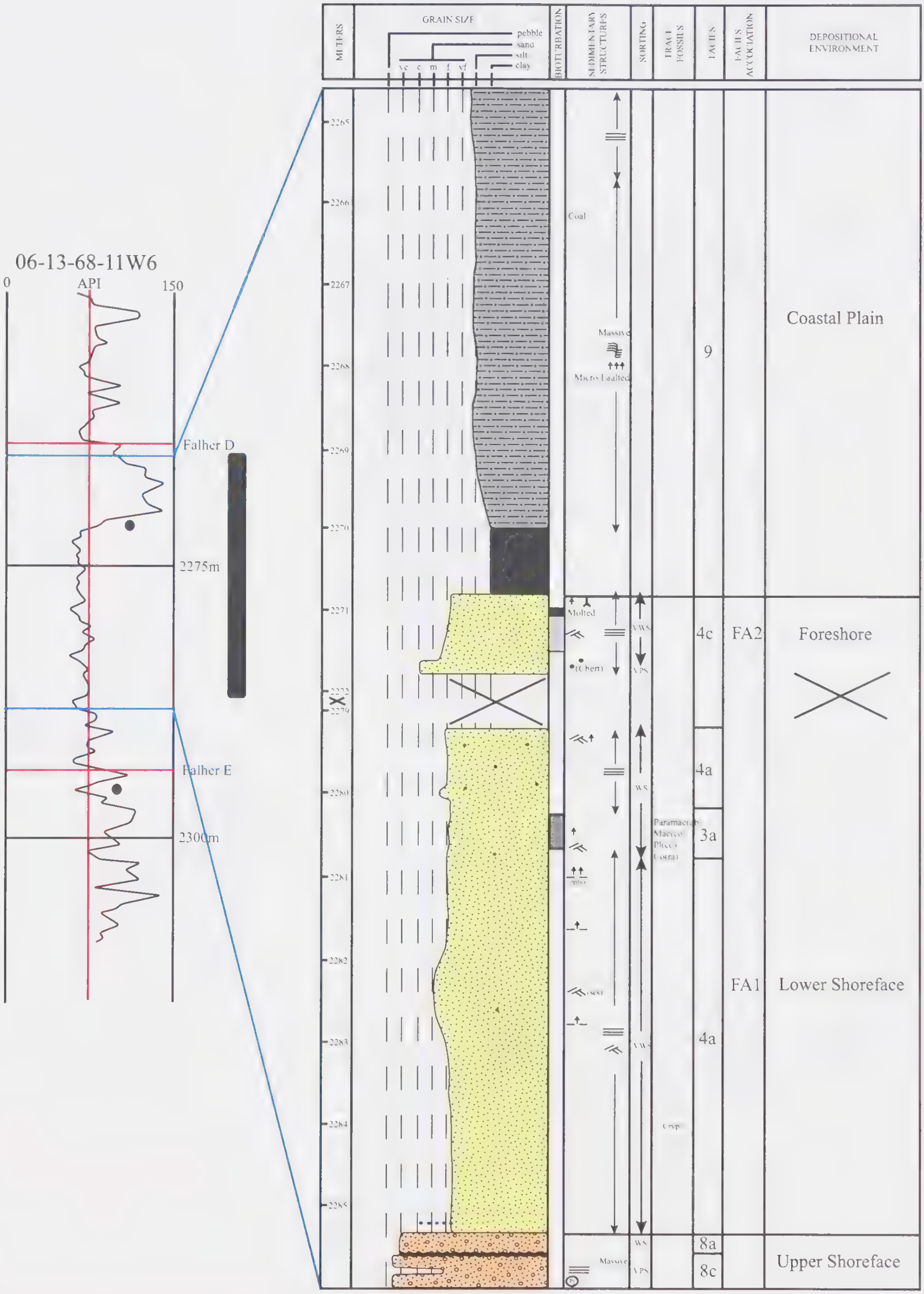
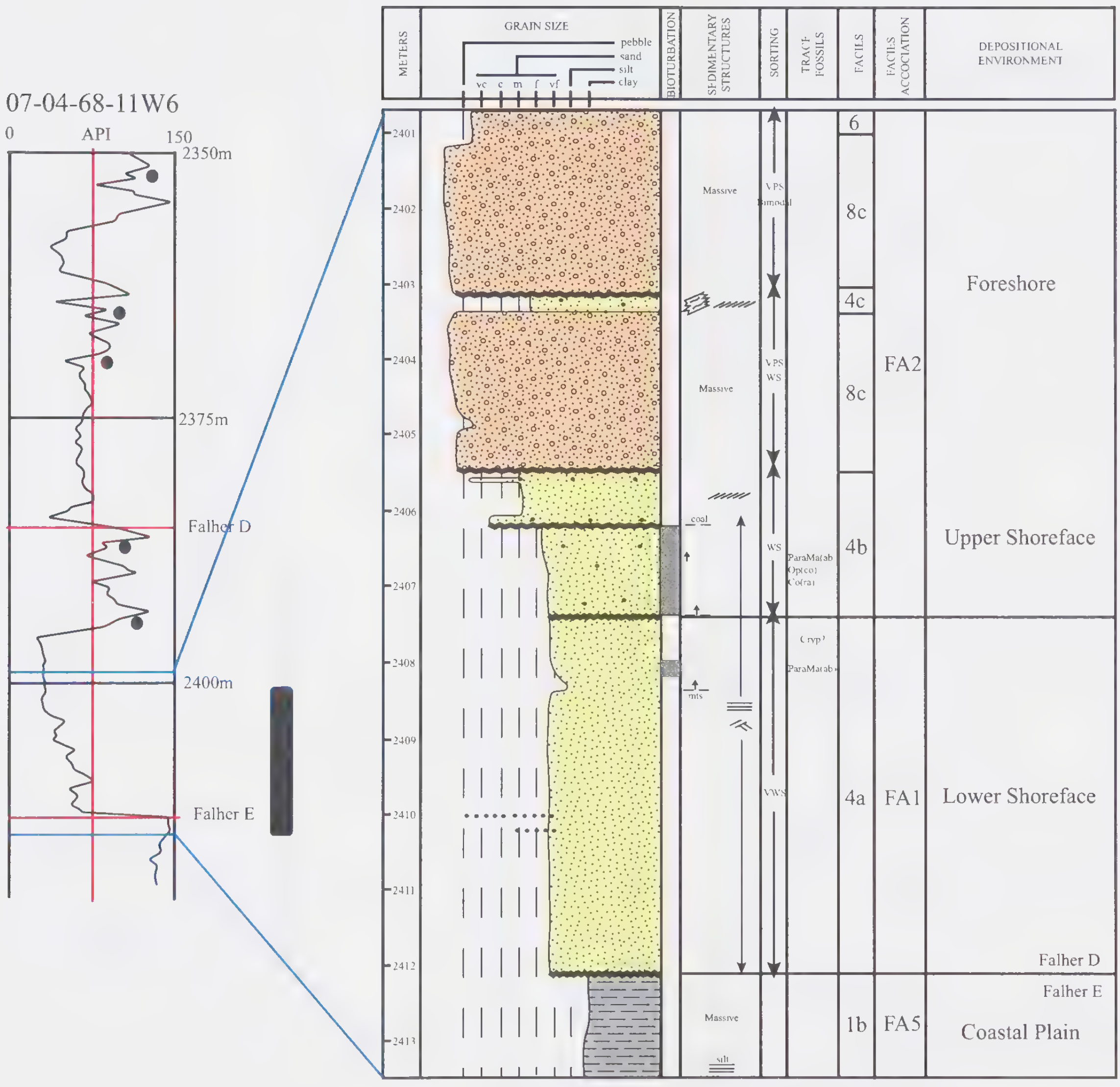
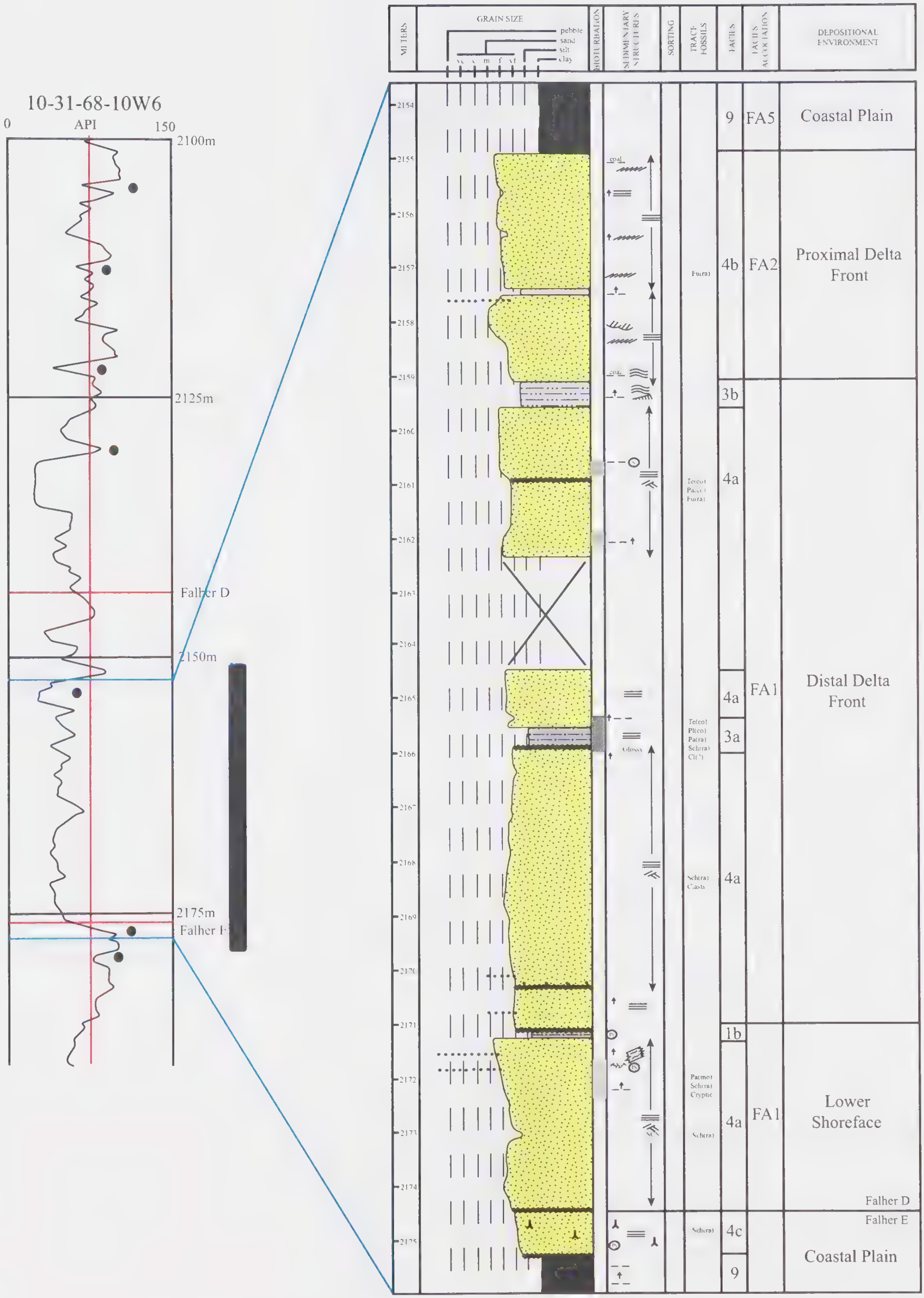
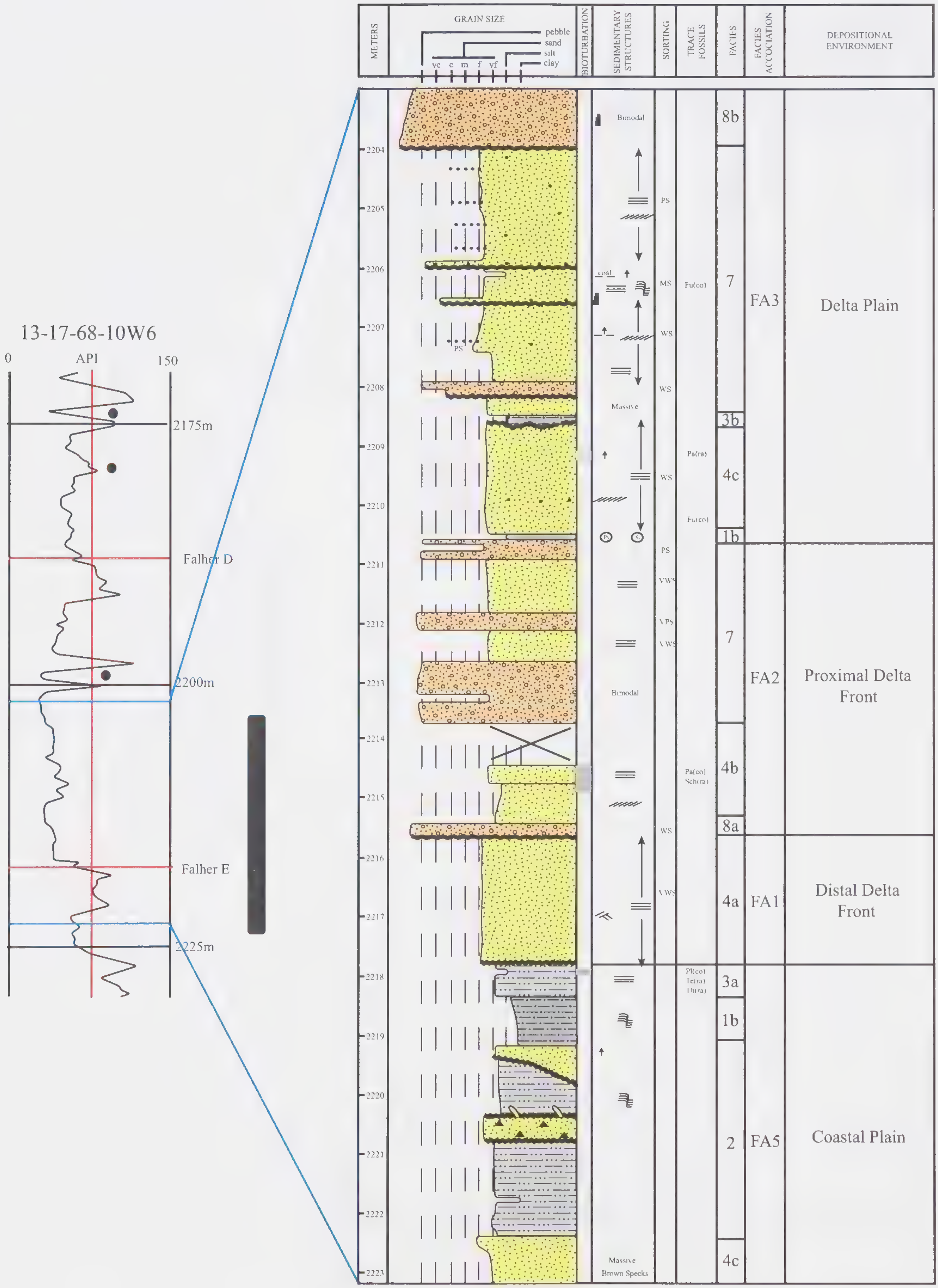
2300m
Falher D
2325m
Falher E
2350m
METERS
GRAIN SIZE
pebble
sand
silt
clay
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ACCOCIATION
DEPOSITIONAL ENVIRONMENT
Brownish Horz
Massive(cgl)
Massive
Slump
4c
4b
7
4a
3b
8a
4a
3a
FA2
FA1
Foreshore
Upper Shoreface
Lower Shoreface

