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THE STRATIGRAPHIC SUCCESSION AND PALEOENVIRONMENTAL INTERPRETATION OF THE MCMURRAY FORMATION, O.S.L.O. AREA, NORTHEASTERN ALBERTA.

BY

DAVID JAMES BECHTEL ©

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 GEOLOGY
EDMONTON, ALBERTA
SPRING, 1996

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Dr. S. George Pemberton - Supervisor

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Dr. D. Craig

Date: APRIL 15, 1996

To Richard and Thelma Bechtel,
my parents.

Abstract

The McMurray Formation/Wabiskaw Member succession in the Other Six Leases Operation (O.S.L.O.) area of northeastern Alberta records a Lower Cretaceous transgression of paleovalleys incised on the pre-Cretaceous unconformity. A study of 25 cores incorporating sedimentological, ichnological, and stratigraphic analysis indicates that the succession records a well preserved and pervasively drilled incised valley fill.

Lowstand fluvial channel and flood basin deposits of the lower member of the McMurray were deposited unconformably on Devonian carbonates. Rising sea levels resulted in the conversion of the paleovalley into an estuary. The middle member of the McMurray Formation is separated from the lower member by a transgressive surface of erosion associated with transgression of the valley. Ichnological and sedimentological evidence suggest the McMurray estuary within the study area was deposited under a mixed wave- and tide-dominated energy regime. The trace fossil assemblage reflects brackish water conditions.

Continued transgression resulted in a landward migration of the outer estuary mouth complex and incision of a high-relief tidal ravinement surface. Reflecting the proximity to the marine environment these upper McMurray deposits have abundant burrowing, an increased diversity of forms, rhythmically interlaminated sand and mud/carbonaceous debris, and evidence of storm deposition. The uppermost McMurray Formation and the overlying Wabiskaw Member of the Clearwater Formation reflect progradation of shoreface successions and their distal equivalents during stillstands within the overall transgression. The trace fossil assemblage records a more diverse assemblage and more robust counterparts to those found within the underlying estuarine deposits.

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I would like to thank those people who made this thesis and my time in graduate studies possible and enjoyable. In terms of possible, undeniably I must thank my supervisor Dr. S. George Pemberton. George provided me with a challenging project and the necessary support to get it done, all within an environment of learning and fun. The "lab" was a great place to laugh, work, tell stories, and make friends. George's interest in the history of our science has spawned a similar interest of my own. Funding for my research was provided by the Alberta Oil Sands Technology and Research Authority (AOSTRA) through Grant No. 615 to Dr. S.G. Pemberton.

My time in grad studies was made better and a little easier by my fellow students: Tom, Indy, Don, Catherine, Howard, Arjun, Mike G., and Jeff. Thanks for the laughs. Catherine's thesis project was adjacent to my own and we did a lot of work together. Her help is greatly appreciated. Howard was available to help me with the computers. Tom Saunders' discussions on ichnology were very helpful and I find his enthusiasm invigorating and contagious.

Sheri Gilmour's support and assistance has been invaluable. I owe her a great deal of thanks. She motivated me, supported me, helped me, and when things got stressful, Sheri was there for me. Thank you.

My parents, Richard and Thelma Bechtel, were also there for me. Their encouragement and support, both moral and financial, made this thesis possible. They saw to it that their son had everything he needed to succeed. In addition, I feel it is my father's desire for knowledge that has led me to a interest in science. The need to know drives my will to learn. I want to thank Brian, Robert, and Kathy for their support and cheers.

Dr. Mike Ranger was the anchor for this thesis. His studies provided the framework for this thesis, his computer applications made the work better, his presence motivated me to work harder, his knowledge was inspiring, and his leadership was undeniably helpful.

No discussion of any aspect of my geological studies and interests would be complete without mentioning Dr. James MacEachern. Since my second year of undergraduate courses James has influenced my life. No single person has had a greater effect on my geological career. From being T.A.ed by James to T.A.ing with James, from the core lab to Southern Wyoming, from across the room to across the telephone no one has imparted more knowledge on me than James. Most of what I know about stratigraphy is what I managed to remember from what James has taught me. I have great memories of our times together and I look forward to a long friendship. Thank you James.

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Introduction

The McMurray Formation of the Mannville Group in northeastern Alberta constitutes the predominant stratigraphic unit of the Athabasca oil sands deposit (Fig. 1). With 209 billion cubic metres (1.3 trillion barrels) of bitumen in place, the deposit is the largest accumulation of bitumen in the world. The bitumen of the oil sands is considered heavy with API (American Petroleum Institute) gravities of between 7° and 10° (Rennie, 1987). Due to its high viscosity, the oil sands deposits require specialized recovery methods including both surface mining processes and *in situ* methods. Maximizing the recovery potential of this vast deposit is dependent upon a clear understanding of the nature, geometry, and internal variations of the reservoir.

Distribution of bitumen within the McMurray Formation is largely controlled by lithology (Carrigy, 1962). Clean, well sorted quartzose sands with high porosity and permeability have the highest degree of bitumen saturation. As the McMurray Formation sediments have undergone little post-depositional modification (cementation, quartz diagenesis, clay authigenesis, *etc.*), Mossop (1980) concluded that bitumen content is dependent upon the depositional environment's influence on facies distribution.

Description and interpretation of the sedimentological features of the McMurray Formation will lead to a better understanding of the physical and biological processes responsible for the distribution of facies within the formation. The physical processes associated with a particular depositional setting result in recognizable structures in the rock record. These physical structures also record variations within the depositional setting. Trace fossils are biologically produced sedimentary structures. The study of the ichnology of the facies within the McMurray Formation will also contribute to the interpretation of the depositional environment. Understanding the significance of both the physical and biological structures of the McMurray Formation will provide a useful paleoenvironmental interpretation of the formation.

In order to maximize our knowledge of the reservoir an understanding of the vertical and lateral variability of the facies is required. The preservation of facies is key to understanding these facies variations. The lateral variability of facies within the McMurray Formation has been previously noted (Mossop, 1980; Rennie, 1987). The vertical succession of facies within the study area is complex. A better understanding of the vertical succession can be achieved by grouping genetically-related facies (genetic stratigraphy) as opposed to simply grouping on a lithostratigraphic basis. The discontinuities bounding these genetically-related units are crucial to the development of a facies model and lead to an understanding of the effect external controls (*e.g.* sea level changes) have on the depositional environment (Walker, 1992). To this end, interpreting the nature of the numerous bounding discontinuities, identified both sedimentologically and ichnologically, within the vertical succession of the McMurray Formation will contribute to the understanding of the preserved rock record.

The objective of this study is to determine, using both sedimentology and ichnology, the effects the nature of the depositional environment had on facies distribution and facies continuity within the McMurray Formation. The importance of grouping genetically-related units is reflected in the use of facies associations. Complete interpretations of the bounding discontinuities reflect an understanding of the importance external controls have on the deposition and preservation of facies. In order to better understand the overall vertical succession of the McMurray Formation an interpretation of the overlying, thin Wabiskaw Member of the Clearwater Formation is included.

Study Area

The study area is the located approximately 45 km north-northeast of Fort McMurray, Alberta and encompasses the oil sand lease referred to as the Other Six Leases Operation (O.S.L.O.) reflecting its joint ownership (Oil Sand Lease #31). It includes part of Township 93 and all of Townships 94 and 95, all Range 8 west of the Fourth Meridian (the Alberta-Saskatchewan border) (Fig. 2). The study is located within the surface mineable area of the oil sands deposit. Within the surface mineable area, overburden thicknesses vary from 5.0 to 50.0 m of glacial deposits and Cretaceous sediments.

The Athabasca oil sands deposit is defined as the oil-impregnated portions of Lower Cretaceous sands in the lower Athabasca River area (Carrigy and Zamora, 1960). The deposit pinches out against the Canadian Shield to the east and the Nisku-Grosmont high to the west (Stewart, 1963). The deposit has been truncated by glacial erosion to the north and its southern limit is poorly defined (Stewart, 1963; Carrigy, 1959).

Within the study area, only the Clearwater and McMurray Formations are preserved. The Wabiskaw Member and the McMurray Formation make up the majority of the Athabasca oil sands deposits reserves with 142 billion cubic metres (893 billion barrels) in place (Energy Resources Conservation Board, 1990).

The study area has approximately 500 well locations, most of which are located in Township 95-8w4. The study included examination of 25 drill cores, varying in length from 55.0 m to 125.0 m. The sedimentological and ichnological features were recorded using the AppleCORE program created by Dr. M.J. Ranger of the University of Alberta. The subsurface analysis also included examination of approximately 100 available well logs. As this number of well logs represented only 20% of the drill holes detailed subsurface mapping was not attempted. The well logs were used to compliment the drill cores in interpreting the stratigraphy of the McMurray Formation.

A drill core study of the McMurray Formation provides unique advantages and disadvantages. The nature of methods for exploiting this valuable resource and for determining subsurface heterogeneity requires abundant drill core information. This combined with the relative ease and low cost of acquiring drill core in this area has resulted in the extensive drill core control available for study. In addition the entire McMurray/Wabiskaw interval is cored, including non reservoir intervals. This affords the researcher opportunity to examine the complete stratigraphic succession. The shallow nature of the deposit has resulted in nearby outcrop exposures, both saturated and unsaturated with respect to bitumen, allowing useful correlation to the subsurface. Ichnology is a particularly useful tool for interpretation of the oil sands. While many sedimentological features are obscured, the trace fossils are recognizable due to their lithologic contrasts. Many burrows include fills and walls/linings of lithologies contrasting the surrounding sediments. As bitumen saturation is limited to the sands the contrasting muds are easily distinguished.

Disadvantages include the already mentioned obscuring of sedimentological features. In addition the core is collected in PVC (polyvinyl chloride) tubing in an attempt to recover the unconsolidated sediments that make up the oil sands. The cores are slabbed and viewed in the tubing; therefore, the researcher may only view a two-dimensional section of the core. The unconsolidated core may be distorted by the coring process; surfaces become distorted or pieces of core may rotate differentially within in the tubing. Sands within the lower portion of the formation are water sands and have little or no bitumen saturation. The sands disaggregate easily and as a result are commonly poorly recovered.

Previous Work

The significance of the Athabasca oil sands deposit has provided impetus for study of the McMurray Formation since the late nineteenth century. Bell (1885) conducted a reconnaissance survey of the area for the Geological Survey of Canada noting its economic significance. McConnell (1893) performed a more detailed study, also for the Geological Survey of Canada, describing the tar sands in detail through outcrop exposures.

McLearn (1917) proposed the name "McMurray" for strata containing the tar sands. Badgely (1952) later named the basal sand of the Clearwater Formation as the Wabiskaw Member. Other early studies (Ells, 1926; Clark and Blair, 1927) focused on the physical and chemical properties of the oil sands, extent and volume of the deposit, and possible exploitation methods. In the 1930's to 1950's focus of research shifted to the origin of the bitumen in the Athabasca oil sands (Ball, 1935; Sproule, 1951; Link, 1951; Hume, 1951).

A single researcher dominated the published studies of the McMurray in the late 1950's to the early 1970's and not surprisingly a single depositional model for the McMurray Formation came into use. Carrigy's (1959, 1962, 1963a, 1963b, 1963c, 1966, 1967, 1971, 1973a) work became the basis for future studies. Carrigy (1966, 1967, 1971) proposed a deltaic complex depositional model that has persisted to more recent publications (Leckie and Smith, 1992). The deltaic model was based on detailed stratigraphic, mineralogic, and sedimentological studies.

Sedimentological studies, focused on small areas of interest, used facies analysis to develop depositional models for the McMurray Formation (Benthin and Orgnero, 1977; Flach, 1977; James, 1977; Nelson and Glaister, 1978; Mossop, 1980). A fluvial interpretation for the lower McMurray was common to all of these studies. It was the interpretation of the middle and upper portions of the formation that varied. The variety of interpretations included a number of coastal environments. A fluvial (with periodic marine incursions) interpretation dominated the next group of publications (Flach, 1977, 1984; Mossop, 1978, 1980; Mossop et al., 1982; Mossop and Flach, 1983; Flach and Mossop, 1985). Smith (1987, 1988a, 1988b) noted the tidal influence on modern deposits analogous to those McMurray Formation. An estuarine depositional model based on sedimentological data has also been developed (MacCallum, 1977; Stewart and MacCallum, 1978; Stewart, 1981; Fox, 1988; Fox and Pemberton, 1989). Incorporation of ichnological interpretations has supported the estuarine model (Pemberton *et al.*, 1982; Ranger and Pemberton, 1992; Bechtel *et al.*, 1994; Yuill *et al.*, 1994; Yuill, 1995). Fox (Table 1, 1988) provides a useful table reviewing the previous McMurray Formation work.

Stratigraphy

Sub-Cretaceous succession

In the study area, the McMurray Formation unconformably overlies a succession of Devonian evaporites and carbonates (Stewart, 1963; Carrigy, 1973a). The Devonian strata pinch out against the Canadian Shield to the east and are approximately 350 m thick in the Fort McMurray area (Norris, 1973).

The Devonian succession consists of: dolomite, anhydrite, gypsum, and halite of the Lower to Middle Devonian Elk Point Supergroup; limestone and dolomite of the Middle Devonian Slave Point Formation; and limestone and dolomites of the Upper Devonian Beaverhill Lake and Woodbend Groups (Carrigy, 1959; Norris, 1973). The Waterways Formation of the Beaverhill Lake Group directly underlies the McMurray Formation within the study area (Fig. 3).

Sub-Cretaceous unconformity

In the study area, the Lower Cretaceous McMurray Formation unconformably overlies the Upper Devonian Beaverhill Lake Group carbonates (Carrigy, 1959; Norris, 1973). This unconformity represents a major depositional break with the area exposed to several periods of subaerial erosion and weathering (Stewart, 1963). Mapping the isopach of the McMurray Formation, which infilled lows within the unconformity, reveals a drainage system characterized by wide river valleys and low, rounded hills (Stewart, 1963; Ranger, 1994).

Cretaceous succession

The Cretaceous stratigraphy of northeastern Alberta include from the base to the top: McMurray, Clearwater, Grand Rapids, Joli Fou, Pelican, and La Biche Formations (Carrigy, 1959). Only the McMurray and Clearwater Formations were encountered within the study area.

The McMurray Formation (McLearn, 1917) has been subdivided into three informal members (Carrigy, 1959). The lack of regional correlation (mappable extent) of these members leaves their status as informal. The lower member of the McMurray Formation is limited to structural lows within the unconformity surface. The middle McMurray is found throughout the study area with its base delineated as the base of the middle McMurray sands. The contact between the lower and middle member becomes problematic at locations where middle McMurray sands rest on lower McMurray sands. Fox (1988) identified a "limy unit" of limited areal extent above the middle McMurray. The upper McMurray is also found within the study area and appears to have a greater variability than the middle McMurray. The top of the Formation was originally identified as the base of the overlying green sand of the Clearwater Formation (McLearn, 1917). The lack of body fossils has made age determination of the McMurray Formation difficult. Burden (1984) provides a useful review of age determination for the McMurray

Formation. Flach and Mossop (1985) provided an age of Aptian for the formation with remnants of older (Neocomian) sediments possibly incorporated within the lower McMurray. On the basis of palynomorph biostratigraphy, Burden (1984) assigned an age of Late Valanginian or Hauterivian to some lower McMurray deposits and Early Barremian to others. Late Barremian, Aptian, and earliest Albian ages were assigned to middle and upper McMurray units (Burden, 1984). The complexity of the McMurray deposits clearly contribute to the difficulty in age determination.