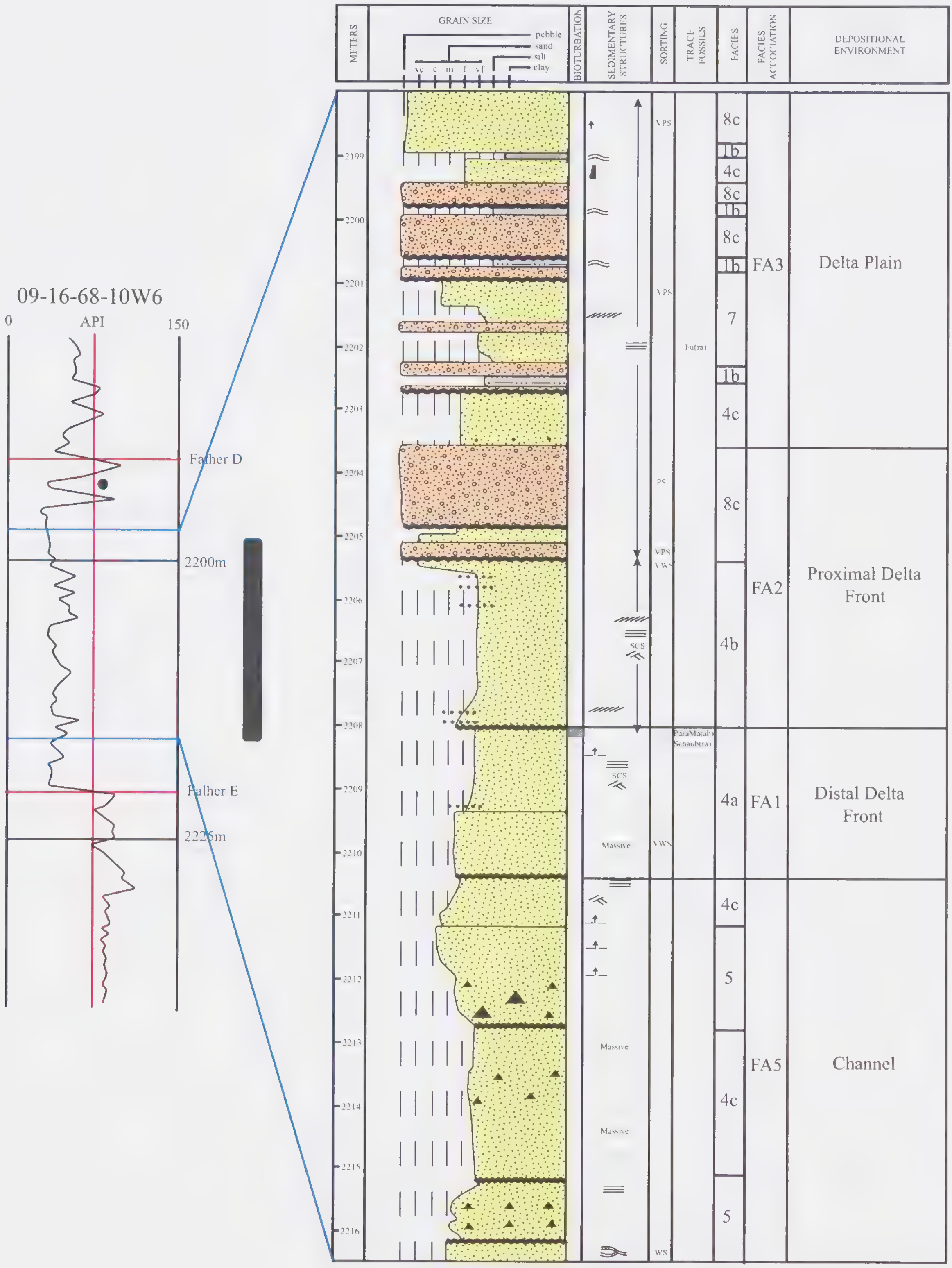


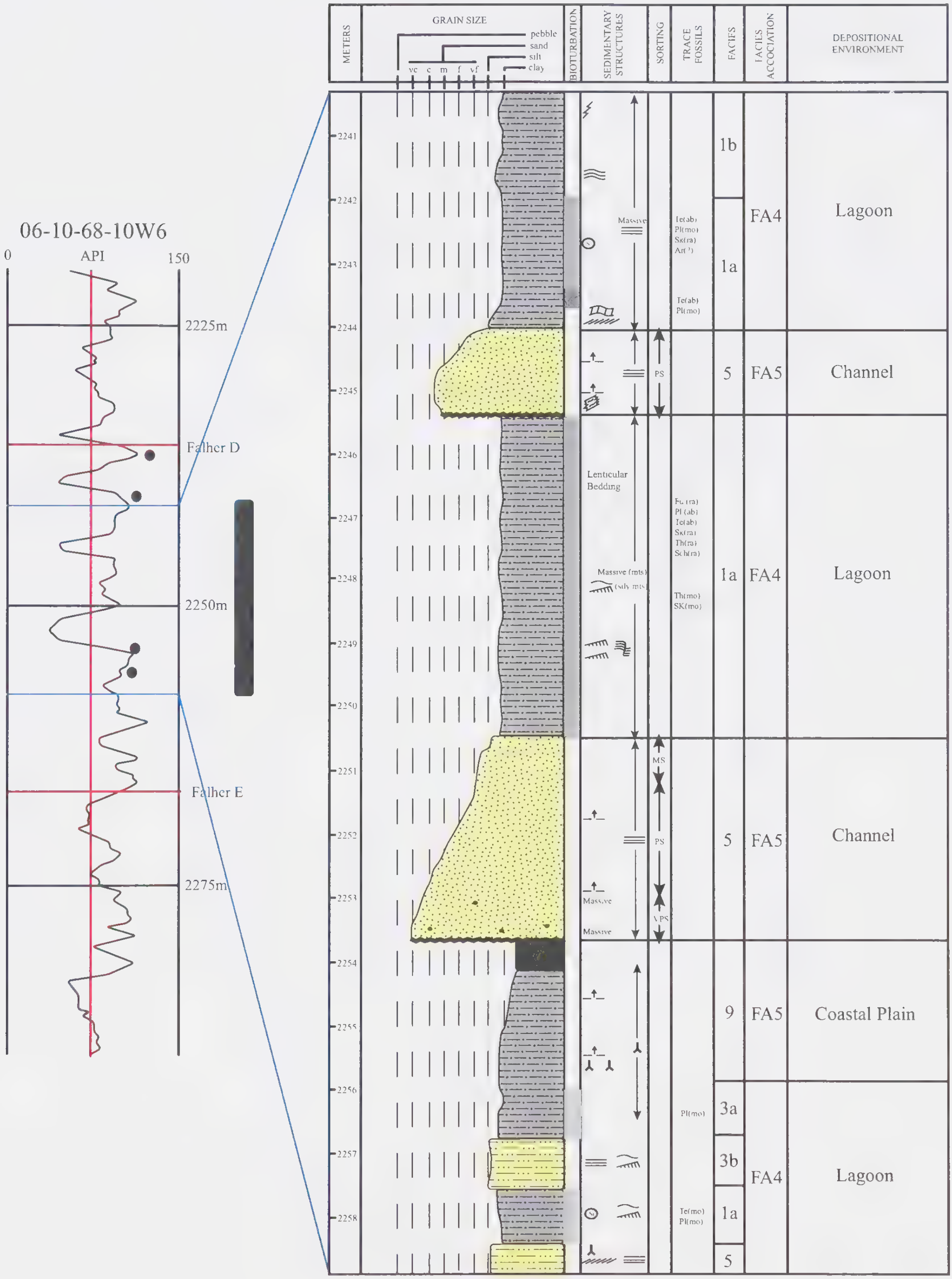
06-13-68-11W6
0
API
150
Falher D
2275m
Falher E
2300m
METERS
GRAIN SIZE
pebble
sand
silt
clay
vc c m f vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
Coal
Massive
Coastal Plain
9
4c
FA2
Foreshore
4a
3a
FA1
Lower Shoreface
8a
8c
Upper Shoreface

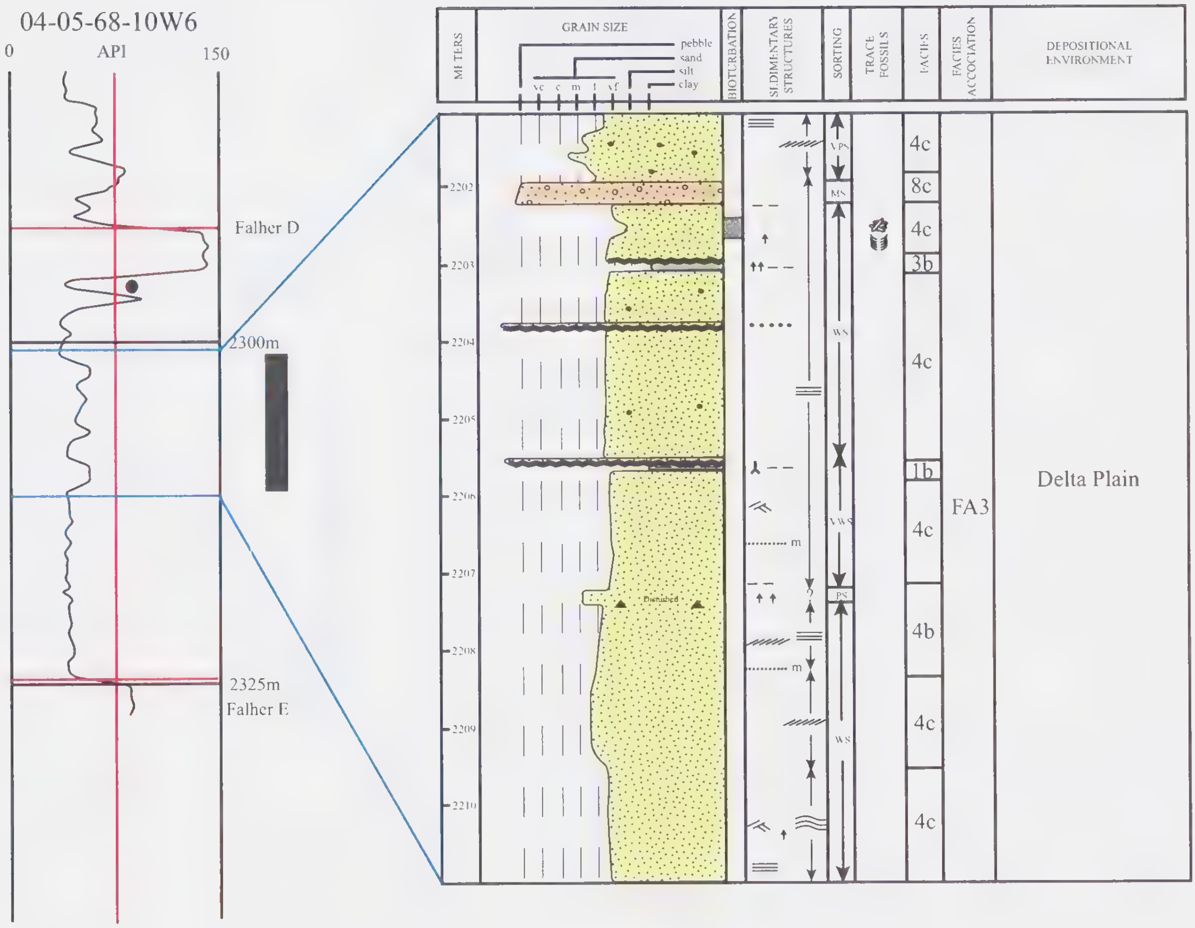

07-04-68-11W6
0
API
150
2350m
2375m
Falher D
2400m
Falher E
METERS
GRAIN SIZE
pebble
sand
silt
clay
vc c m f vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
2401
2402
2403
2404
2405
2406
2407
2408
2409
2410
2411
2412
2413
Massive
Massive
coal
Massive
6
8c
4c
8c
4b
4a
1b
FA2
FA1
FA5
Foreshore
Upper Shoreface
Lower Shoreface
Falher D
Falher E
Coastal Plain

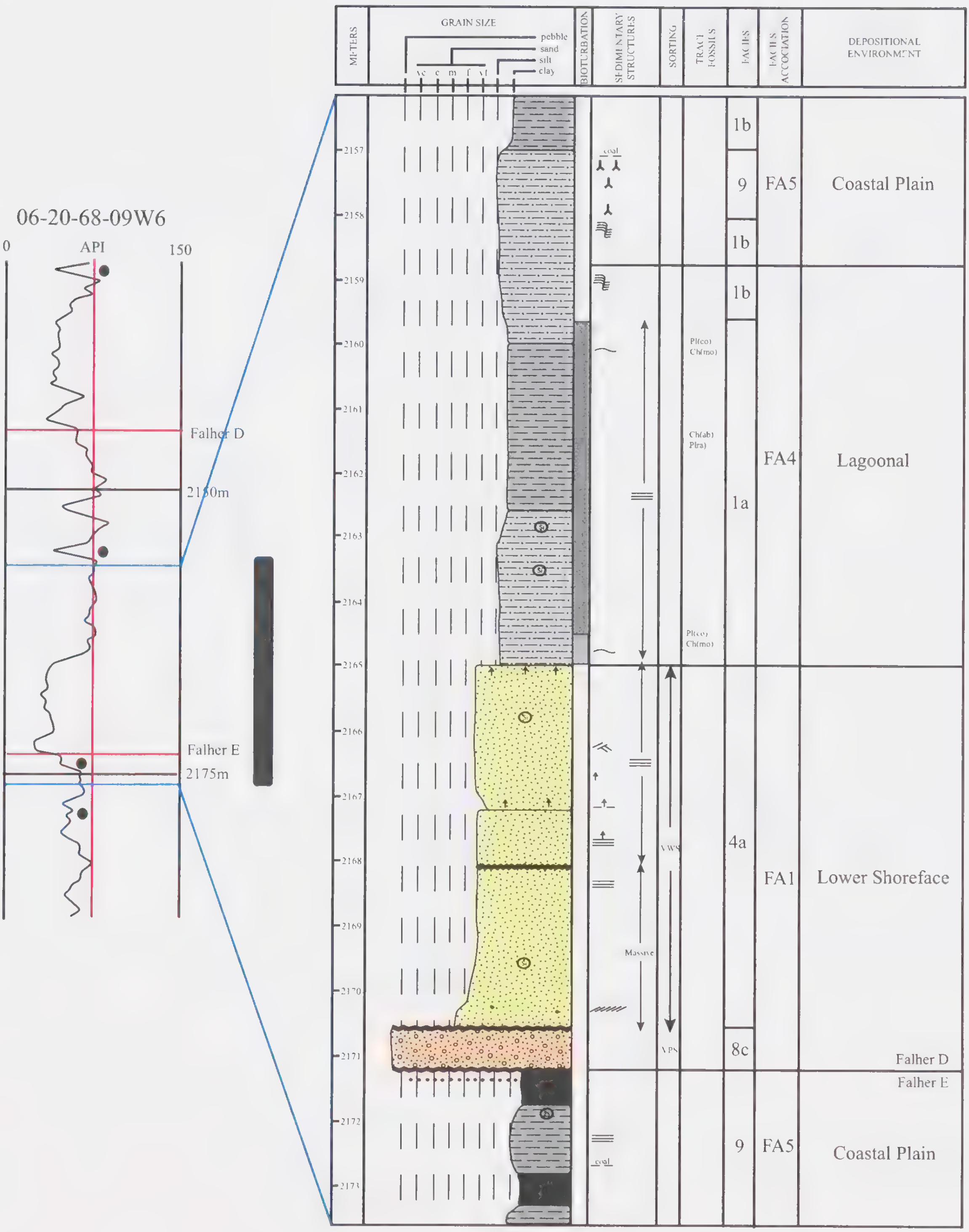

10-31-68-10W6
0
API
150
2100m
2125m
Falher D
2150m
2175m
Falher E
METERS
GRAIN SIZE
pebble
sand
silt
clay
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
9
FA5
Coastal Plain
4b
FA2
Proximal Delta Front
3b
4a
4a
FA1
Distal Delta Front
3a
4a
1b
4a
FA1
Lower Shoreface
Falher D
Falher E
4c
9
Coastal Plain

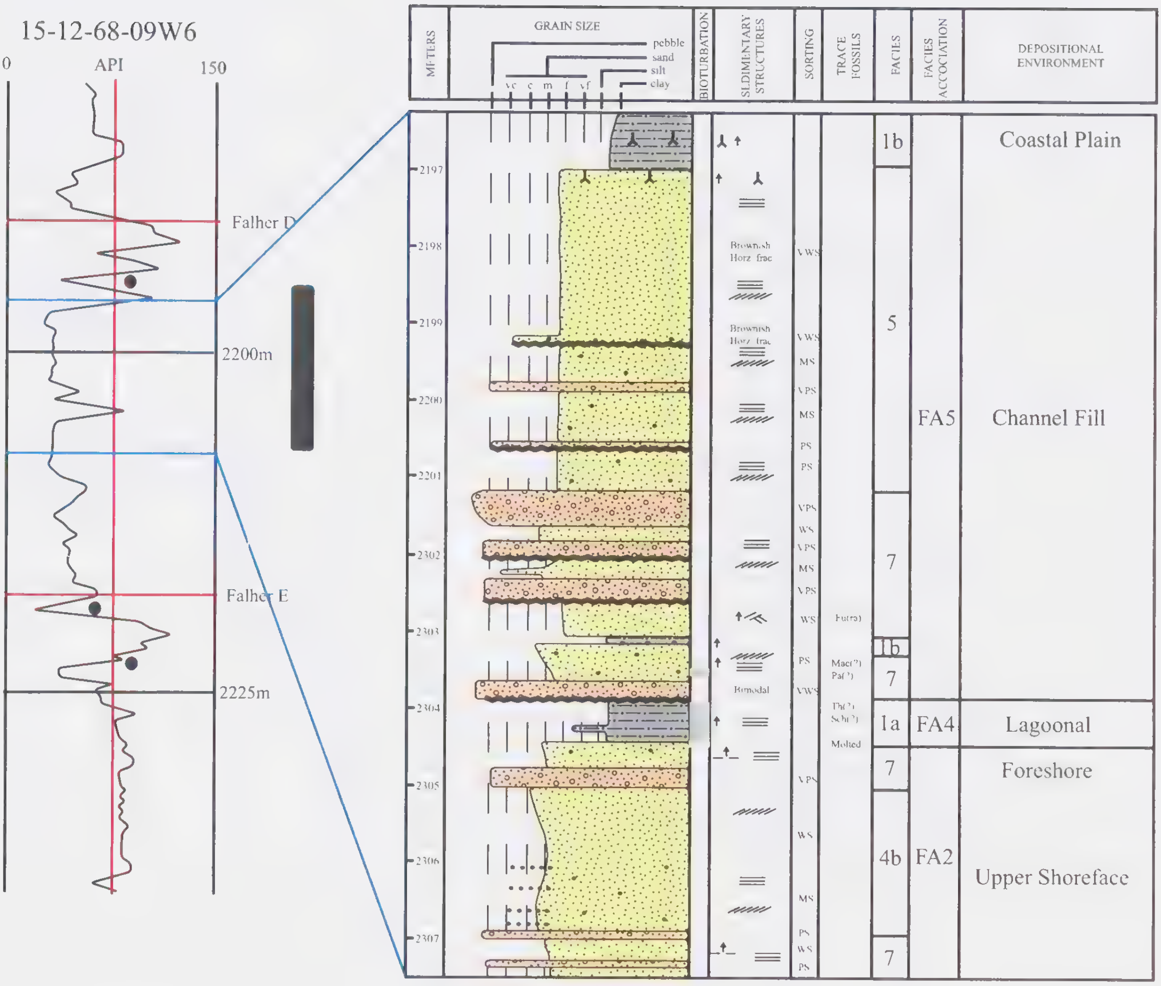

13-17-68-10W6
0
API
150
2175m
Falher D
2200m
Falher E
2225m
METERS
GRAIN SIZE
pebble
sand
silt
clay
vc c m f vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ACCOCIATION
DEPOSITIONAL ENVIRONMENT
Bimodal
Massive
Massive
Brown Specks
8b
7
3b
4c
1b
7
4b
8a
4a
3a
1b
2
4c
FA3
FA2
FA1
FA5
Delta Plain
Proximal Delta Front
Distal Delta Front
Coastal Plain

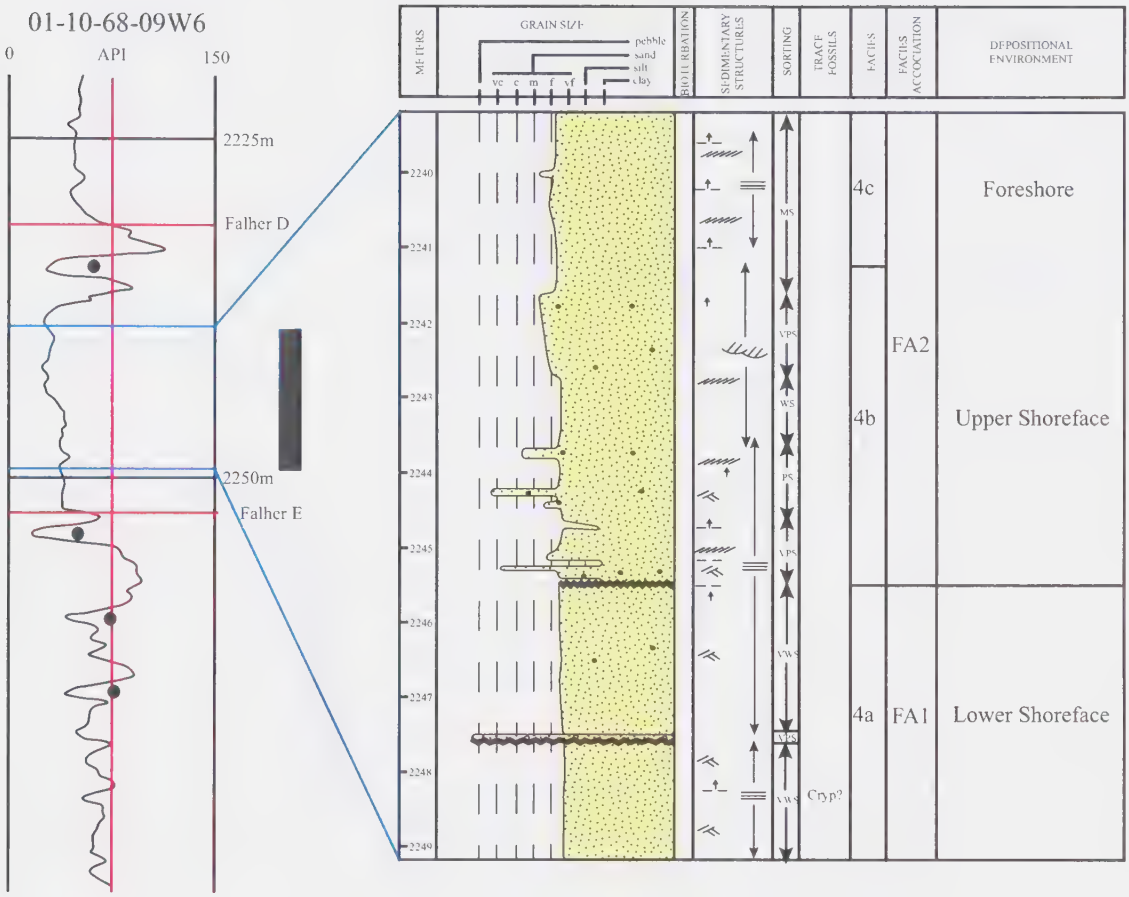

09-16-68-10W6
0
API
150
Falher D
2200m
Falher E
2225m
METERS
GRAIN SIZE
pebble
sand
silt
clay
vc c m f vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
2199
2200
2201
2202
2203
2204
2205
2206
2207
2208
2209
2210
2211
2212
2213
2214
2215
2216
VPS
PS
VWS
SCS
Massive
WS
Fu(ra)
8c
1b
4c
7
4b
4a
5
FA3
FA2
FA1
FA5
Delta Plain
Proximal Delta Front
Distal Delta Front
Channel