The Clearwater Formation (McConnell, 1893) overlies the McMurray Formation. The base of the Clearwater Formation is identified as the base of the glauconitic Wabiskaw Member sand (Badgely, 1952). In the study area, the Wabiskaw Member was identified by the first occurrence of glauconite and the increased bioturbation associated with larger trace fossils than the underlying McMurray Formation. The Clearwater Formation is of Albian age (Burden, 1984; Flach and Mossop, 1985).

Regional Stratigraphy

The McMurray, Clearwater, and Grand Rapids Formations make up the Mannville Group (Nauss, 1945; Badgely, 1952) in the Athabasca oil sands area. The lower part of the Mannville Group includes all strata above the unconformity surface and below the Wabiskaw Member (glauconitic sands) (Glaister, 1959). The McMurray Formation has been equated to the lower part of the Mannville Group (Ellerslie or Basal Quartz) in central Alberta (Williams, 1963), the Dina Formation in the Lloydminster area (Glaister, 1959), the Gething Formation (Bullhead Group) in the peace River area, the Gladstone Formation (Blairmore Group) of the Alberta Foothills (McLearn, 1945; Mellon, 1967), and the Sunburst Sandstone in southern Alberta (Williams, 1963) (Fig. 4).

Controls on McMurray Formation Deposition

The McMurray Formation was deposited unconformably on the Devonian strata with the McMurray deposits infilling lows and thinning over highs. Clearly the paleotopography of the unconformity surface and structure of the underlying Devonian strata influenced McMurray deposition. The Precambrian basement and Devonian strata dip towards the west at approximately 4.0 m/km (Carrigy, 1959). Post-Cretaceous tilting was estimated 1.0 m/km to the southwest (Martin and Jamin, 1963).

The McMurray Formation was deposited within a north-northwest trending trough bounded by the Canadian Shield to the east and the Wainwright Ridge-Grosmont High to the west (Stewart, 1963; Ranger and Pemberton, 1988; Ranger 1994). The

McMurray sedimentary subbasin (Ranger, 1994) formed as the result of dissolution of the Prairie Formation (Elk Point Supergroup) evaporites (Fig. 3). With removal of the evaporites, overlying Beaverhill Lake Group carbonates subsided and the area became a locus of sedimentation. The thickest McMurray intervals occur within the limit of Prairie evaporite solution ("Elk Point Depression" of Stewart, 1963). Evidence of continued subsidence is present within the Athabasca oil sands area. In the Bitumount subbasin (Ranger, 1994) area the McMurray and Clearwater Formations show collapse of approximately 60.0 m (Stewart, 1963). Carrigy (1959) uses modern saline springs as evidence of continuing solution of the Prairie evaporites. Stewart (1963) suggests that deep-seated structures resulting from faulting in the Precambrian basement are also reflected on the unconformity surface.

Large paleovalleys developed on the irregular unconformity surface (Stewart, 1963; Ranger, 1994). Martin and Jamin (1963) reported slopes on the unconformity surface as high as 70.0 m/km. Within the O.S.L.O area the highest gradient on the unconformity is 75.0 m/km. These drainage systems occupied both the lows produced by the removal of the Prairie evaporites and the areas of less resistant carbonates. The axis of the McMurray valley system (Ranger, 1994) trends parallel to the edge of the exposed Canadian Shield and within the limit of Prairie evaporite solution (Stewart, 1963). Stewart (1963) noted the correlation between salt dissolution and paleodrainage patterns. Spurs from main ridges of the unconformity surface may represent divides between tributary valleys. Resistant ridges and less resistant valleys formed on the unconformity surface depending on the subcrop lithology. Martin and Jamin (1963) noted numerous north-northwest trending ridges that parallel subcrop edges of resistant Devonian strata. The Grosmont High (the northern extension of the Wainwright Ridge and western edge of the McMurray basin) is a resistant ridge of Nisku Formation and Grosmont Formation carbonates (Stewart, 1963; Ranger, 1994). The Beaverhill Lake Ridge formed as the result of salt solution to the east of the ridge (Martin and Jamin, 1963).

Within the study area, subsidence appears to have had a significant control on McMurray Formation deposition and preservation. The structure on the unconformity surface (Fig. 5) corresponds well to the isopach of the McMurray Formation (Fig. 6). The McMurray Formation thickens and thins over the lows and highs, respectively, on the unconformity surface. The formation thins (to approximately 50.0 m) through the middle of Township 94-8w4 and in the southern portion of Tp. 93. Thick (up to 140.0 m) McMurray intervals are present in Tp. 95 and the southwest corner of Tp. 94. The maximum thickness of the original McMurray intervals cannot be determined as the result of glacial erosion removing the top of the formation. The thin McMurray through Tp. 94 is interpreted as a paleovalley divide trending west-northwest. A spur of this ridge trends northeast across Tp. 93. The maximum relief on the unconformity is approximately 75.0 m/km.

The thick McMurray deposits in Tp. 95 are interpreted to be the result of salt dissolution in the Devonian Prairie evaporites. Stewart (1963) locates the Bitumount Basin at Tp. 96-10w4, just to the northwest of the study area. Ranger (1994) includes Tp. 95 as part of his Bitumount subbasin. The association of thick McMurray deposition (Bitumount subbasin) and post-Cretaceous subsidence (Bitumount Basin) suggests that the area was (and maybe is) subject to significant subsidence. The effect this subsidence has on the study area is recognized at many levels. The area in the west central portion of Tp. 95 is a low on the unconformity surface, a thick of the McMurray isopach, a low on the top of the McMurray (noting the effects of glacial erosion), a low on the base of the glacial drift, and a present day topographic low.

Geological Framework

Sediments of the McMurray and Clearwater Formations were deposited in the Western Canadian Foreland Basin (Leckie and Smith, 1992). Prior to development of the foreland basin the western edge of the continent was a passive margin. Collision of foreign terranes to the west continental margin during Middle to Late Jurassic time resulted in the development of the Western Canada Foreland Basin (Leckie and Smith, 1992). Foreland basins are asymmetric with the deepest portion of the basin being adjacent to the fold-thrust belt as the result of thrust-belt loading and sediment loading in the basin itself (Leckie and Smith, 1992). The result in the Western Canada Foreland Basin is a westward thickening wedge of clastic sediments.

The clastic wedge foreland basin has been subdivided based on strata bounded by major unconformities (Leckie and Smith, 1992; Stott, 1993). Stott (1984, 1993) assigned two of three clastic wedges in the Rocky Mountain Foothills to the Columbian Orogeny (Late Jurassic to Early Cretaceous). Leckie and Smith (1992) identified 5 cycles of sedimentation within the foreland basin; the first two of which are associated with the Columbian Orogeny and equate to the two clastic wedges of Stott (1993). The first wedge/cycle contains deposits of the Fernie Formation, the Minnes and Kootenay Groups, and the Nikanassin Formation (Leckie and Smith, 1992; Stott, 1993). These sediments are found only in the western part of the basin (Cant, 1989). The second wedge/cycle includes the Bullhead, the Blairmore, the Fort St. John, the Luscar, and the Mannville Groups (Leckie and Smith, 1992; Stott, 1993). Subsequent clastic wedges

(Stott, 1993) and cycles (Leckie and Smith, 1992) reflect periods of quiescence and then the Laramide Orogeny (Late Cretaceous to Paleocene).

The Bullhead, the Blairmore, and the Mannville Groups were deposited on the sub-Cretaceous unconformity (Fig. 7). This unconformity is present along the entire length of the Rocky Mountain Foothills (Stott, 1993) and east across the prairies (Leckie and Smith, 1992). The sub-Cretaceous unconformity contains three main northwest trending paleovalleys: the Spirit River valley system, the Edmonton Channel valley, and the McMurray valley system (Ranger, 1994). The Spirit River valley system trends northward along the western edge of the basin and likely drained much of western Alberta, and at times probably the western United States (Ranger, 1994). The Edmonton Channel valley trends north-northwest and extends to southeastern Alberta and southwestern Saskatchewan (Williams, 1963; Ranger, 1994). The McMurray valley system (St. Paul Channel of Williams, 1963) lies along the eastern edge of the basin (Ranger, 1994). Bounded by the Wainwright Ridge-Grosmont High to the west and the Canadian Shield to the east, the McMurray valley system eroded into the Devonian strata and formed the subbasin into which McMurray Formation sediments were deposited.

Marine incursions from the north flooded these valley systems (Williams, 1963). Each of the three valley systems would have reacted independently to transgressions of the Boreal Sea depending on sediment supply and topography (Ranger, 1994). Transgression of the McMurray valley system is the result of subsidence of the foreland basin, subsidence due to dissolution of the Devonian strata, and eustatic sea level rise (Leckie and Smith, 1992; Ranger, 1994). At end of McMurray time (early Albian), the Boreal Sea transgressed southward depositing the shales of the Clearwater Formation (Williams, 1963).

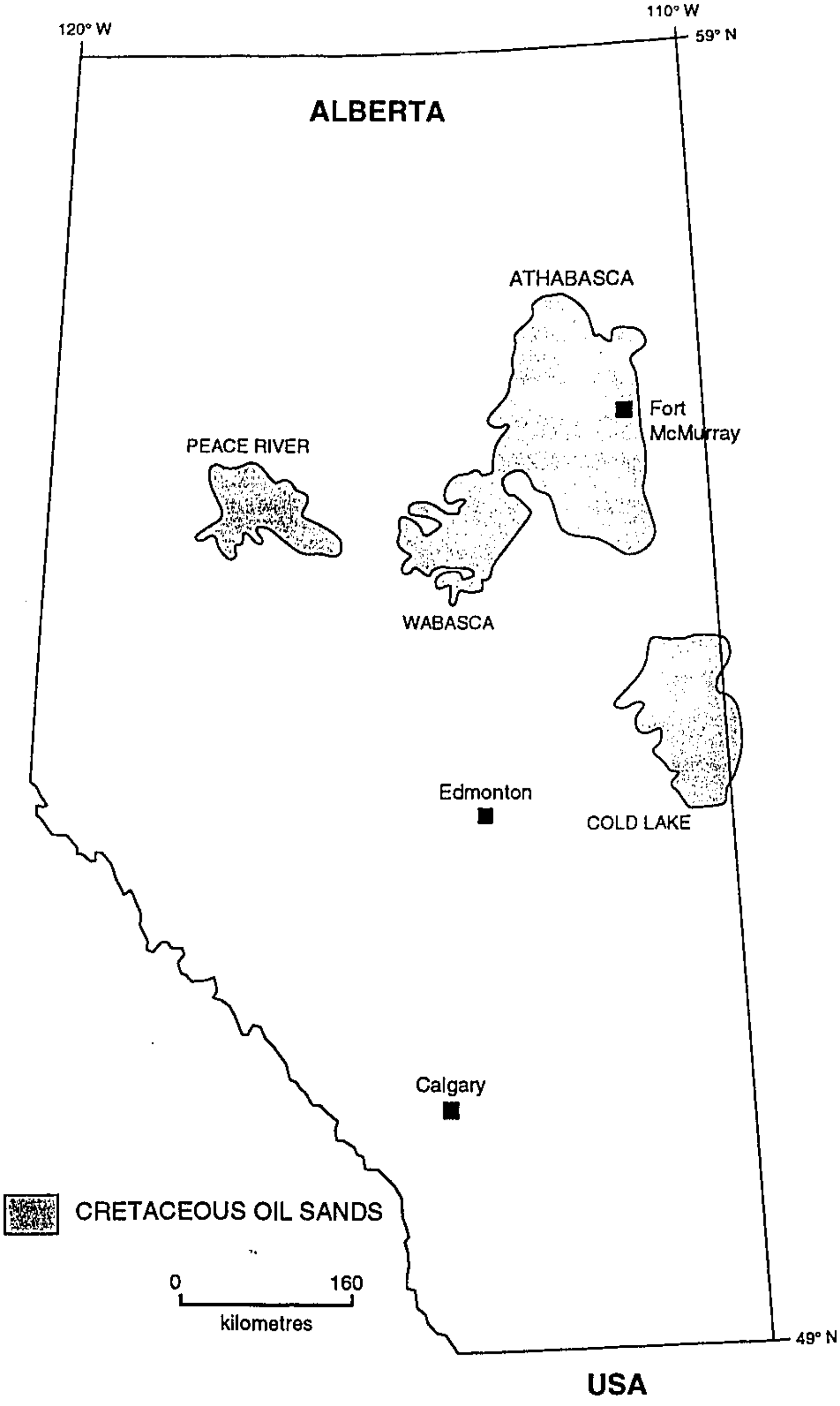

Figure 1. Location of Cretaceous oil sand deposits in Alberta, Canada (modified from Mossop *et al.* 1982).

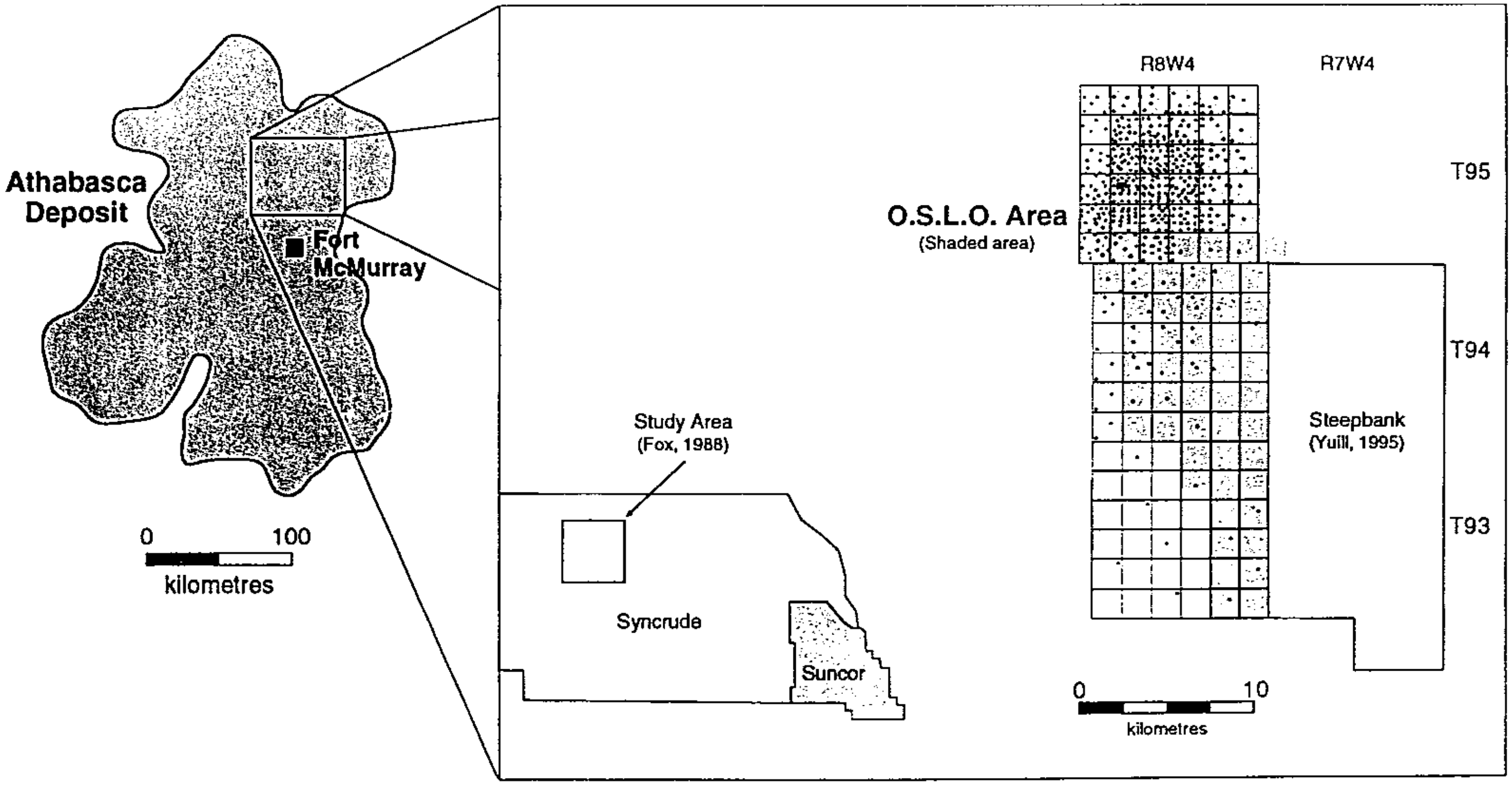

Figure 2. Location map of the Other Six Leases Operation (O.S.L.O.) area with respect to other Athabasca oil sands areas. Well distribution for the O.S.L.O. area is shown.