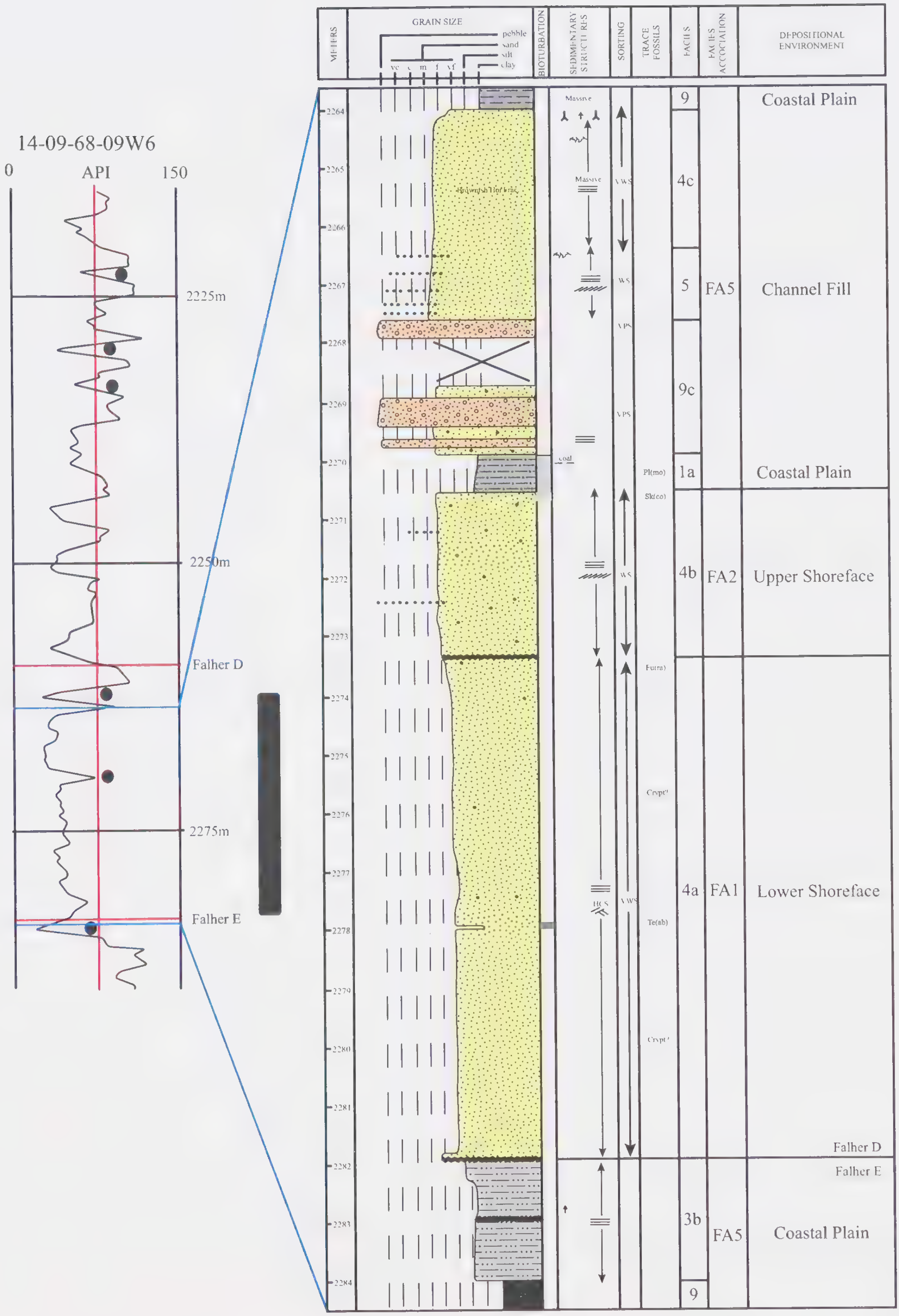

06-10-68-10W6
0
API
150
2225m
Falher D
2250m
Falher E
2275m
METERS
GRAIN SIZE
pebble
sand
silt
clay
vc c m f vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ACCOCIATION
DEPOSITIONAL ENVIRONMENT
2241
2242
2243
2244
2245
2246
2247
2248
2249
2250
2251
2252
2253
2254
2255
2256
2257
2258
Massive
Lenticular Bedding
Massive (mts)
Massive
Massive
PS
MS
PS
VPS
1b
1a
5
1a
5
9
3a
3b
1a
5
FA4
FA5
FA4
FA5
FA5
FA4
Lagoon
Channel
Lagoon
Channel
Coastal Plain
Lagoon

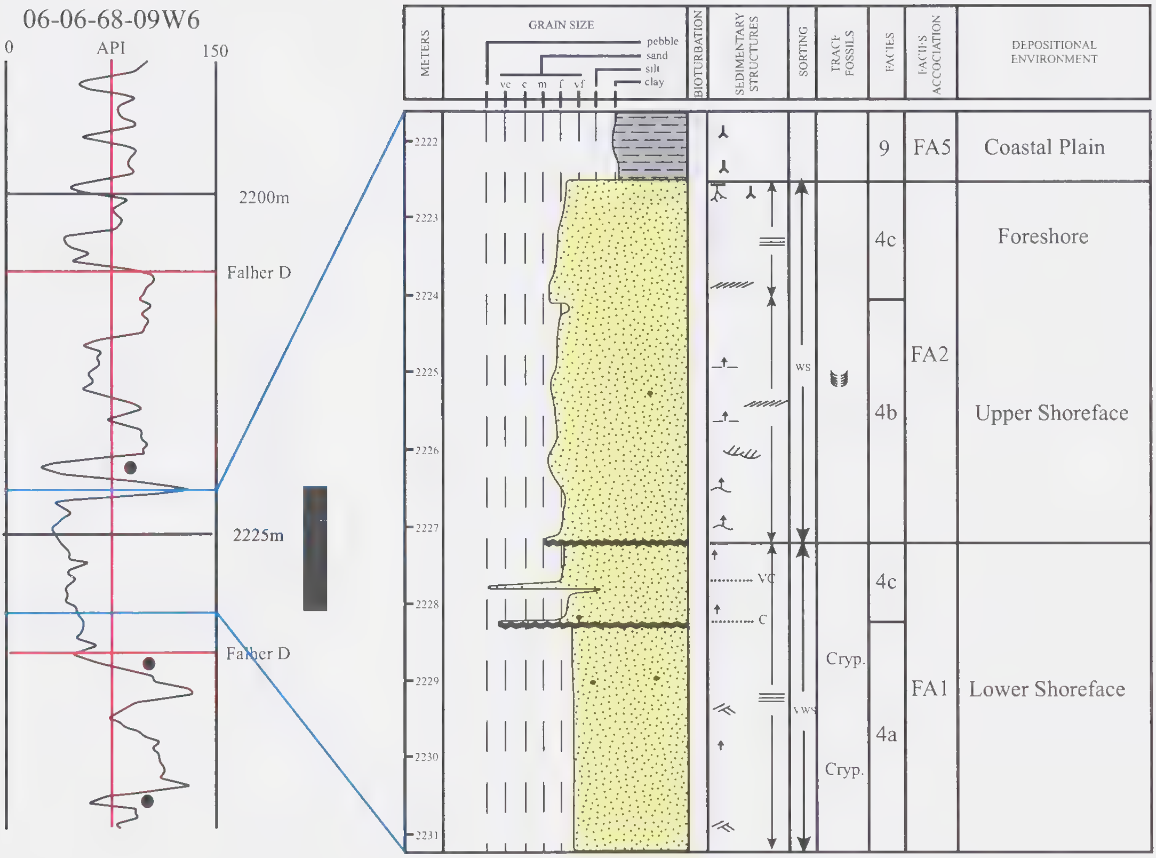

04-05-68-10W6
0
API
150
Falher D
2300m
2325m
Falher E
METERS
GRAIN SIZE
pebble
sand
silt
clay
vc c m f vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ACCOCIATION
DEPOSITIONAL ENVIRONMENT
2202
2203
2204
2205
2206
2207
2208
2209
2210
4c
8c
4c
3b
4c
1b
4c
4b
4c
4c
FA3
Delta Plain