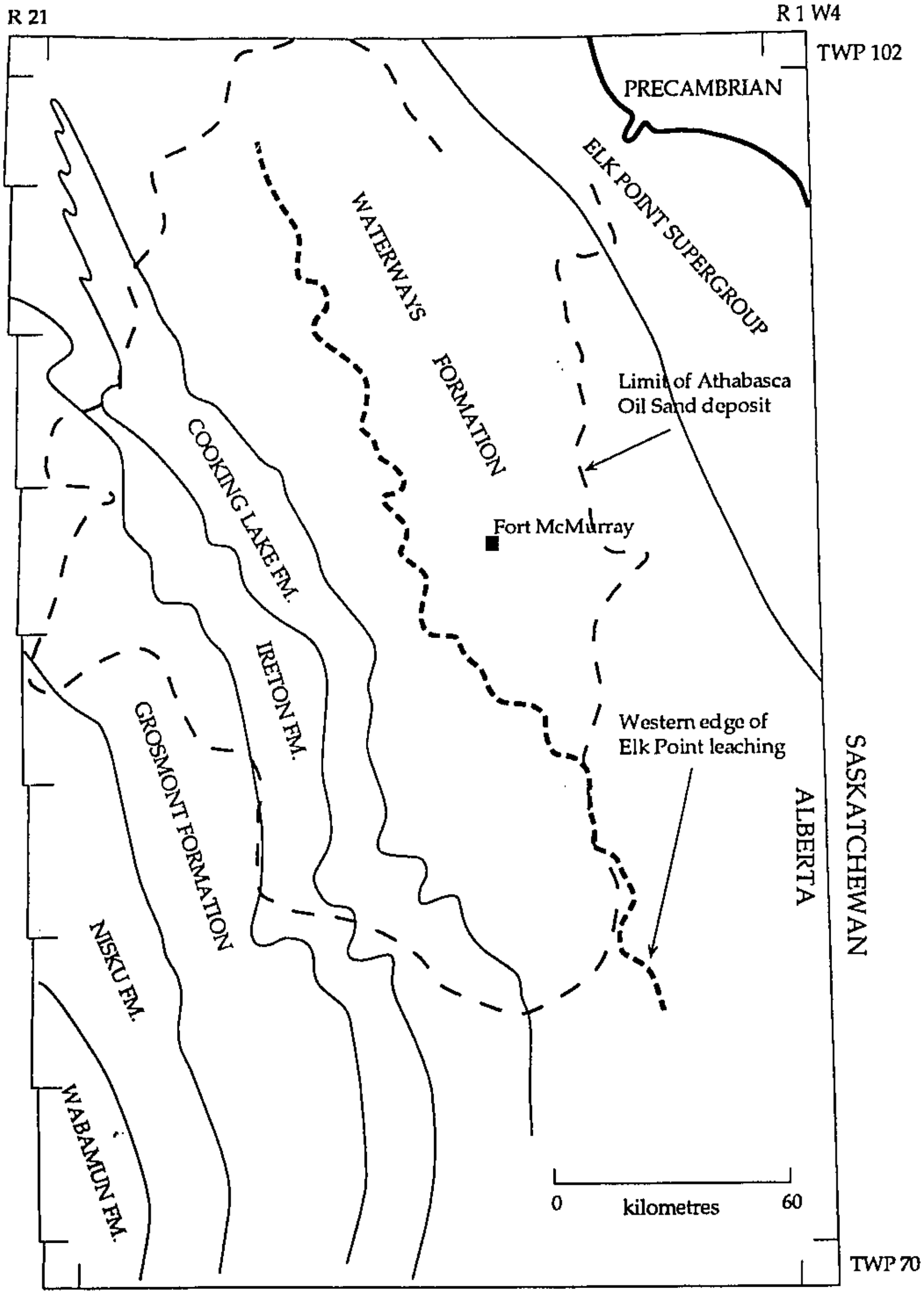

Figure 3. Subcrop map of Devonian strata at the sub-Cretaceous unconformity with outline of Athabasca oil sand deposit and westen edge of Elk Point leaching (modified from Stewart, 1963; Norris, 1973).

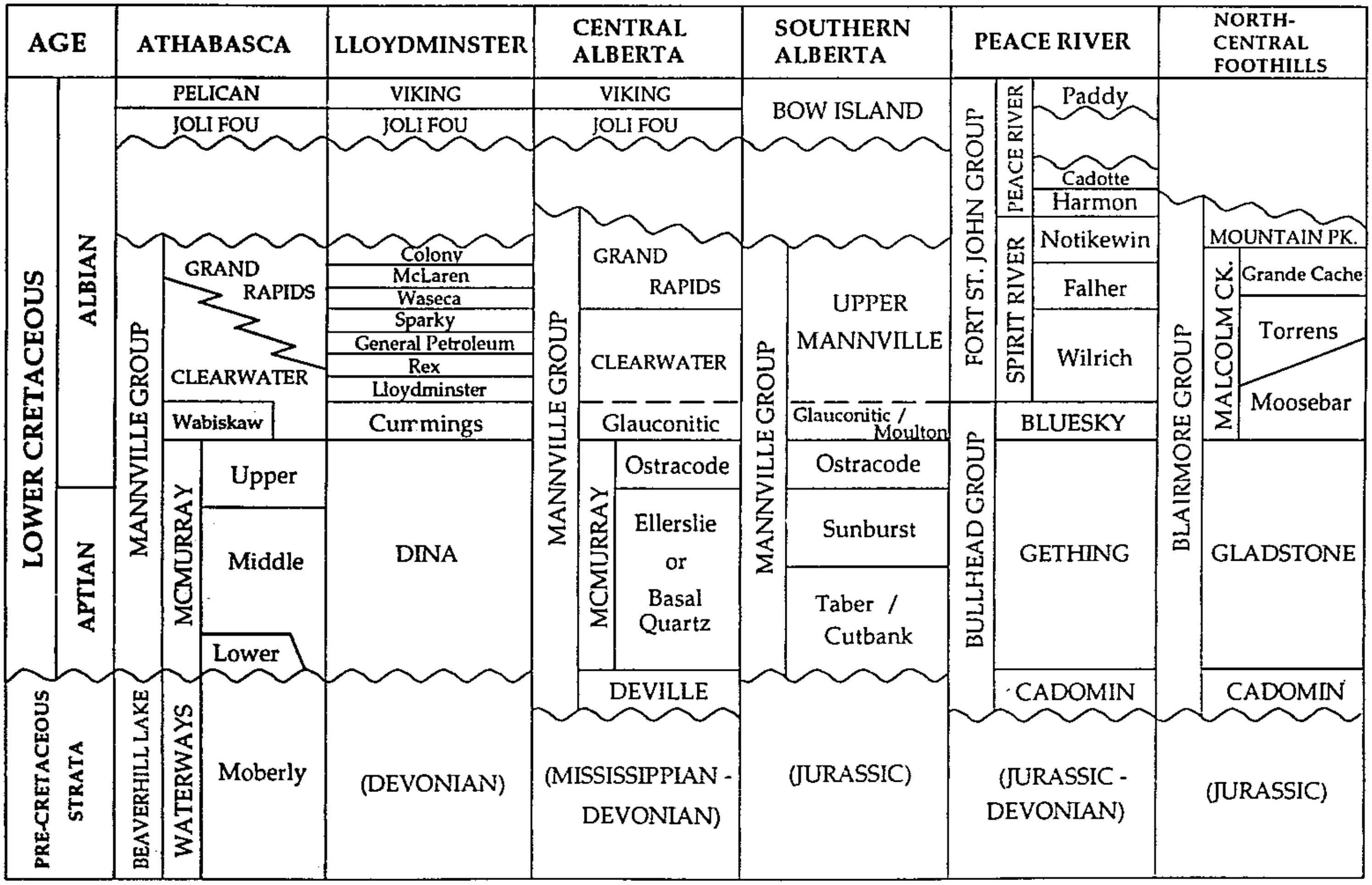

Figure 4. Stratigraphic correlation chart of the Lower Cretaceous in Alberta (from Yuill, 1995). Parentheses indicate ages, not formation names.

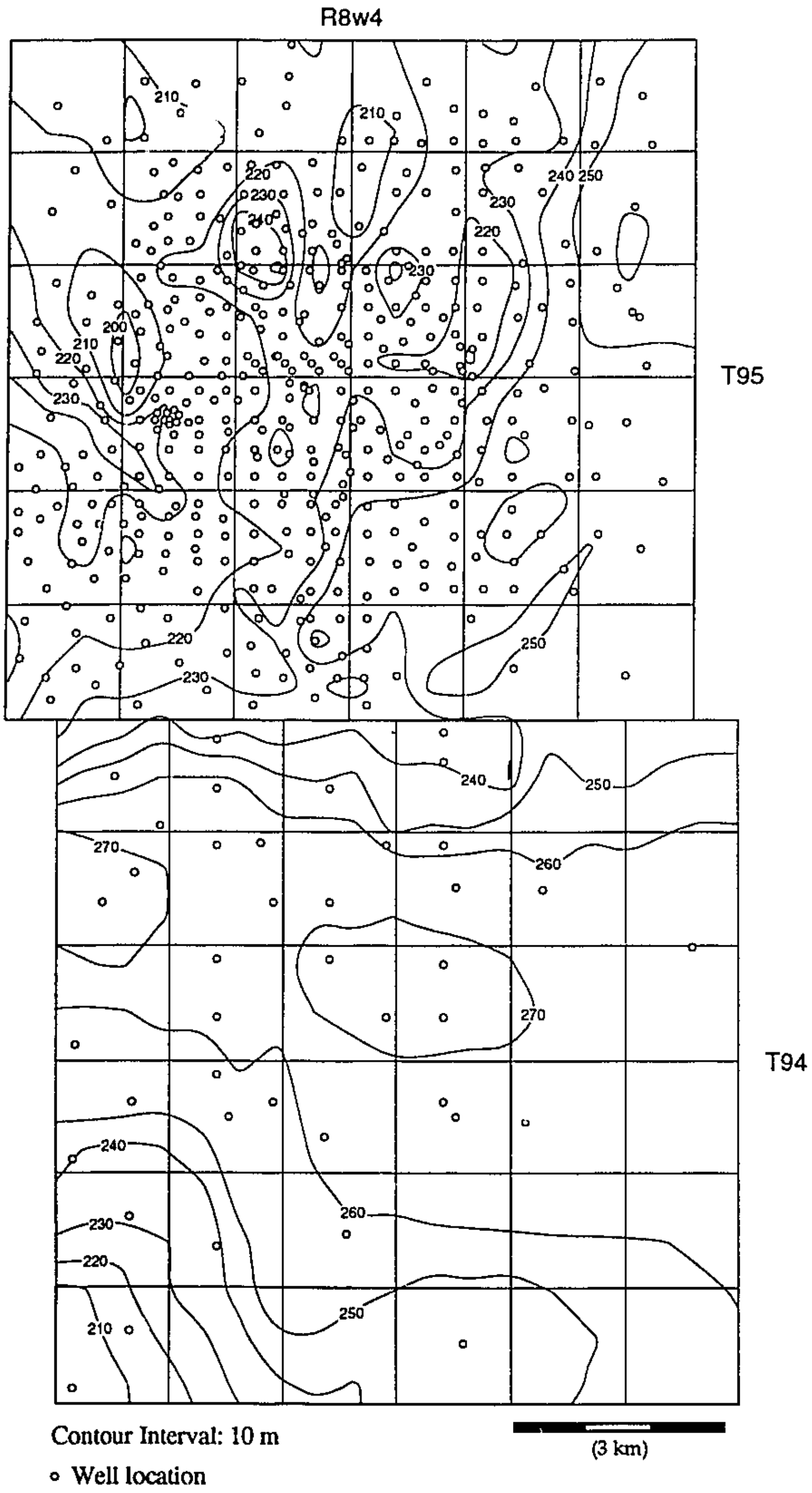

Figure 5. Structure of the sub-Cretaceous unconformity within the O.S.L.O. area

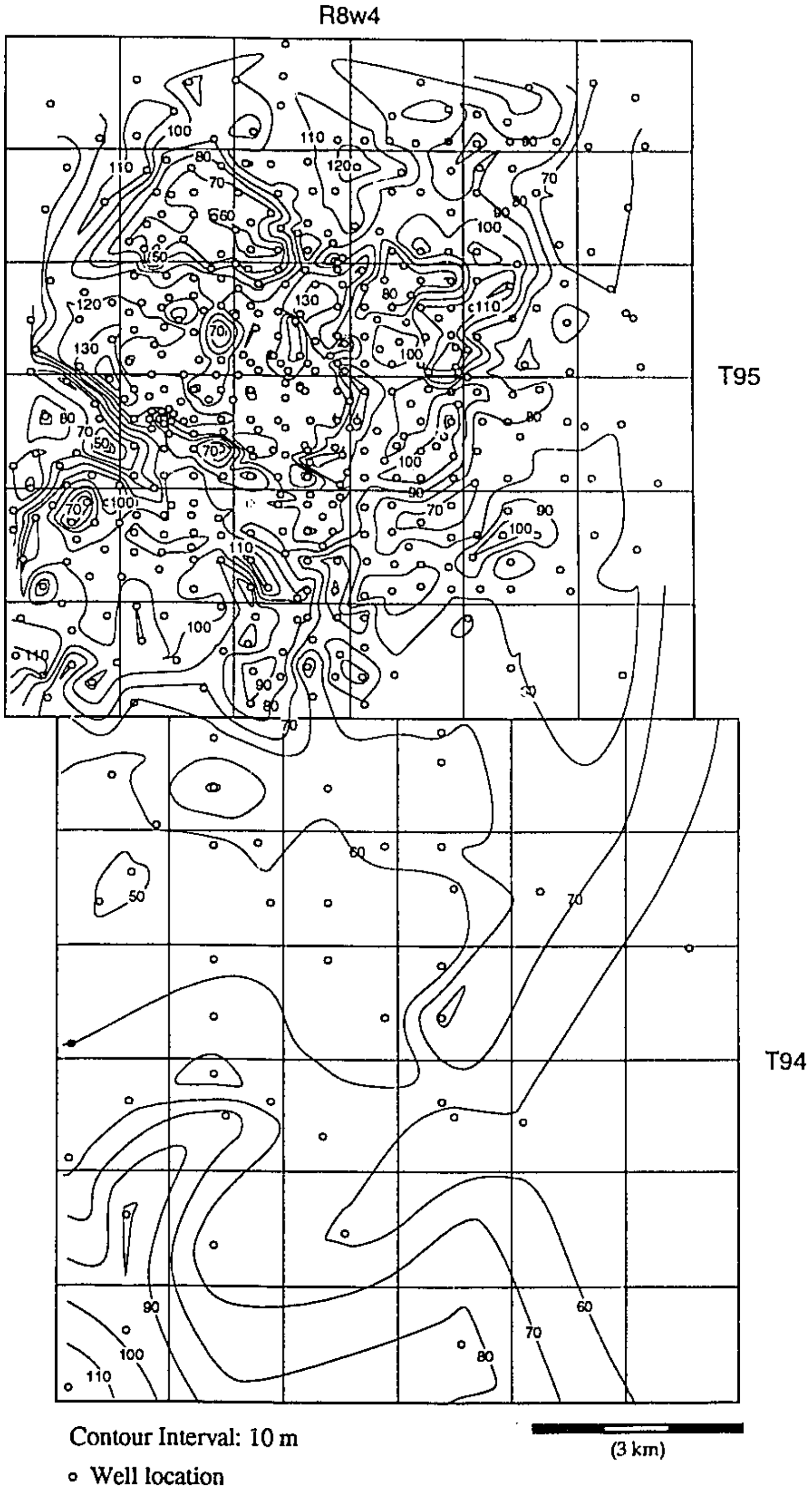

Figure 6. Isopach map of the McMurray Formation within the O.S.L.O. area.

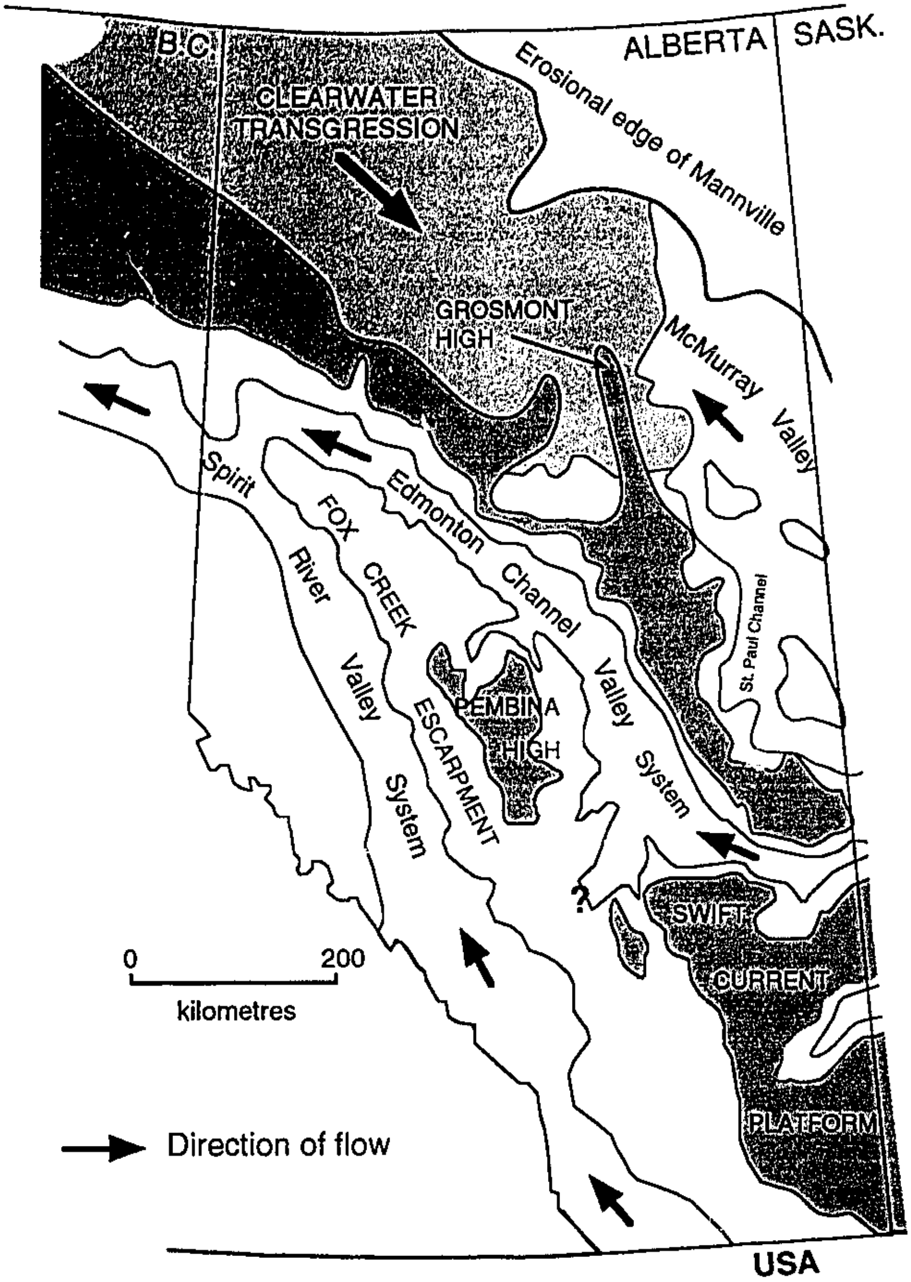

Figure 7. Lower Cretaceous paleotopography prior to depostion of the Mannville (modified from Fox, 1988; Ranger 1994).

Chapter 2 - Facies Description and Interpretation

Characteristic groupings of sedimentological features of the McMurray Formation and Wabiskaw Member has resulted in the identification of facies. The facies may have a combination of sedimentological and ichnological characteristics. That is, an abundantly burrowed sand facies is separate from a unburrowed sand facies. Certain sedimentological features may be common to several facies. For example, small-scale cross-stratification is a single facies when it occurs exclusively over a sufficient interval and it is also a feature of several other facies. In addition, for ease of understanding the interpretation the facies have been grouped into genetically-related associations. This chapter will present the observed features and interpretation of each facies; the succeeding chapter will interpret the facies associations.

Facies Association 1 (FA1) - Fining-upward sandy association

The fining-upward sandy association (FA1) is found throughout the McMurray Formation within the study area, but is typically found within the lower and middle McMurray members. The middle McMurray member is composed entirely of FA1.

The association is made up of six facies: large-scale cross-stratified sand (F1), small-scale cross-stratified sand (F2), sand-dominated inclined heterolithic stratification (F3), mud-dominated inclined heterolithic stratification (F4), massive grey mud (F5), and flat lying, thinly interbedded sand and mud (F6). The lower contact of this facies association is sharp, with indications of scouring. The facies association is commonly preserved as repeating, stacked cycles of its constituent facies with variable degrees of individual facies preservation. That is, facies capping the cycles within the association are commonly eroded by subsequent cycles. Other than the sharp contacts at the base of these cycles, contacts between facies of FA1 are commonly gradational. The upper contact of this facies association is typically sharp and commonly shows indications of erosion.

Facies 1 (F1) - Large-scale cross-stratified sand

Description:

Facies 1 is characterized by large-scale cross-stratified sand, and is present within the study area with various degrees of bitumen saturation. "Large-scale" is used here to refer to cross-strata sets that exceed the width of the core and individual units exceeding 5 cm in thickness. Cross-strata sets range in thickness from 5 cm to greater than 75 cm (maximum length of a single core), with an average thickness of about 40 to 50 cm. Individual cross-strata range in thickness from 0.5 cm to 3 cm, with an average of about 1 cm. The individual cross-strata are recognized due to grain size variations and the resulting differential bitumen saturation. The cross-strata dips range from 5° to 30°, with an average dip of about 15°, with cross-strata dip reversals between adjacent sets being relatively common (Fig. 8a-c).

Grain size within this facies can vary within individual cross-strata, within cross-strata sets, within cross-strata cosets, and stratigraphically throughout the McMurray Formation. Grain sizes range from upper fine sand to pebbles. Individual cross-strata commonly have normal (fining-upward) grading, though uniform grain sizes within a single cross-strata can also be observed. The coarser grains (coarse sand to pebbles) are typically found in the lower cross-strata of a set, in the lower sets of a coset, and in the lower and middle McMurray Formation members. The pebbles and granules typically occur as dispersed grains. Upper portions of these large-scale cross-stratified units are moderately to well sorted and are mainly upper fine in grain size. Large-scale cross-stratified sands are commonly upper fine-grained in the upper member of the McMurray Formation.

Within this facies, cross-strata within a set commonly parallel the lower bounding surface of the set. Within smaller sets, the cross-strata intersect the lower surface tangentially, with the angle of inclination of cross-strata increasing towards the top of the set. Locally, the cross-strata will intersect the lower bounding surface at a sharp angle.

Mud laminae are commonly found interstratified within this facies. The mud may be present as a single mud laminae or as interlaminated mud and sand. The contact with the underlying large-scale cross-stratified sand may be sharp, gradational, or, rarely, burrowed. The muds appear to drape the underlying sands conformably. The occurrence of the mud laminae increases upward in a large-scale cross-stratified unit.

Mud and interlaminated sand and mud intraclasts are common in this facies (Fig. 8c). The intraclasts are typically aligned with the surrounding cross-strata, are angular to subrounded, and make up 5% to 40% of the large-scale cross-stratified sand. Units containing intraclast contents of 40% and higher are delineated as the subfacies "mud intraclast breccia" (F1a). The mud intraclasts are commonly found in the upper portion of a large-scale cross-stratified unit and in association with the sand-dominated inclined heterolithic stratification (F3). Intraclasts vary in size from 0.5 cm to greater than 10 cm (long axis), with an average size of about 5 cm. As larger intraclasts exceed the size of the 6 cm core it is difficult to discern large imbricated clasts from interbedded units of other facies. The intraclasts appear to be made up of the same lithologies as sand-dominated inclined heterolithic stratification (F3), mud-dominated inclined heterolithic stratification (F4), and grey mud (F5).

A variety of other features are commonly found within this facies throughout the McMurray Formation. Abundant carbonaceous debris and common coal fragments conformably drape the cross-strata of this facies. It is these dark laminations of carbonaceous debris that delineate the upper fine-grained portion of the cross-strata. Common coal laminae are typically discontinuous across the width of the core, supporting an allochthonous origin. Wood fragments up to 3 cm thick, including an example with preserved growth rings, are present locally. Rounded to subrounded elongate mud intraclasts typically less than 1 cm in length are found in association with these coal and wood fragments. Shell fragments are also present locally. In the lower member of the McMurray Formation, limestone clasts, with lithologies the same as the underlying Devonian, and with lengths exceeding the core diameter are present.

This facies can be found above most of the other facies defined in this study. Basal contacts are typically sharp with indications of scour. Commonly, underlying lithologies are present in the lowest portion of this facies. It is also common to find coal fragments, pebbles, carbonaceous debris, and pyritized mud intraclasts immediately above these contacts. Flat or wavy contacts are present as well. This facies is commonly gradationally overlain by mud intraclast breccia (F1a), small-scale cross-stratified sand (F2), or sand-dominated inclined heterolithic stratification (F3), and locally, is found intercalated with laminated to burrowed sand (F12) within the upper McMurray Formation.

Ichnology:

Bioturbation is virtually absent within the sands of this facies. Some burrows can be recognized within the mud laminae of this facies within the middle and upper members of the McMurray Formation. *Planolites* and *Cylindrichnus* may be present in the mud laminae. Some *Cylindrichnus* may be found within the cross-stratified sands, but these are likely to have subtended from a mud laminae that was removed by subsequent erosion, preceding renewed sand depositional processes. Both the *Planolites* and *Cylindrichnus* present are simple morphologic forms with diameters of less than 1 cm.

Interpretation:

Facies 1 is interpreted to have been deposited within fluvial to estuarine channels. The large-scale cross-stratified sand was deposited as the result of migration of two-dimensional (straight-crested) and three-dimensional (linguoid or lunate) subaqueous dunes on which cross-strata are deposited as the result of deposition as foreset laminae on the slip face (lee face) of the dune. The term "dune" includes both the 2-D and 3-D bedforms previously referred to as megaripples (Reineck and Singh, 1980; Harms *et al.*, 1982). 2-D megaripples have also been referred to as sand waves and 3-D megaripples have been referred to as dunes (Reineck and Singh, 1980).

Three-dimensional bedforms result in different cross-stratification than 2-D bedforms. Differentiating in core whether large-scale cross-stratification is the result of 2-D bedforms or the result of 3-D bedforms can be problematic. Straight-crested (2-D) dunes result in tabular cross-stratification (Harms and Fahnestock, 1965). Trough cross-stratification is the result of migration of linguoid (3-D) dunes. In this study, trough cross-stratification is recognized where cross-strata are curved and meet the lower bounding surface tangentially and angle of inclination of cross-strata increases towards the top of the set. This reflects the preservation of toesets to foresets during bedform migration. It is the predominant form found within Facies 1. Tabular cross-stratification is recognized where cross-strata intersect the lower bounding surface at a steep angle.

Dunes are deposited within the lower flow regime where resistance to flow is large and sediment transport is relatively small (Reineck and Singh, 1980). Straight-crested (2-D) dunes form within the lower part of the lower flow regime while linguoid (3-D) dunes form within the upper part of the lower flow regime (Reineck and Singh, 1980; Harms and Fahnestock, 1965).

There is abundant evidence within F1 of fluctuating flow energies. Carbonaceous debris, wood fragments, and mud intraclasts were likely deposited within the scours at the toesets of subaqueous dunes. The mud intraclasts must have undergone transport, particularly where they are small and rounded. Flow must have waned to allow deposition of this lighter material. The presence of mud laminae indicates sufficient decreases in flow velocities to allow deposition from suspension. The gradational nature of the transition to small-scale cross-stratification (F2) indicates a waning flow regime.

The larger (0.5 to 10 cm) intraclasts found within this facies reflect the erosive nature of this depositional environment, likely associated with fluctuating flow regimes. The angular nature of these clasts suggest little or no transport (Smith, 1972). These intraclasts have lithologies similar to other facies associated with F1. Incorporation of these clasts within this facies will be discussed as part of the discussion of Facies Association 1.

The limited bioturbation within this facies is indicative of the nature of the environment in which the unit was deposited. The constantly shifting nature of the substrate of this relatively high energy environment and persistent avalanching of sand on the bedform slip face may have prevented significant colonization by benthic organisms and inhibited preservation of their biogenic structures.