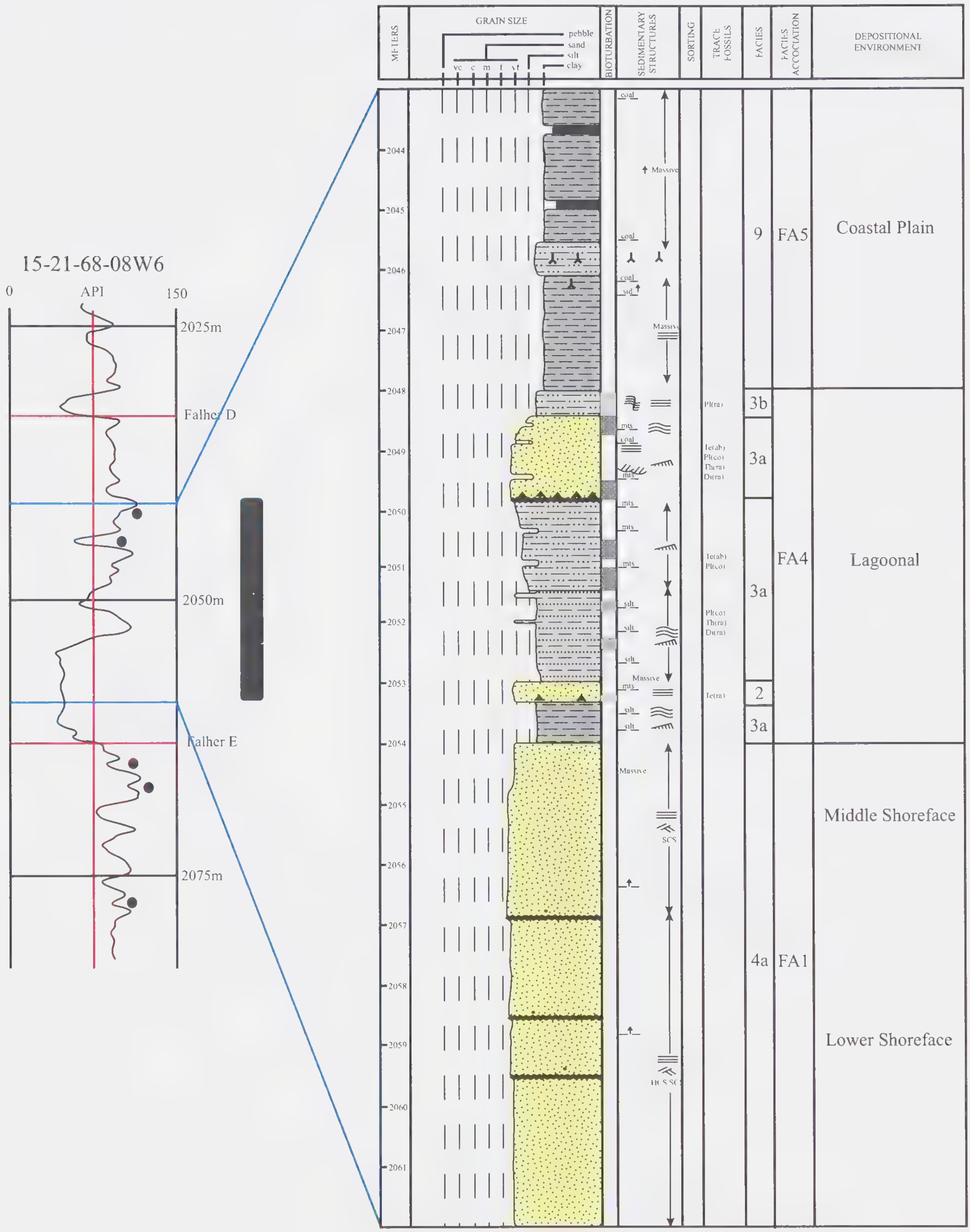

06-20-68-09W6
0
API
150
Falher D
2150m
Falher E
2175m
METERS
GRAIN SIZE
pebble
sand
silt
clay
vc c m f vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
2157
2158
2159
2160
2161
2162
2163
2164
2165
2166
2167
2168
2169
2170
2171
2172
2173
coal
1b
9
1b
FA5
Coastal Plain
1b
Pl(co)
Ch(mo)
Ch(ab)
Pl(ra)
1a
FA4
Lagoonal
Pl(co)
Ch(mo)
WWS
Massive
PS
4a
FA1
Lower Shoreface
8c
Falher D
Falher E
9
FA5
Coastal Plain
coal

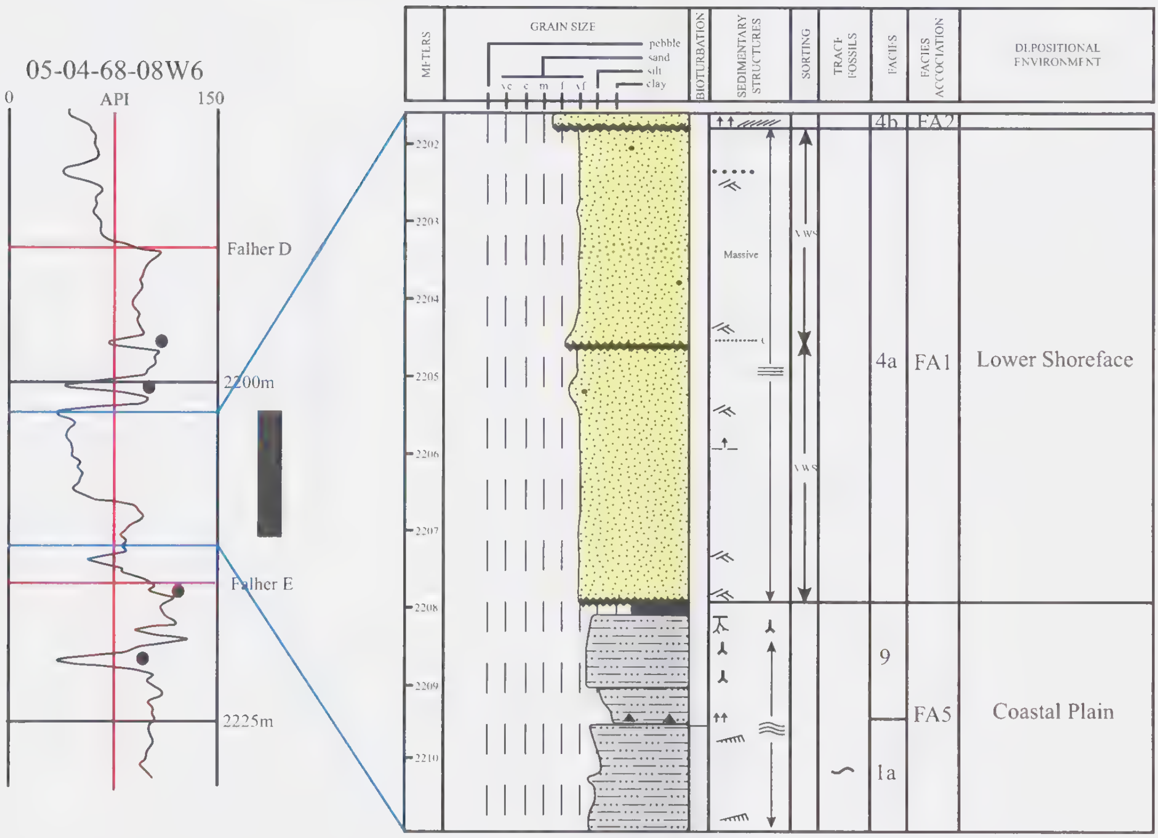

15-12-68-09W6
0
API
150
Falher D
2200m
Falher E
2225m
METERS
GRAIN SIZE
pebble
sand
silt
clay
vc c m f vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ACCOCIATION
DEPOSITIONAL ENVIRONMENT
1b
Coastal Plain
5
FA5
Channel Fill
7
1b
7
1a
FA4
Lagoonal
7
Foreshore
4b
FA2
Upper Shoreface
7

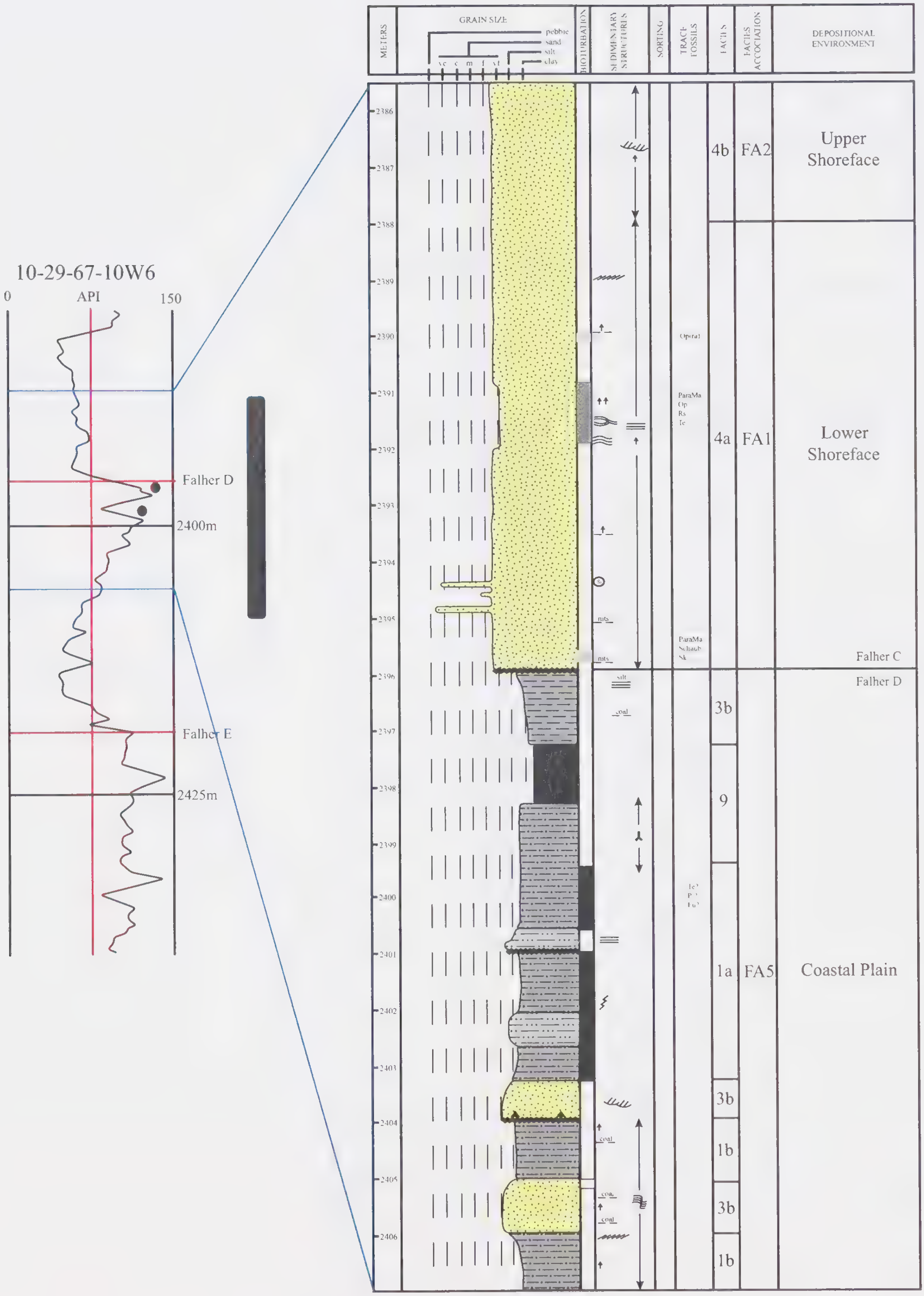

01-10-68-09W6
0
API
150
2225m
Falher D
2250m
Falher E
METERS
GRAIN SIZE
pebble
sand
silt
clay
vc c m f vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ACCOCIATION
DEPOSITIONAL ENVIRONMENT
2240
2241
2242
2243
2244
2245
2246
2247
2248
2249
MS
VPS
WS
PS
VPS
VWS
VPS
VWS
Cryp?
4c
4b
4a
FA2
FA1
Foreshore
Upper Shoreface
Lower Shoreface