Within the middle and upper members of the McMurray Formation, lower energy portions of this facies, highlighted by the presence of mud drapes, may have small, morphological simple forms as part of a low diversity assemblage. This is indicative of stressed environmental conditions, consistent with brackish water conditions and contrasts markedly with a high diversity marine trace fossil assemblage. The lower member examples of this facies are completely devoid of trace fossils. This is likely an indication of a greater influence of freshwater or fluvial conditions (Pemberton and Wightman, 1992) during deposition of the lower McMurray Formation.

Subfacies (F1a) - Mud intraclast breccia

Description:

Mud intraclast breccia is defined as a subfacies of large-scale cross-stratified sand (F1) due to its similarity to F1. The only variation is the amount of mud intraclasts within a matrix of fine to coarse sand (Fig. 8d). Units with mud intraclast contents exceeding 40% are delineated as F1a. The subfacies is typically found in association with the upper portions of large-scale cross-stratified sand (F2) units. Not surprisingly, it is commonly found in gradational contact with F1 with high mud intraclast content. Intraclast composition for this subfacies is the same as that described for F1.

Ichnology:

The ichnology of this subfacies is the same as large-scale cross-stratified sand (F1).

Interpretation:

F1a is interpreted to have been deposited in a environment similar to large-scale cross-stratified sand (F1). The only variation from F1 is the nature of clast deposited; F1a has a higher content of intraclasts of associated facies. Since the angular nature of these clasts suggest little or no transport (Smith, 1972) and F1a contains more intraclasts it is therefore interpreted to be closer to the clast source. Due to its obvious association with other facies, a more complete interpretation of this subfacies will be discussed as part of the discussion of Facies Association 1.

Facies 2 (F2) - Small-scale cross-stratified sand

Description:

Facies 2 is characterized by small-scale cross-stratified sand. It generally has a very high degree of bitumen saturation. F2 is found throughout the McMurray Formation, but is predominantly found within the lower and middle members. The term "small-scale" is used since the cross-sets are typically less than 5 cm thick. Similar sedimentary structures may be found within other facies, but F2 is composed exclusively of small-scale cross-stratification.

F2 is well-sorted, very fine- to fine-grained sand. The nature of the stratification is dependent on the orientation of the slabbed surface of the core. As a result, the cross-beds may appear tabular or trough-shaped. Tabular forms are planar cross-stratified with nearly parallel, commonly inclined, bounding surfaces. Within a coset, cross-strata typically dip in the same direction (Fig. 9a,b). Trough-shaped forms have concave-upward lower boundary surfaces and truncated upper surfaces. Cross-strata within a cross-strata set parallel the lower bounding surface. Carbonaceous debris is a common component of the fine-grained laminations. Examples of wavy and flaser bedding are commonly associated with F2 (Fig. 9b). Mud laminae are also present within this facies.

The facies is commonly found in gradational contact with large-scale cross-stratified sand (F1) and both sand-dominated (F3) and mud dominated (F4) inclined heterolithic stratification. It may also have sharp contacts with a number of other facies.

Ichnology:

Bioturbation within Facies 2 is rare to absent. Escape structures and *Conichnus* can be present within the sand. Mud interlaminae associated with the sand beds may contain *Planolites*, *Palaeophycus*, *Skolithos*, and *Cylindrichnus*.

Interpretation:

Facies 2 is interpreted to have been deposited through two processes within an estuary channel: 1) under waning flow conditions on larger channel bedforms and 2) on point bar surfaces. Small-scale cross-stratification is the result of the migration of ripples (Harms and Fahnestock, 1965), and can be referred to as ripple bedding. Tabular-shaped sets of ripples are the result of viewing the ripples in a vertical section that is parallel to flow direction. Trough-shaped sets are the result of viewing the ripples in sections perpendicular to flow.

Small-scale cross-stratification (ripple bedding) can be produced by wave action, current flow, or a combination of the two. Determination of the process responsible for the ripple generation is useful in identifying the depositional environment. The observed ripple bedding of this study lacks the features of wave ripples as described by Reineck and Singh (1980). Therefore the ripple bedding of F2 is interpreted to be the result of current flow or combined flow. Cross-laminations within the ripples indicates sediment transport and bedform migration associated with current ripples. Current ripples dominate the observed ripple structures. Combined flow ripples (asymmetrical oscillation ripples) are also present. Combined flow ripples are the result of migration of a wave ripple as the result of an imbalance of oscillatory flow or imposition of a current on the oscillatory flow (Harms *et al.*, 1982). The fluctuating nature of flow responsible for combined flow ripples is consistent with the tidal processes associated with estuarine conditions. Standing water conditions associated with tidal slacks allows for the development of waves.

Small-scale cross-stratification forms under the lower part of the lower flow regime (Harms and Fahnestock, 1965; Reineck and Singh, 1980). Such conditions are present within estuarine channels. During waning flow conditions, possibly associated with the onset or termination of the slack period of the tidal cycle, or with falling water levels during ebb tide, smaller scale bedforms develop on top of larger bedforms. Harms and Fahnestock (1965) observed small-scale cross-stratification, formed during emergence, as a layer mantling large scale-cross-stratification within the Rio Grande River. Small-scale cross-stratification may also form during high tide cycles where flood tide has inundated the upper portions of a point bar. Mud laminae within F2 are another indication of fluctuating flow conditions as slack water allows suspension deposition of the mud.

Facies 2 has a trace fossil assemblage similar to that of F1 and again reflects the unstable and shifting nature of the substrate. The low diversity, stressed assemblage present in the facies is attributed to brackish water conditions (Pemberton and Wightman, 1992).

Facies 3 (F3) - Sand-dominated inclined heterolithic stratification

Description:

Facies 3 is characterized by inclined, thickly interbedded to finely interlaminated sand and mud (Fig. 10b). This facies is more common within the middle member than in the upper and lower members of the McMurray Formation. The apparent degree of inclination of the strata is dependent upon the angle at which the core was slabbed, with the highest angles associated with sections paralleling deposition dip. The strata have apparent angles of dip varying from 0-15°. The term "inclined heterolithic stratification" (IHS) is adopted from Thomas *et al.* (1987) which was used to replace "epsilon cross-stratification" (ECS) of Allen (1963). Sand-dominated IHS is an end member of a continuum which has mud-dominated IHS (Facies 4) as its counterpart. For this study, IHS is termed "sand-dominated" if the sand interbeds comprise 50% or greater of the facies. F3 has internal scour surfaces where distinct changes in the sand to mud ratio above and below such contacts are visible.

The facies comprises medium- to thickly-interbedded sand and mud. The interbedding occurs as normally graded "couplets", with sharp-based sand (coarse layer) either grading into or passing abruptly into overlying mud or interlaminated sand and mud (fine layer) (Fig. 11c). Thomas *et al.* (1987) used the term "member" to describe these layers. Due to its stratigraphic significance "member" will not be used within this study. The descriptive term "layer" will be used. Contacts between underlying sands and overlying muds may be burrowed. Sand interbeds are typically 7-30 cm in thickness, but may be up to 70 cm thick. Mud interbed thicknesses typically vary from 1-20 cm, though they may reach 30 cm thick in exceptional cases. Synaeresis cracks are locally present.

The coarse layer of the couplets typically consists of small- to large-scale cross-stratified fine to very fine sands. Large-scale trough and tabular cross-stratification, ripple (small-scale) cross-stratification, and flat to low angle planar stratification (Fig. 11a) are visible where sufficiently low bitumen saturations allow identification. Mud intraclasts from underlying couplets are commonly incorporated within the coarse layer.

The fine layer of the couplet is either massive grey mud or mud interlaminated with sand or silt (Fig. 11b). The massive grey mud beds can reach thicknesses of 30 cm, but are typically 5-10 cm thick. Interlaminated mud and sand or silt has wavy and/or lenticular bedding.

F3 generally has gradational upper and lower contacts, although sharp contacts are also present locally. The facies typically overlies large-scale (F1) and small-scale (F2) cross-stratified sand and commonly passes into overlying mud-dominated IHS (F4).

Ichnology:

Bioturbation intensity within Facies 3 typically varies from rare to common, with some thin monospecific horizons resulting in an abundant degree of burrowing. Burrows are typically found within the fine layer or subtending from it into the underlying coarse layer. Trace fossils include: *Cylindrichnus*, *Planolites*, *Gyrolithes*, *Teichichnus*, *Skolithos*, *Palaeophycus*, *Arenicolites*, and fugichnia (escape structures). Fugichnia are found within the sand interbeds.

A characteristic feature of the sand-dominated IHS is the abundance of monospecific assemblages of *Cylindrichnus*, *Planolites*, or *Gyrolithes* (Fig. 11d-f). That is, within certain beds, each of these trace fossil genera can be found to the exclusion of the other forms. Sand-filled, sharp-walled *Planolites* with a significant and observable vertical component are commonly found within mud interbeds of the fine layer (Fig. 11e). The *Planolites* appear to subtend into the mud from an overlying sand bed. The number of burrows decrease away from the sand-mud contact. The *Planolites* assemblage is most common in otherwise weakly burrowed examples of this facies, within the lower portion of the middle McMurray.

The vertical component of *Cylindrichnus* and mud-filled *Gyrolithes* define a preferred burrow fabric. The long axis of burrows show a common orientation, which is typically perpendicular, to the IHS bedding planes. Burrowing intensity within these beds is abundant. Two forms of *Gyrolithes* have been observed within the study area. The distinction between the two forms is in their radius of spiral to length ratio. Informally named for this study, *Gyrolithes* Type I has a higher radius of spiral to length ratio and greater shaft diameter, giving it a more robust appearance, and is present within sand-dominated IHS (Fig. 11c, f). *Gyrolithes* Type II will be described with mud-dominated IHS (F4).

Interpretation:

Sand-dominated inclined heterolithic stratification is interpreted to represent lateral accretion deposits associated with tidally-influenced point bars of a meandering estuarine channel. The most distinctive feature of this facies is the regular (cyclic) alternation of coarser- and finer-grained units (layers). The coarse layer is interpreted to be the result of traction bedload deposition associated with higher flow velocities, while the fine layer is the result of deposition from suspension during periods of lower flow conditions (Thomas *et al.*, 1987). The sedimentary structures of the coarse layer (sand) indicate deposition predominantly under lower flow regime current conditions (trough and tabular cross-stratification and ripple lamination), with rarer examples of upper flow regime conditions (planar stratification). The nature of the fluctuations in flow conditions are indicated by the nature of the contacts between layers. The sharp contacts may indicate rapid changes in flow velocities or erosion of the underlying layer. Gradational contacts indicate a gradual change in flow velocities, typically waning.

IHS has been interpreted to be the result of point bar deposition on the inclined surface of a point bar within a meandering channel (Allen, 1963; Mossop and Flach, 1983; Thomas *et al.*, 1987; Smith, 1987; Rahmani, 1988). In their discussion of IHS, Thomas *et al.* (1987) reported that in the majority of studies, IHS is interpreted to be the result of lateral migration of point bars.

Inclined heterolithic stratification has been interpreted within the McMurray Formation to have been deposited under fluvial (Mossop and Flach, 1983; Flach and Mossop, 1985) and estuarine (Smith, 1987, 1988a; Ranger and Pemberton, 1992; Bechtel *et al.*, 1994) conditions. It is therefore necessary to discuss the evidence for tidal influence in both sedimentological and ichnological terms.

Sedimentologically, this facies demonstrates the cyclic nature of tidally influenced deposits. Nio and Yang (1991) stated that the cyclicity of tidal deposits constitutes their most characteristic feature. The alternation of sharp-based sand and overlying mud indicates the fluctuating nature of the flow velocities. The interbedding of sand and mud, though not quantified for this study, appears to be predominantly rhythmic rather than random. Sand beds would have been deposited by higher energy flow conditions associated with ebb and/or flood periods of the tidal cycle while muds would have been associated with the intervening slack water periods (Fox, 1988). Sand beds and thin mud laminae may have been deposited during a single tidal cycle. Thicker mud beds, however, are difficult to reconcile to single slack water periods. They may be the result of multiple low energy cycles associated with neap tide periods or to suspension deposition following a flood event.

Angular rip-up clasts and intraclasts of fine layers (mud) may indicate the fluctuating nature of water levels within the channel. Muds deposited during high water levels (flood or spring tides) are exposed during low water levels (ebb or neap tides) and are allowed to consolidate and desiccate. Subsequent flood tide conditions may then erode and transport the mud as rip-up clasts. The angular nature of these rip-ups suggests short transport distances (Smith, 1972).

Synaeresis cracks support the cyclic nature of this depositional environment, as well as provide evidence for a marine water influence. In general, synaeresis cracks are regarded to form as the result of fluctuations in salinity (Burst, 1965). Such salinity variations are favoured within settings subject to both fluvial and marine influences, such as an estuary.

The trace fossil assemblage of F3 clearly demonstrates the influence of brackish water conditions. Thomas *et al.*, (1987) suggested that the recognition of trace fossils is the single most significant criteria for distinguishing tidally influenced IHS from fluvial IHS. Brackish water environments produce a trace fossil assemblage with the following distinct characteristics (Wightman *et al.*, 1987; Benyon and Pemberton, 1992; Pemberton and Wightman, 1992; Ranger and Pemberton, 1992): 1) due to the stressed conditions, trace fossils are typically smaller than their fully marine counterparts; 2) the trace fossils are typically restricted to morphologically simple forms; 3) low diversity, including locally monospecific assemblages; 4) high abundances; and 5) in fluctuating energy conditions, producing substrates of variable consistency, a combination of traces from both *Skolithos* and *Cruziana* ichnofacies. Examples of F3 trace fossils commonly associated with the *Skolithos* ichnofacies (Pemberton *et al.*, 1992b) include: *Skolithos*, *Arenicolites*, and *Palaeophycus*. *Teichichnus*, *Cylindrichnus*, and *Planolites* are typically associated with the Cruziana ichnofacies (Pemberton *et al.*, 1992b). Facies 3 trace fossils generally associated with brackish water conditions (Pemberton and Wightman, 1992) include: *Skolithos*, *Planolites*, *Palaeophycus*, *Teichichnus*, and *Gyrolithes*. Fugichnia reflect episodic deposition commonly associated with settings dominated by fluctuating energy conditions.

The cyclic nature of the environment in which F3 was deposited is clearly supported by the trace fossil assemblage. The monospecific assemblages of *Cylindrichnus* and *Gyrolithes* represent opportunistic colonization of the substrate following an environmental stress (Fig. 11d, c). The stress on the benthic population may result from several possible events, including: turbidite deposition, oxygen deficiencies, storm deposition, or salinity variations (Pemberton *et al.*, 1992a). Pemberton *et al.* (1992a) discussed the trace fossil assemblage associated with storm deposits. The assemblage is distinguished by a laminated storm deposit of sandstone with a trace fossil assemblage limited to biogenic structures accredited to opportunistic colonists and escape structures. The opportunistic organisms, displaying a r-strategy in population dynamics, colonize the substrate after a disturbance and dominate until the fair-weather population can become established again. The fair-weather community, displaying an equilibrium K-strategy, results in a more diverse trace fossil assemblage. The r-strategy of population dynamics represent organisms that emphasize rapid growth and reproduction, while the K-strategy is dependent on the carrying capacity of the environment (Pemberton *et al.* 1992a). *Cylindrichnus* and *Gyrolithes* are interpreted to be the dwelling structures (domichnia) of such opportunistic organisms. The high energy event that imposed the physical stress on this facies was unlikely to have been a storm event, but rather a high energy depositional event associated with a strong tidal current within the estuarine channel or to a fluvial flooding event. The coupling of these physical stresses such as salinity fluctuations or periodic subaerial exposure (*e.g.* low tide) probably accounts for the general absence of a competitive equilibrium assemblage in F3. The cyclic nature of these events results in the repetition of monospecific assemblages observed within this facies.