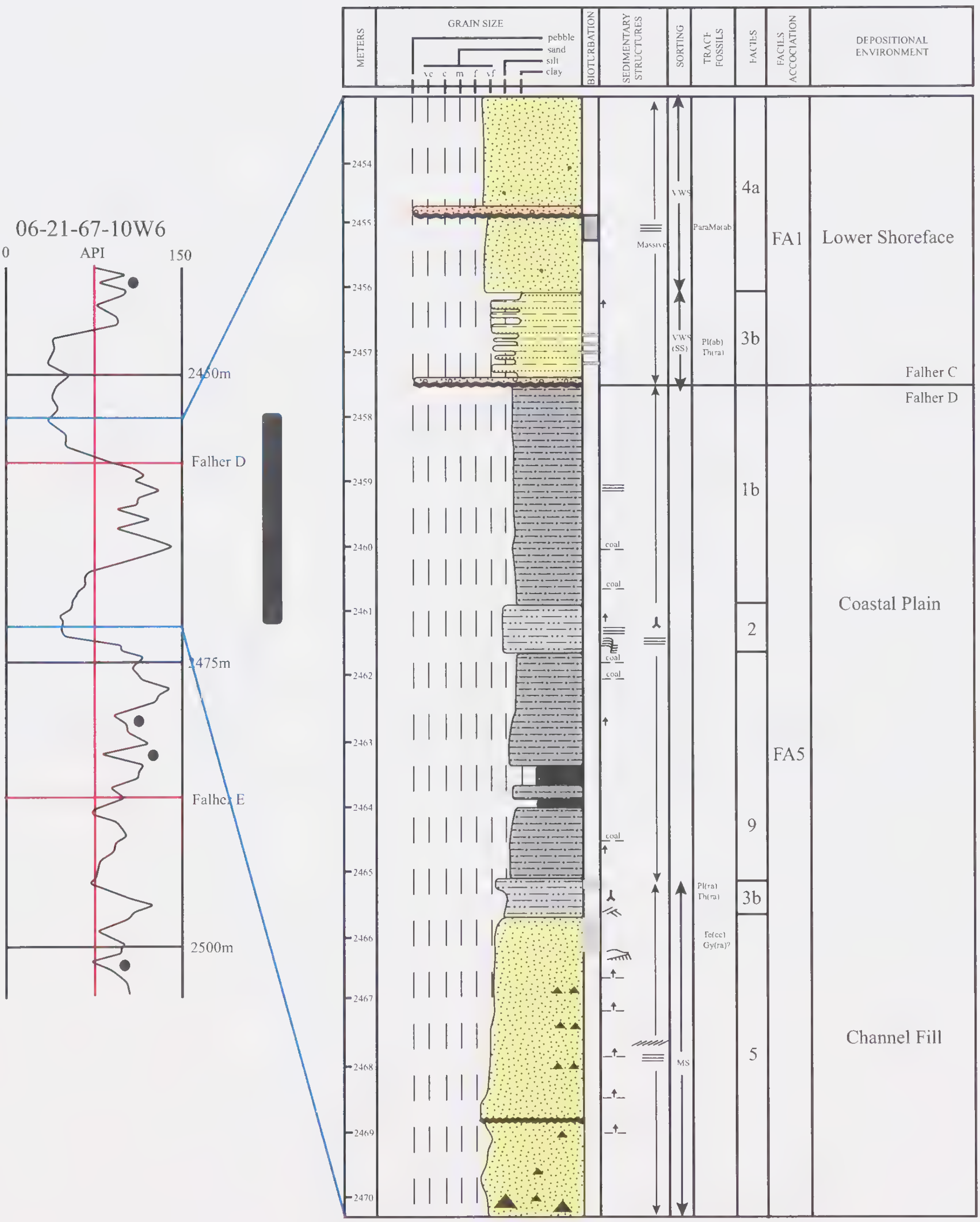

14-09-68-09W6
0
API
150
2225m
2250m
Falher D
2275m
Falher E
METERS
GRAIN SIZE
pebble
sand
silt
clay
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
Massive
coal
HCS
9
4c
5
9c
1a
4b
4a
3b
FA5
FA2
FA1
Coastal Plain
Channel Fill
Upper Shoreface
Lower Shoreface
Falher D
Falher E


06-06-68-09W6
0
API
150
2200m
Falher D
2225m
Falher D
METERS
GRAIN SIZE
pebble
sand
silt
clay
vc
c
m
f
vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ACCOCIATION
DEPOSITIONAL ENVIRONMENT
2222
2223
2224
2225
2226
2227
2228
2229
2230
2231
WS
VC
C
Cryp.
Cryp.
9
4c
4b
4c
4a
FA5
FA2
FA1
Coastal Plain
Foreshore
Upper Shoreface
Lower Shoreface

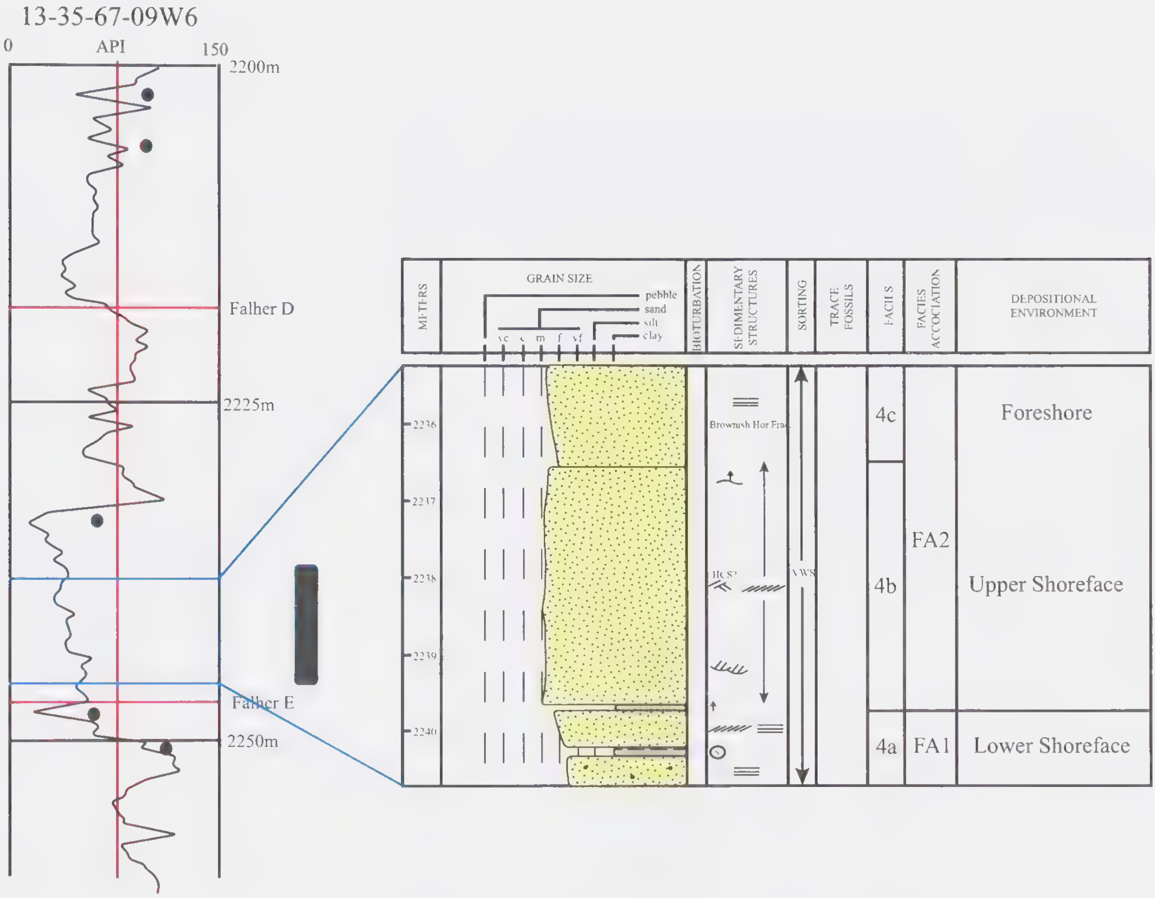

15-21-68-08W6
0
API
150
2025m
Falher D
2050m
Falher E
2075m
METERS
GRAIN SIZE
pebble
sand
silt
clay
vc c m f vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ACCOCIATION
DEPOSITIONAL ENVIRONMENT
9
FA5
Coastal Plain
3b
3a
3a
2
3a
FA4
Lagoonal
4a
FA1
Middle Shoreface
Lower Shoreface

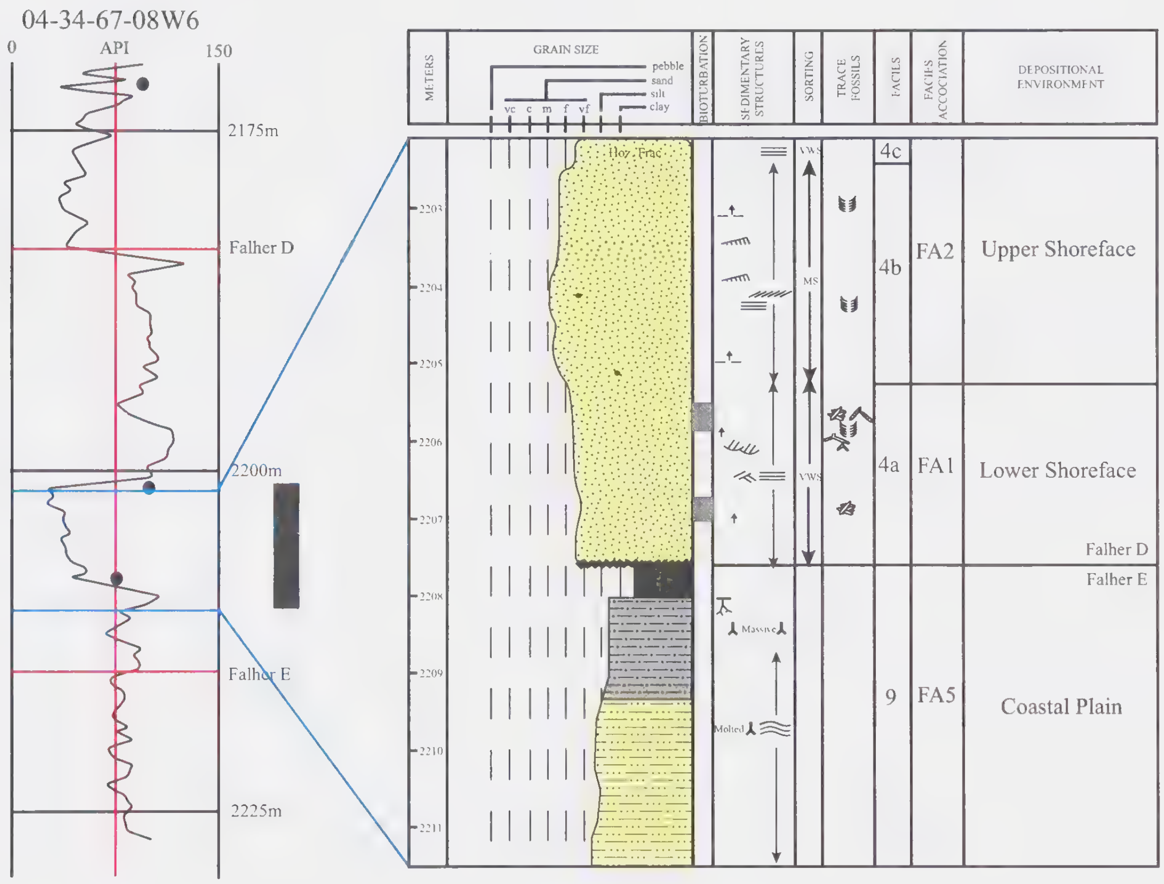

05-04-68-08W6
0
API
150
Falher D
2200m
Falher E
2225m
METERS
GRAIN SIZE
pebble
sand
silt
clay
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ACCOCIATION
DEPOSITIONAL ENVIRONMENT
Massive
4b
FA2
4a
FA1
Lower Shoreface
9
FA5
Coastal Plain
1a

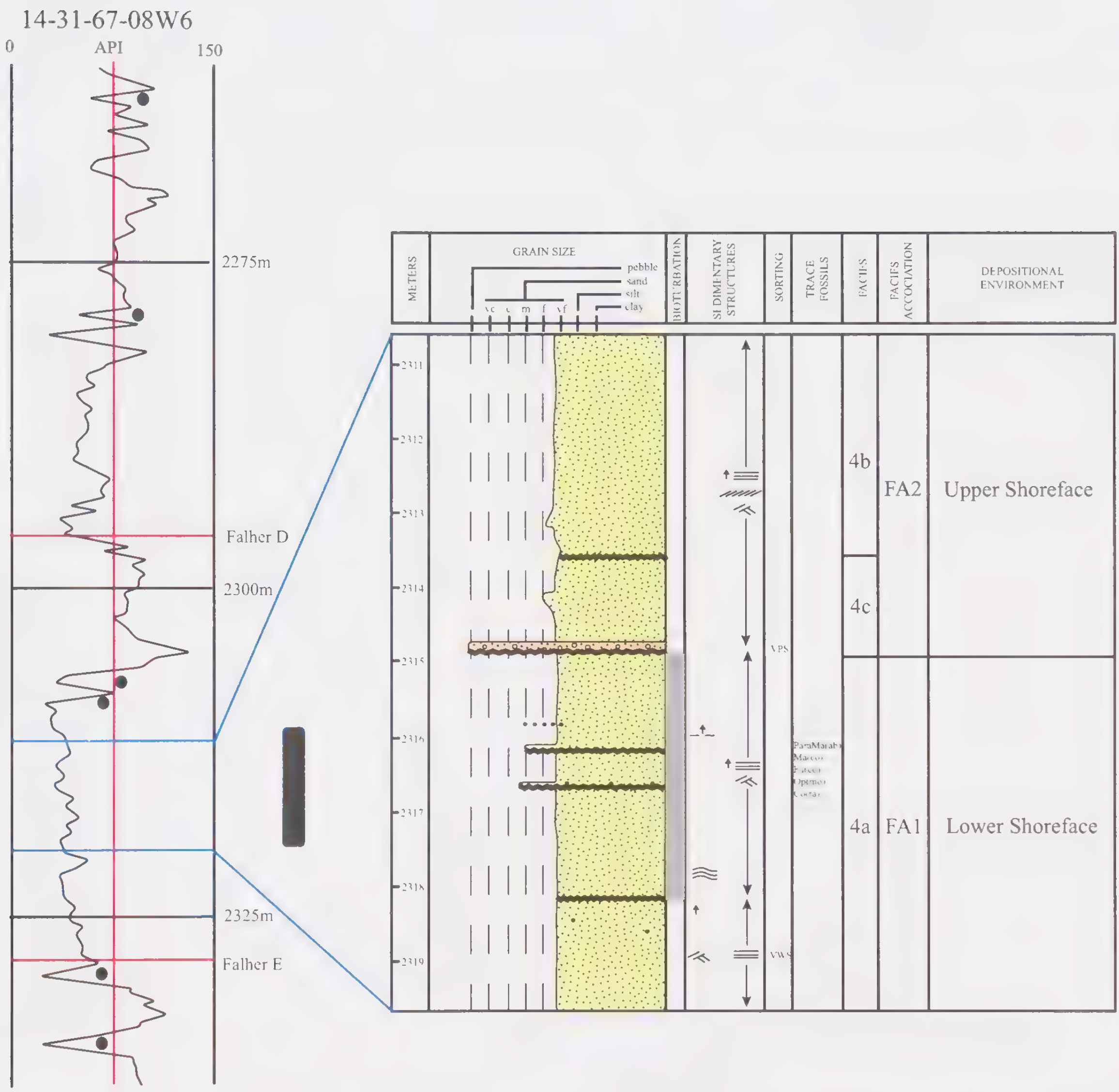

10-29-67-10W6
0
API
150
Falher D
2400m
Falher E
2425m
METERS
GRAIN SIZE
pebble
sand
silt
clay
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
4b
FA2
Upper Shoreface
4a
FA1
Lower Shoreface
Falher C
Falher D
3b
9
1a
FA5
Coastal Plain
3b
1b
3b
1b



06-21-67-10W6
0
API
150
2450m
Falher D
2475m
Falher E
2500m
METERS
GRAIN SIZE
pebble
sand
silt
clay
vc
c
m
f
vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ACCOCIATION
DEPOSITIONAL ENVIRONMENT
2454
2455
2456
2457
2458
2459
2460
2461
2462
2463
2464
2465
2466
2467
2468
2469
2470
Massive
coal
VWS
VWS (SS)
MS
ParaMot ab
Pl(ab) Th(ra)
Pl(ra) Th(ra)
Te(cc) Gy(ra)?
4a
3b
1b
2
9
3b
5
FA1
FA5
Lower Shoreface
Falher C
Falher D
Coastal Plain
Channel Fill


13-35-67-09W6
0
API
150
2200m
Falher D
2225m
Falher E
2250m
METERS
GRAIN SIZE
pebble
sand
silt
clay
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ACCOCIATION
DEPOSITIONAL ENVIRONMENT
4c
Foreshore
FA2
4b
Upper Shoreface
4a
FA1
Lower Shoreface


04-34-67-08W6
0
API
150
2175m
Falher D
2200m
Falher E
2225m
GRAIN SIZE
pebble
sand
silt
clay
vc c m f vf
METERS
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ACCOCIATION
DEPOSITIONAL ENVIRONMENT
Hoz. Frac
2203
2204
2205
2206
2207
2208
2209
2210
2211
VWS
MS
VWS
Massive
Molted
4c
4b
4a
9
FA2
FA1
FA5
Upper Shoreface
Lower Shoreface
Falher D
Falher E
Coastal Plain


14-31-67-08W6
0
API
150
2275m
Falher D
2300m
2325m
Falher E
METERS
GRAIN SIZE
pebble
sand
silt
clay
vc
c
m
f
vf
BIOTURBATION
SEDIMENTARY STRUCTURES
SORTING
TRACE FOSSILS
FACIES
FACIES ACCOCIATION
DEPOSITIONAL ENVIRONMENT
2311
2312
2313
2314
2315
2316
2317
2318
2319
VPS
VWS
4b
4c
4a
FA2
FA1
Upper Shoreface
Lower Shoreface