Marginal marine organisms which are continually subjected to relatively high physiological stress (r-selected), such as those living in the unpredictable environment of an estuary must have broad environmental tolerances (Pemberton *et al*, 1992a). Benyon and Pemberton (1992) suggest that salinity levels are the limiting control on bioturbation intensity and trace fossil distribution in the Grand Rapids Formation (Mannville Group) within the Cold Lake oil sands deposit.

Gyrolithes, while present within other facies, is a distinctive constituent of the trace fossil assemblage of F3. Gernant (1972) suggested that *Gyrolithes* is an indicator of marginal marine depositional environments. Benyon and Pemberton (1992) assigned their "*Gyrolithes* Association" to the stressful environment associated with brackish water conditions. The *Gyrolithes* Type I found within F3 displays a more robust appearance than the form found within F4. This may be the result more stable conditions within the deeper portions of the estuarine channel.

The monospecific *Planolites* assemblage found within this facies is further evidence of the cyclic, fluctuating nature of this depositional environment. These unlined burrows could not be maintained within soft muddy substrates, yet they occur within the mud interbeds of the fine layer of the IHS couplets (Fig. 11e). The sharp-walled nature of the burrows suggest that the substrate was cohesive at the time of excavation. In addition, the sand infill appears to be structureless and therefore is interpreted to be the result of passive infilling during deposition of the overlying sand bed. These features are consistent with traces fossil belonging to the *Glossifungites* ichnofacies (MacEachern *et al.*, 1992b) where a depositional hiatus, typically accompanied by subsequent erosion, provides the firmground substrate into which the burrows are excavated. Keith *et al.* (1988) reported similar occurrence of the *Glossifungites* ichnofacies within the McMurray Formation. The contacts at the top of the mud beds of the IHS are not be assigned the stratigraphic significance commonly associated with the *Glossifungites* ichnofacies (MacEachern *et al.*, 1992b), but a short depositional hiatus associated with autocyclic fluctuations attributable to a dynamic environment. Low water levels, associated with a low tide or neap tide, allow the muds to be dewatered and become cohesive. Subsequent submergence allows colonization by opportunistic organisms, deposition of the overlying sand bed, and passive sand infill of the burrows.

The strong vertical component of these traces is atypical for *Planolites*, a feeding structure (fodinichnia) with a predominantly horizontal attitude. The trace fossil may be better defined as a simple inclined shaft, some displaying a u-shaped morphology (?*Arenicolites*). As a result, it may in fact be a dwelling structure (domichnia) of an opportunistic organism which is consistent with the behavior of other traces found within this facies.

In summary, F3 was deposited in brackish water under cyclically fluctuating energy conditions, as demonstrated both sedimentologically and ichnologically. The most likely depositional environment for such features correspond to lateral accretion associated with tidally-influenced point bars of a meandering estuarine channel. Those examples of this facies that have to rare to no bioturbation will be discussed as part of the interpretation of F4.

Facies 4 (F4) - Mud-dominated inclined heterolithic stratification

Description:

Mud-dominated IHS constitutes the fine-grained end member in a continuum with sand-dominated IHS (F3). This facies is characterized by inclined, thin- to medium-scale, interbedded to interlaminated sand and mud (Fig. 10a). For this study, IHS is termed "mud-dominated" if the sand interbeds comprise less than 50% of the facies. The strata have apparent angles of dip varying from 0 - 12°.

Like sand-dominated IHS, this facies comprises of sand and mud couplets and more rarely, interlaminated silt and mud couplets. The coarse layer of the couplet is typically sharp-based, and grades into the fine layer. Contacts between underlying sand and overlying muds are locally burrowed. Sand interbeds are typically 3 - 5 cm in thickness, but may be up to 15 cm thick. Mud interbeds vary from 1 - 10 cm in thickness, but locally up to 20 cm thick.

The coarse layer of the couplets typically consists of small-scale cross-stratified, well-sorted, fine to very fine sands. The fine layer of the couplet is either thinly laminated mud (Fig. 12a) or more rarely, interlaminated sand and mud. Micro-faulting, with displacements of less than 2 cm, is present within this facies. Synaeresis cracks, infilled with sand from overlying sand beds, are also present.

F4 has gradational upper and lower contacts, although sharp contacts are locally present. The facies typically overlies sand-dominated IHS (F3), although locally, directly overlies large-scale cross-stratified sand (F1), and small-scale cross-stratified sand (F2). Facies 3 commonly passes upward into either grey mud (F5) or flat-lying, thinly interbedded sand and mud (F6).

Ichnology:

Mud-dominated IHS (F4) varies from unburrowed to abundantly-burrowed, but is typically moderately-burrowed. The variation from unburrowed to abundantly-burrowed sand and mud is a distinctive feature of F4 (Fig. 12a, c). Completely bioturbated beds of sandy mud are intercalated with unburrowed mud with sand interlaminae. Each layer of these burrowed/unburrowed cycles are 5-8 cm thick. The burrowed layer may contain a monospecific assemblage of *Teichichnus* (Fig. 12c) or *Gyrolithes* (Fig. 12b), or may contain a more diverse assemblage of *Planolites*, *Palaeophycus*, small *Skolithos*, *Teichichnus*, small *Arenicolites*, and *Cylindrichnus*.

The second type of *Gyrolithes* identified within the study area is most commonly found in association with this facies, but may also be found within grey mud (F5). *Gyrolithes* Type II is distinguished from Type I by its lower radius of spiral to length ratio as well as its smaller shaft diameter. This gives *Gyrolithes* Type II a finer, less robust appearance than *Gyrolithes* Type I (Fig. 12b). *Gyrolithes* Type II also lacks the gradual tapering (decrease in radius of spiral with depth) displayed by *Gyrolithes* Type I. The length of the vertical component of the two types is similar.

Interpretation:

Mud-dominated IHS is interpreted to represent lateral accretion deposits associated with tidally-influenced point bars of a meandering estuarine channel, similar to Facies 3. Facies 4 is distinguished from F3 by its higher mud content. As with F3, the facies is characterized by alternating coarser- and finer-grained units (layers) forming heterolithic couplets. The regular alternation of fine and coarse layers is attributed to flow energy fluctuations associated with tidal flux. The interpretation of Facies 3 has a more extended discussion of the evidence of marine and tidal influences on these facies. The discussion here will be limited to those features distinct to Facies 4.

The key feature of this facies is the high mud content. A possible explanation for the fine-grained nature of this facies is the typical fining-upward progression associated with channel point bar deposits (Jackson, 1976; Smith, 1987). Thomas *et al.* (1987) identified seven types of fining trends within a point bar, five of which occur at a scale that may explain the fine-grained nature of F4: 1) overall vertical fining-upward; 2) lateral fining away from the channel axis; 3) lateral fining toward the channel as the result of abandonment; 4) along strike (down-flow) fining associated with the curvature of the point bar; and 5) up-dip fining within individual inclined units. These various fining-upward trends would result in mud deposition in lower energy zones of the point bar. Jackson (1976) identified three depositional models (fully developed, intermediate, and transitional facies) that vary based on their relative position within a mixed-load fluvial channel meander loop. A distinctive variation between the three models is the relative amount of mud capping the fining-upward succession; the mud is thickest within the fully developed facies model (Jackson, 1976). Many muddy IHS deposits (F4) may therefore be the result of deposition within lower energy zones of the point bar.

While the majority of F4 deposition can be explained by processes associated within normal point bar development, the effects of deposition within an estuary can also explain the laterally extensive (laterally correlatable over the entire study area) distribution of this facies. Deposition of mud is a significant component of estuarine systems (Dalrymple *et al.*, 1992). Dörjes and Howard (1975) identified the middle region of the Ogeechee River/Ossabaw Sound tide-dominated estuary as an area with muddy substrates and higher suspended solid contents than the inner and outer regions. In his review of the modern Gironde estuary, a tide-dominated system, Allen (1991) identified a marked decrease in channel sediment grain size as an indicator of the fluvial to tidal transition within that estuary. Dalrymple *et al.* (1992) discuss the tripartite zonation of facies associated with estuaries. In wave-dominated systems the outer zone consists of marine-sourced sand transported landward, a central basin zone of mud, and a fluvial-sourced sand transported seaward.

Two main features of an estuary contribute to the nature of F4: the salt wedge and the turbidity maximum. The salt wedge reflects a hydrologic stratification within the estuary, where more dense, more saline water flows below less dense and less saline water with the boundary between the two constituting an inclined plane sloping landward (Postma, 1967). Such estuaries are thus characterized by the development of a seaward thickening wedge of higher salinity bottom water (the salt wedge). The wedge will shift upstream or downstream in response to the tide (Postma, 1967). The limit of salinity intrusion (landward edge of the salt wedge) provides a control on the distribution of marginal marine infauna. Burrowing will rapidly decrease landward of the salt wedge due to the paucity of fresh water burrowing organisms. Large numbers of trace making organisms are typically limited to the seaward portion of the wedge.

The turbidity maximum is a zone within the estuary with high suspended sediment concentrations (Allen, 1991). Density currents (estuarine circulation) and tidal current asymmetry (time-velocity asymmetry) contribute to the trapping of suspended sediments within the turbidity maximum (Allen, 1991). Estuarine circulation is the result of density differences between marine and fresh water. Due to density gradients, bottom-hugging marine water has a net transport upstream, while the over-riding fresh water has a net transport downstream (Postma, 1967). This results in a stratification of the estuarine waters during periods of sufficient fresh water input such as during high river discharge. Suspended sediments may become trapped in a cyclic circulation as they pass between the two opposing flow patterns. During periods of low river flow, tidal current asymmetry (time-velocity asymmetry) and the associated slack water lags (Postma, 1967) can maintain the turbidity maximum (Allen, 1991). Kranck (1991) argued that flocculation of suspended sediments also contributes to the maintenance of the turbidity maximum by allowing aggregates of smaller grains to form and settle out from suspension. These suspended grains would otherwise be carried out of the estuary. The turbidity maximum also acts as a source of fine-grained, suspension transported sediments that are deposited during slack water periods of the tidal cycle (Allen, 1991).

Variations in the flow conditions within the estuary affects the size and position of the turbidity maximum. During seasons of low river flow the turbidity maximum and its associated mud deposition is displaced landward and extends landward of the upstream edge of the salt wedge. During seasons of high river flow the turbidity maximum is displaced seaward and straddles the limit of salinity intrusion (Allen, 1991). This cyclic process could explain the distinctive variations between burrowed and unburrowed intervals of this facies. During periods of low river flow, mud deposition occurs landward of the salt wedge in waters too fresh for abundant numbers of burrowing organisms. The burrowed units would then be the result of mud deposition occurring with higher salinity conditions conducive to the opportunistic organisms during periods of high river discharge. In a discussion of mudflat channels in Scotland, de Mowbray (1983) concluded that sedimentation on the lateral accretion deposits is principally the result of sedimentation from suspension, and that deposition varies seasonally.

The neap-spring tidal cycle also has an effect on the turbidity maximum (Allen, 1991). During spring tides, higher flow velocities result in the erosion and resuspension of sediment and the turbidity maximum expands. During neap tides, lower flow velocities favor increased suspension deposition and the maximum shrinks (Allen, 1991). This process results in the regular alternation of sand and mud characteristic of this facies.

The trace fossil assemblage within F4 reflects brackish water conditions, for reasons outlined in discussion of F3. Abundantly burrowed intervals are consistent with the observations of Dörjes and Howard (1975) who found the muddy sediments of their 'upper middle' Ogeechee River-Ossabaw Sound estuary to be completely mottled by biogenic processes, with only rare beds retaining visible remnant physical structures. The weakly- to unbioturbated intervals are consistent with Allen's (1991) conclusion that high turbidity and strong tidal currents are responsible for the lack of burrowing present within the "estuarine funnel zone" of the Gironde estuary.

Facies 4 is interpreted to have been to deposited within the low energy environments associated with the lateral accretion deposits of an estuarine channel. The uncertainty of this interpretation lies in determining whether these muddy deposits are the result of a low energy environment associated with a meandering channel and therefore reflect part of the typical fining-upward succession of a tidally-influenced point bar deposit, or whether they correspond to mud deposition within the turbidity maximum of the estuarine environment. The majority of examples of this facies may be a combination of the two.

The occurrence of the second type of *Gyrolithes* found within this facies may represent a response to a more severe depositional environment. *Gyrolithes* Type II (Fig. 12b) has a smaller shaft diameter, a lower radius of spiral to length ratio, and lacks the gradual tapering of the *Gyrolithes* Type I (Fig. 11c). The smaller size likely reflects the relatively higher physiological stress associated with salinity variations and high water turbidity in the middle portion of an estuary. *Gyrolithes* is interpreted to reflect the organism's attempt to escape salinity fluctuations at the sediment-water interface (Benyon and Pemberton, 1992). The lack of tapering and increased depth of penetration (especially relative to shaft diameter) of *Gyrolithes* Type II may reflect the trace-maker's escape capabilities relative to *Gyrolithes* Type I.

Facies 5 (F5) - Grey mud

Description:

Facies 5 is found throughout the McMurray Formation; however, it is most common in the middle member. It is characterized by thinly interlaminated to massive grey mud with a low degree of burrowing. The facies varies in thickness from 0.5 to 5 m, but is typically 1 m thick. The lower contacts of the facies are typically gradational while the upper contacts are typically sharp.

Distinct sedimentary structures are difficult to discern within this facies (Fig. 9d). F5 can be massive, completely lacking any visible sedimentary structures. Other manifestations of the facies include flat to low angle laminated silt and, rarely, very fine sand. The laminations are typically lenticular, but may also be parallel laminated.

Features other than sedimentary structures and trace fossils can be used to recognize this facies. Locally, rooting is present within this facies (Fig. 9d). Siderite is present as a cement and pyrite can be found as nodules.

The facies typically gradationally overlies mud-dominated IHS (F4) and, less commonly, has a sharp basal contact with sand-dominated IHS (F3) and large-scale cross-stratified sand (F1). A variety of overlying facies have a sharp contact with F5.

Ichnology:

Facies 5 typically lacks any visible burrowing. *Gyrolithes* Type II is only locally present (Fig 9c).

Interpretation:

Facies 5 was deposited under conditions of sufficiently low flow velocities to allow the fine-grained sediments to fall from suspension. Likely locations of such conditions associated with other facies of this association include: 1) channel abandonment fill; 2) chutes or swales along a point bar; and 3) adjacent lakes or ponds. The thickness of the facies eliminates mud deposition resulting from a flooding event as a possible interpretation. Compaction and a low preservation potential would limit the thickness of such 'event' deposits.

Channel abandonment is the result of cut-off of meander loops. Channel abandonment can be the result of two processes: 1) chute cut-off or 2) neck cut-off (Reineck and Singh, 1980). Chute cut-off occurs when the new channel is cut along a chute on the point bar; neck cut-off occurs when the new channel is cut between the narrow neck between two meander loops (Reineck and Singh, 1980). Chute cut-off results in a deposit that has smaller mud deposits and thicker underlying sand, silt, and mud (Reineck and Singh, 1980). This cut-off type best fits the examples of F5 found within this study area.

The paucity of trace fossils within this facies may be the result of the depositional environment. The restricted nature of the channel abandonments and other standing water bodies limits the circulation required by burrowing organisms. These depositional environments may only receive water during episodic flooding events. Another explanation for the lack of observed trace fossils may be the lack of lithologic contrast that is so useful at identifying traces in other facies.

The occurrence of *Gyrolithes* Type II may again indicate the stressed nature of this environment.

Facies 6 (F6) - Flat-lying, thinly interbedded sand and mud

Description:

Facies 6 is found in the upper portions of the middle member as well as within the upper member of the McMurray Formation. It is unique within the McMurray Formation due to its lateral extent which permits correlation between wells. It is characterized by regular, thin interbeds of sand and mud with a variable degree of burrowing, ranging from rare to common (Fig. 13). F6 can vary from sand-dominated (Fig. 13a) to mud-dominated (Fig. 13b), but is typically sand-dominated. The rhythmic interbeds vary in thickness from 0.5 cm to 5 cm, with rare sand beds reaching 30 cm. Thin sand interbeds are horizontal to low angle planar, thinly laminated (1-2 mm thick). Thicker sand beds are current ripple laminated and horizontal to low angle planar laminated. Mud interbeds may appear structureless or contain very thin (less than 1 mm) sand laminae. Contacts between interbeds, where not disturbed by burrowing, are generally sharp.

The sand interbeds are well to very well sorted with grain sizes varying from lower very fine to lower fine. The coarser grain sizes are commonly found as burrow infill sediments. Flat-lying sand laminae are a distinctive feature of this facies. Individual laminae vary from 2 -6 mm in thickness. Each lamination is sharp based with very fine to fine sand grading up to dark carbonaceous debris. Where not disturbed by burrowing, the laminae appear to have a rhythmic pattern. Interlaminated sand and mud are also present as pinstripe bedding or the genetic term "tidal bedding", again a recognition of the rhythmic bedding. Examples of wavy and lenticular bedding (Reineck and Wunderlich, 1968) are present within this facies.

Locally present within this facies are 5 - 30 cm thick, sharp based sand beds. These beds are typically current ripple, combined flow ripple and climbing ripple cross-laminated, though horizontal to low angle planar laminae may also be present. Flow reversals and multidirectional flow patterns are present (Fig. 13c). These beds have sharp upper contacts and are draped by mud interbeds.

Other physical features of this facies include: coal or wood fragments and siderite cemented zones. Synaeresis cracks are a common and distinctive feature (Fig. 13a, c). Rooting is locally present within the mud-dominated examples of this facies.

Facies 6 is typically found in the upper portions of FA1 and is therefore associated with grey mud (F5) and mud-dominated IHS (F4). Contacts with those facies are gradational or distinct. Upper contacts are typically sharp, but locally may be gradational.

Ichnology:

Bioturbation intensity within F6 varies from rare to abundant, but is typically common. Trace fossils are relatively small. Identifiable trace fossils include: *Planolites*, *Teichichnus*, *Cylindrichnus*, *Palaeophycus*, *Skolithos*, *Lockeia*, small *Arenicolites*, small *Conichnus*, *Ophiomorpha*, and *Terebellina* (Fig. 13). Fugichnia (escape traces) are commonly associated with the sand 5 - 30 cm thick beds, which otherwise have little evidence of burrowing activity.

Several apparently biogenic structures occur within this facies and are difficult to identify with certainty to a genus level. Inclined unlined shafts are present and may represent the vertical component of *Planolites* or simply constitute inclined *Skolithos*. Trace fossils with a thicker mud wall than typically observed in most *Cylindrichnus* may actually constitute small *Rosselia*. Locally, some *Teichichnus*-like structures display a strong lateral shift of burrow position.

Interpretation:

Facies 6 is interpreted to have been deposited within the tidal flat deposits. Through interpretation of the facies association, the tidal flats are interpreted to have been deposited flanking an estuarine channel and point bar complex rather than the widespread 'classic' coastline tidal flats of Evans (1965) or Klein (1977). The tidal flat environment responsible for deposition of F6 is topographically higher than the point bar and represents the vertical accretion deposits of a meandering channel succession. Fringing tidal flats have been described in the Gironde estuary (Allen, 1991).

The combination of horizontal to low angle planar stratification and current ripple cross-laminated sand demonstrates the fluctuating nature of the flow conditions responsible for the deposition of F6. Horizontal planar stratification is the result of upper flow regime plane beds (Harms and Fahnestock, 1965). Upper flow regime plane beds generally form in very shallow flows. Plane beds can form in lower flow velocities in finer grained sands than those required for coarser sands. The current ripple cross-laminations are the result of deposition within the lower flow regime, similar to the small-scale cross-stratified sand (F2). The decrease in flow regime from upper to lower flow regime may be the result of waning flow associated with termination of flood conditions or slack water periods associated with tidal flow.

Wavy and lenticular bedding indicate cyclic energy levels with sand deposition during higher flow conditions and mud deposition from suspension during low energy conditions. While this stratification is not restricted to tidal environments, they are a commonly used indicator of such environments (Reineck, 1967; Reineck and Wunderlich, 1968; Klein, 1977; Reineck and Singh, 1980). Under tidal conditions the sand is deposited during current activity and the mud is deposited during slack water periods (Reineck and Singh, 1980).

The 5 - 30 cm thick sand beds intercalated within this facies are interpreted to represent episodic depositional events. Horizontal to low angle planar stratification represents the upper flow regime conditions associated with the high energy portion of the event. As the flow energy wanes climbing ripple cross-lamination develops. Climbing ripples form as the result of abundant sediment supply. In comparison to current ripples, suspension deposition provides much of the sediment (Reineck and Singh, 1980). Climbing ripple cross-lamination therefore represents waning flow conditions as abundant sediment previously held in suspension is deposited. Current ripple cross-laminated sand represents lower flow regime current deposition. With cessation of the depositional event and the associated waning of current activity, wave energy becomes a component of ripple modification and combined flow ripples develop. The paucity of burrowing is attributed to rapid deposition. The relative abundance of escape traces support this interpretation.

The waning of flow energy could be the result of three processes, possibly a combination of the three. Firstly, as the sediment laden flow leaves the channel, flow becomes unconfined on the tidal flat. Flow energy decreases and deposition occurs. Secondly, the decrease in energy may also be the result of cessation of an episodic flooding event, such as a seasonal flood or storm event. Finally, waning energy may be the result of waning tidal energy associated with the cycle. The paucity of these deposits suggests episodic rather than tidal processes (periodic) are responsible for their development. Reineck and Singh (1980) suggested that in tidal flat areas with high sedimentation rates climbing ripples are possible.

The trace fossil assemblage demonstrates a higher diversity of traces than other facies within Facies Association 1. The is likely the result of more marine conditions. Studies of the Ogeechee River-Ossabaw Sound estuary demonstrate an increase in species diversity towards the fully marine environment (Dörjes and Howard, 1975; Howard *et al*, 1975). The trace fossils of F6 are small relative to their fully marine counterparts, similar to other facies within the association. The trace fossils trace assemblage contain traces common to both the *Skolithos* and *Cruziana* ichnofacies. The synaeresis cracks suggest an environment subject to fluctuating salinities.

The above evidence suggests Facies 6 was deposited within an intertidal tidal flat flanking estuarine channels and point bar complexes. For this study Facies 6 has not been differentiated into sand-dominated, equal amounts of sand and mud, or mud-dominated facies. Doing so may lead to defining the three facies as sand flat, mixed flat, and mud flat facies. This would be consistent with a number of tidal flat facies models (Klein, 1977, Reineck and Singh, 1980). In general, many of the examples of this facies grade from approximately equal amounts of sand and mud to mud-dominated. This is consistent with the fining-upward nature of prograding tidal flat deposits (Evans, 1965; Klein, 1977). This facies represents mixed flat to mud flat environments. Many of the features of this facies, including its interstratified nature, are very similar to modern tidal flat deposits from The Wash in England as described by Evans (1965). Mud-dominated examples of this facies are very similar to those from the Lower Pennsylvanian of Indiana interpreted as intertidal tidal-flat by Kvale and Barnhill (1994). Modern tidal flat deposits are typically abundantly bioturbated (Reineck and Singh, 1980; Clifton, 1983). Facies 6 has a higher degree of burrowing than other facies within this facies association with some intervals displaying abundant bioturbation.

Facies 6 has a number of features useful in identifying the depositional environment as intertidal, as compared to subtidal. Clifton (1983) identified 12 criteria useful for differentiating intertidal deposits from subtidal deposits based on modern and Pleistocene deposits in Willapa Bay, Washington. Those criteria found within F6 that indicate intertidal deposition include: 1) lack of medium- and large-scale crossbedding, 2) directionally inconsistent (not unidirectional) ripple lamination, 3) locally present rooting, and 4) thin, regular alternations of clay, silt, and fine sand. Other criteria require examination of fossil material, paleocurrent data, and the associated runoff channel facies (not identified within this facies). Rooting is the only feature Clifton (1983) identifies as diagnostic of intertidal facies, the others are characteristic of intertidal deposits.

Facies Association 2 (FA2) - Muddy association

This facies association is found exclusively within the lower member of the McMurray Formation. The association is made up of five facies unique to this facies association: massive white to light grey mud (F7), dark grey carbonaceous mud (F8), coal (F9), chaotic, interbedded sand and silty mud (F10), and siltstone (F11). In addition, grey mud (F5) can be found within this association. With the exception of root traces, bioturbation within this facies association is rare to absent. The lower contact of this facies association is typically gradational with the underlying FA1. Contacts between facies of FA2 are commonly sharp though locally gradational contacts are present. FA2 is sharply overlain by FA1 of the middle member of the McMurray Formation.

Facies 5 (F5) - Grey mud

This facies is described as part of FA1.

Facies 7 (F7) - Massive white to light grey mud

Description:

Facies 7 is found only within the lower member of the McMurray Formation. It is characterized as a massive, white to light grey mud with rooting and carbonaceous debris (Fig. 14a). This facies varies from relatively soft, blocky mud that breaks easily and swells upon wetting to a hard, well-cemented mud.

Facies 7 lacks any physical structures (massive) but has a number of other physical features. If not massive, the mud generally has a blocky texture with swelling clays filling the fractures. Rooting is a distinctive feature of this facies. The root traces are typically filled with carbonaceous material. Carbonaceous debris is locally present. Siderite is a common cement and results in a brown staining of the facies. Small (less than 1 mm) nodules or grains of disseminated siderite are present in F7. Pyrite is locally present. No bioturbation was observed within F7.

Upper and lower contacts of this facies are typically gradational, though locally they may be sharp and undulating (irregular). The facies is typically found in association with grey mud (F5), dark grey to black carbonaceous mud (F8), and siltstone (F11).

Interpretation:

Facies 7 is interpreted to have been deposited within the flood basin adjacent to a fluvial channel system. Mud sized particles have low settling velocities and require extremely low energy environments for deposition from suspension. Flood basin deposits are the result of suspension deposition by overbank flows that deposit the coarser grains on levees and crevasse splays (Reineck and Singh, 1980). The decrease in flow velocity is the result of unconfined flow as the overbank flow moves away from the channel. Mud deposition may also occur within this environment as sediment laden water evaporates or drains.

The term "flood basin" is used here as defined by Reineck and Singh (1980). It is one of three major groups of fluvial deposits, with channel deposits and bank deposits constituting the other two. Flood basins are often sites of pedogenesis (soil formation) as the result of rare inundation and a paucity of coarse grains (Collinson, 1986). Grey coloring, rooting, carbonaceous debris, pyrite nodules, and siderite nodules are evidence of soil formation under humid climatic conditions (Reineck and Singh, 1980; Collinson, 1986).

Facies 8 (F8) - Dark grey carbonaceous mud

Description:

Dark grey carbonaceous mud is found only within the lower member of the McMurray Formation. Its dark color is the result of a high organic content (Fig. 14b, c). The facies appears massive with rare sand and silt laminae. Dispersed sand grains, mud intraclasts, coal fragments (Fig. 14b), carbonaceous debris, pyrite nodules, and coal laminae are common features of F8. Rooting is rare within this facies, yet commonly, root traces extend down from this facies into underlying facies. Extensive rooting can make the lower contacts of this facies indistinct (Fig. 14d). No bioturbation was observed within F8.

Upper and lower contacts of F8 are typically distinct or sharp. These contacts are commonly undulating and/or fractured with infill by sediments from the overlying facies. Facies 8 is commonly found in intercalated with the other fine-grained sediment facies of FA2, especially coal (F9).

Interpretation:

Facies 8 is interpreted to have been deposited within a marsh environment as part of the flood basin adjacent to a fluvial channel system. The interpretation as part of flood basin deposits is similar to that of Facies 7. Facies 8 lacks preserved rooting but commonly shows penetration of rooting into underlying facies. This feature, the abundance of carbonaceous debris, and coal laminae suggest a well vegetated environment. Dispersed sand grains, mud intraclasts, and coal fragments were deposited as the result of the baffling of overbank flows by marsh plants.

Facies 9 (F9) - Coal

Description:

Facies 9 is found only within the lower member of the McMurray Formation. It is characterized by 10 to 20 cm thick beds of dark grey to black coal (Fig. 14e, f). The coal would be described as durain and fusain in macroscopic textural terms. Durain coal dominates the facies and is dense coal lacking glossy and conchoidal fractures. The broken surface is not smooth. Fusain coal is fibrous and soils the fingers on contact. F9 has sand and silt lenses, dispersed sand and silt grains, carbonaceous debris, and pyrite nodules. The coal is commonly fractured. Upper contacts are sharp while lower contacts are typically sharp, but may be gradational. F9 is commonly found intercalated with the other fine-grained sediment facies of FA2, especially dark grey carbonaceous mud (F8).

Interpretation:

Coal forms as the result of burial of peat deposits. The necessary conditions for peat formation include extensive plant growth and inhibition of aerobic decay processes. Abundant accumulation of dead vegetation that is water saturated due to high ground water tables in an area free of inorganic sediment deposition allows peat formation. Compaction of the peat during burial is significant. Peats deposited under anaerobic and subsiding conditions will attain the thicknesses necessary for a significant coal bed.

Facies 9 is interpreted to have been deposited in a flood basin adjacent to a meandering fluvial channel. Blatt (1982) noted the requirements for thick peat deposits: 1) slow, continuous rise of ground water, 2) protection of the peat swamp from marine inundations and fluvial floods, and 3) an area of low relief landward of the peat swamp, free of fluvial sediment input, to prevent interruption of the peat forming processes. The flood basin as defined by Reineck and Singh (1980) provides such requirements. Protected from fluvial influence by levee deposits, flood basins can remain wet and have sufficient plant material to allow for peat formation within a subsiding environment. The silty nature of the coal and sand and silt interbeds are the result of periodic fluvial flood conditions. Intercalation of coal and dark grey carbonaceous mud (F8) indicate the fluctuating nature of flood basin deposition.

Facies 10 (F10) - Chaotic, interbedded sand and silty mud

Description:

Facies 10 is a highly variable facies and difficult to recognize. It is best characterized as an interbedded sand and silty mud which commonly displays high angles of inclination and chaotic bedding (Fig. 15a, b, d). Facies 10 is only found within the lower member of the McMurray Formation. Intervals of F10 are typically only 2-3 m thick. Bitumen saturation is highly variable, though typically low.

F10 is typically poorly-sorted, very fine- to fine-grained sand with silty mud interbeds. Current ripple cross-lamination is the predominant sedimentary structure, though horizontal to low angle planar stratification is locally present. Mud laminae and carbonaceous debris laminae are present within this facies. Other physical features of F10 include: abundant carbonaceous debris, rooting, coal fragments, dispersed sand grains (typically at the base of unit), mud intraclasts, and pyrite nodules. In some examples of this facies chaotic bedding persists throughout the entire unit. Locally, stratification inclines up to 45° (Fig. 15d). This inclination does not appear to be depositional. Escape traces that are perpendicular to the bedding planes are also inclined (Fig. 15d).

Facies 10 is typically sharp-based and may overlie any facies of Facies Association 2. This facies has gradational upper contacts with grey mud (F5), massive white to light grey mud (F7), dark grey carbonaceous mud (F8), and siltstone (F11).

Ichnology:

Bioturbation within Facies 10 is rare to absent. Small vertical shafts of *Skolithos*, *Arenicolites*, and *Planolites* may be present within interbedded sand and carbonaceous debris laminae. Escape structures are commonly present within F10.

Interpretation:

Facies 10 is interpreted to have been deposited as crevasse-splay deposits adjacent to a channel. Crevasse-splay deposits are the result of overbank flow associated flooding events. Crevasses are breaches in the channel levees. Crevasse-splay deposits and levee deposits constitute the 'bank deposits' of the fluvial environment (Reineck and Singh, 1980). Crevasse-splay deposits are tongues of sediment thinning in the direction of the flood basin (Reineck and Singh, 1980). Deposition of suspension sediments occurs as flow energy decreases away from the channel. Coarser sands and silts are deposited close to the channel and finer sediments are deposited further out on the flood basin (Collinson, 1986).

Current ripples cross-lamination and horizontal to low angle planar stratification are found within crevasse-splay deposits (Reineck and Singh, 1980). Climbing ripples, characteristic of these deposits, were not observed within this facies. Rooting and abundant carbonaceous debris suggest the presence of vegetation. The thicknesses of F10 deposits are consistent with crevasse-splay deposits described by Reineck and Singh (1980) being tens of centimeters to a few metres thick. Mud intraclasts, coal fragments, and dispersed sand grains suggest episodic event deposition. This facies is similar to the 'bioturbated rippled sandstone' facies of Pemberton and Wightman (1992). The facies was interpreted to be part of an Upper Mannville crevasse-splay deposit.

Escape traces within this facies suggest rapid deposition. The trace fossil assemblage has a very low diversity, suggesting a stressed environment. This assemblage suggests deposition within a restricted, brackish water environment (Pemberton and Wightman, 1992). As bioturbation is only locally present, most examples of this facies may have been deposited under fresh water conditions.

Interpretation of the chaotic bedding and steeply inclined stratification is problematic. If the deformation is post-depositional, the interpreted depositional environment lacks the relief required for significant slope instability. Other possible interpretations include deformation due to compaction of underlying muds, high subsidence events, or slope failure associated with a nearby channel. The chaotic bedding may be the result of rapid depositional events.

Facies 11 (F11) - Siltstone

Description:

Facies 11 is found only within the lower member of the McMurray Formation. It is characterized by a predominantly massive siltstone. Locally, the facies is thinly interbedded sand and silty shale (Fig. 15c) with lenticular and wavy bedding and current ripple cross-lamination. Root traces and carbonaceous debris are a common feature. The lower contacts of F11 may be gradationally or sharp. The underlying facies may be any of the fine-grained facies of FA2. The upper contacts of the facies are always gradational with siltstone passing into the muddy facies of FA2.

Ichnology:

Bioturbation within Facies 11 is rare to absent. Locally, the facies contains vertical and horizontal sand-filled, sharp-walled burrows with diameters varying between 0.5 and 1.0 cm and may be *Thalassinoides*.

Interpretation:

Facies 11 is interpreted to represent the distal portion of a crevasse-splay deposit. It is therefore closely associated with F10 and should be considered an intermediate facies between chaotic, interbedded sand and silty mud (F10) and dark grey carbonaceous mud (F8). Deposition within a current is indicated by the current ripple cross-stratification. The lenticular and wavy bedding may be the result of irregular deposition due to episodic floods or tidal processes. Within waning flow energies silt deposition occurs after sand deposition and prior to mud deposition. Rooting and carbonaceous debris suggest the presence of plants.

The presence of trace fossils suggests, at least locally, marine water influence. Therefore some examples of this facies may have been deposited within a brackish water environment within the flood basin.

Facies Association 3 (FA3) - Flat-lying, sand and mud association

This facies association comprises the majority of the upper member of the McMurray Formation. The constituent facies are typically flat-lying, relatively laterally extensive, often well burrowed, and composed of varying degrees of interbedded very fine sand and mud.

Facies association 3 includes three facies that are also found within FA1: grey mud (F5), flat-lying, thinly interbedded sand and mud (F6), and a subfacies of sand-dominated inclined heterolithic stratification (F3) has been identified. It is delineated as Facies 3a. In addition, three facies are unique to FA3: laminated to burrowed sand (F12), well burrowed sand (F13), and well burrowed interbedded sand and mud (F14). Well burrowed sand (F13) and well burrowed interbedded sand and mud (F14) appear to vary in only their mud content and therefore could be considered subfacies of one another. Yet within observed core the two facies are never found in contact with one another. As this study is using the association of facies as a facies classification and interpretation tool, the lack of direct association of these two facies has been addressed by identifying them as distinct facies. Contacts between the constituent facies are typically gradational, but may also be sharp. The lower contact of this association is typically sharp but may be difficult to discern. The upper contact is sharp.

Subfacies 3a (F3a) - Sand-dominated inclined heterolithic stratification

The sand-dominated inclined heterolithic stratification of FA3 can be distinguished from that of FA1 and has therefore been identified as a subfacies of F3. Only those features that differ from F3 will be presented here.

Description:

Sedimentary features can be used to distinguish F3a from F3. The thickness of both the coarse and fine layers is significantly less than that found within F3 (Fig. 16a, b, c). The coarse layer rarely exceeds 15 cm and is commonly less than 5 cm and the fine layer rarely exceeds 10 cm and is commonly less than 2 cm. F3a lacks the larger scale cross-strata found within F3. The coarse member of the couplets are characterized by rhythmic laminations of sand and carbonaceous debris (Fig. 16c). The sands are well-sorted, very fine- to fine-grained and are wavy parallel laminated and only rarely ripple laminated. The fine layer of F3a lacks the massive grey mud and is limited to interlaminated mud and sand. Synaeresis cracks are more common in F3a.

Facies 3a is found gradationally overlying laminated to burrowed sand (F12) and well burrowed interbedded sand and mud (F14). Facies 3a grades upward into well burrowed sand (F13) and flat-lying, thinly interbedded sand and mud (F6).

Ichnology:

The trace fossil assemblage of F3a of Facies Association 3 can be distinguished from that of F3 of Facies Association 1. The degree of burrowing of F3a varies from moderate to common, overall more bioturbation than F3. F3a has a higher diversity of trace fossils and lacks the monospecific assemblages of F3. Trace fossils include: *Planolites*, *Palaeophycus*, *Terebellina*, *Arenicolites*, lined and unlined *Skolithos*, *Teichichnus*, *Conichnus*, *Lockeia*, *Ophiomorpha*, possible *Rosselia*, and escape structures (Fig. 16). Subfacies 3a lacks the monospecific assemblages of *Cylindrichnus*, both types of *Gyrolithes*, and *Planolites* that are characteristic of Facies 3.

Interpretation:

Facies 3a is interpreted to represent lateral accretion deposits associated with an estuary mouth channel. Only the part of the interpretation that differs from Facies 3 will be presented here. A more thorough discussion of this depositional environment can be found in the interpretation of Facies 3.

The processes responsible for the physical structures of Facies 3a vary slightly from those responsible for F3. The lesser bed thickness of F3a may be the result of two influences: less available sediment and/or higher frequency cyclic processes. If less sand and mud are available for sedimentation less deposition will occur during each cycle regardless of whether the controlling cycle is neap/spring tides or daily tides. If the cycle has a higher frequency such as daily tides versus neap/spring tides then thinner layers will be deposited. That is, within a given tidal regime, a bedform developed throughout spring tides may be thicker than a bedform accumulated through a single daily tide. The lack of large-scale cross-stratification may be the result of the fine-grained nature of the facies. Dunes (megaripples) generally do not form in fine-grained sediments (Harms *et al.*, 1982). Parallel lamination and ripple cross-lamination demonstrate upper flow regime to lower flow regime conditions within a current. The higher number of synaeresis cracks within F3a may reflect more frequent salinity variations.

The trace fossil assemblage of F3a demonstrates more marine conditions than Facies 3. The higher diversity (four additional genera) of trace fossils suggests relatively more marine conditions (Pemberton and Wightman, 1992). This is consistent with the observations made in Ogeechee River-Ossabaw Sound estuary (Dörjes and Howard, 1975, Howard *et al*, 1975). Howard *et al.* (1975) reported more species and more individuals within the point bars of the lower (closer to the marine environment) region of the estuary. While greater abundances (moderate to common) were also observed, caution must be used in making conclusions regarding the nature of the water of this depositional environment. A direct relationship between abundant individuals and abundant burrowing was not observed in the Ogeechee River-Ossabaw Sound estuary (Howard *et al.*, 1975). In fact point bars within the middle region of the estuary have few individuals and the most abundant bioturbation. The observations from the Ogeechee River-Ossabaw Sound estuary are used here to demonstrate that the diverse assemblage of F3a is approaching that of more fully marine conditions. The lack of the distinctive brackish water trace fossils (*Cylindrichnus* and *Gyrolithes*) found within F3a also suggests more marine conditions.

Facies 3a appears to be similar to the point bar deposits of the "lower region" of the Ogeechee River-Ossabaw Sound estuary. Small-scale cross-stratification, abundant burrowing, and the first indication of mud layers that become more common up the estuary are the distinctive features of the lower region point bars observed by Howard *et al.* (1975).

Facies 5 (F5) - Grey mud

This facies is described as part of FA1.

Facies 6 (F6) - Flat-lying, thinly interbedded sand and mud

This facies is described as part of FA1.

Facies 12 (F12) - Laminated to burrowed sand

Description:

This facies is found within the lower portion of the upper member of the McMurray Formation. F12 is characterized by variably stratified fine sand intercalated with well burrowed zones (Fig. 17a, b, c). These laminated to burrowed successions are typically sharp-based laminated to thinly bedded sands passing upward to well burrowed silty sands. Bioturbation increases upward to the sharp contact with the overlying laminated sand. The upper burrowed portion is not always present. These laminated to burrowed successions are 8 - 40 cm thick. Contacts between beds are undulating to low angle planar.

The sand of this facies is well sorted, upper very fine- to lower fine-grained. The sand is undulatory, low-angle parallel laminated and ripple cross-laminated (Fig. 17a, b). Ripple cross-laminations are predominantly current rippled. Combined flow ripples, climbing ripples and mud intraclasts are also present. The laminated nature of the sand is demarcated by the rhythmic alternation of fine sand and carbonaceous debris. Gastropod shells are found exclusively within this facies.

The lower contacts of this facies are commonly sharp based. Upper contacts may be gradational or sharp. The facies is found in contact with numerous other facies.

Ichnology:

Facies 12 varies from non-burrowed to abundantly burrowed. Bioturbation within the laminated portions of the facies is rare to absent. *Arenicolites*, *Skolithos*, *Cylindrichnus*, and common escape structures (Fig. 17c) are locally present within these laminated horizons. Locally, the escape structures can be seen extending through the laminated interval to an overlying burrow of the burrowed zone (Fig. 17f). Burrowed portions of the facies have a common to abundant degree of burrowing. The trace fossils include: *Planolites*, *Palaeophycus*, *Skolithos*, *Arenicolites*, both types of *Gyrolithes*, *Cylindrichnus*, *Teichichnus*, and *Ophiomorpha* (Fig. 17d, e, f). The trace fossils of the burrowed intervals display cross-cutting relationships (Fig. 17e).

Interpretation:

Facies 12 is interpreted to have been deposited as shallow sand bodies within the estuary mouth. It is difficult to assign a precise name to these sand bodies. The variations of the numerous sand bodies found within a single estuary make identification in the rock record difficult. Multiple scour events, periodic exposure, fluctuating tidal energies, and storm deposits are only a few of the variables that affect these sands. Differing nomenclature used by various authors also contributes to the difficulty in assigning a precise name to a preserved estuarine sand succession. Sand bank, swash bar, sand flat, inlet shoal, channel bar, sandflat and sandwave are examples of names used to describe various estuarine sand bodies (Visher and Howard, 1974; Greer, 1975; Goldring *et al.* 1978; Homewood and Allen, 1981; Archer *et al.* 1994).

The undulatory, parallel laminated very fine and fine sands of Facies 12 likely reflect the sedimentary structures of bedforms that extend beyond the scale of the slabbed core. The low angle to horizontal laminations may be a component of hummocky cross-stratification (HCS), swaley cross-stratification (SCS), or quasi-planar lamination (QPL). All three of these stratification types have low angle (<15°) laminations and undulatory truncation surfaces (MacEachern, 1994). HCS and QPL are commonly associated with waning flow ripple cross-lamination. Oscillation ripples may be found capping HCS beds while QPL is associated with combined flow and current ripple laminations. Ripple laminations are not commonly found in association with SCS as it is the result of erosional amalgamation of successive depositional events.

HCS and SCS are deposited during high energy oscillatory conditions associated with a storm event (Arnott, 1993); SCS results from relatively higher energy conditions (Leckie and Walker, 1982). QPL is also associated with high energy storm deposition, but under combined flow conditions (Arnott, 1993). The ripple cross-lamination represents waning flow conditions. It is unlikely that the three stratification types could differentiated from one another in core (MacEachern, 1994). Since HCS, SCS, and QPL are all the result of storm deposition they will be considered a single stratification type for this interpretation. The association of this stratification with current and combined flow ripples indicate some current deposition and therefore the undulatory, parallel laminations may represent QPL.

The nature of the bioturbation of Facies 12 indicates episodic event deposition. Burrowing is limited to the upper portions of the laminated sand to burrowed sand couplets. The trace fossil assemblage therefore represents colonization after storm deposition by opportunistic organisms and subsequent burrowing by the equilibrium (resident) organisms. *Arenicolites* and *Skolithos* within the laminated sands are interpreted to represent the activities of opportunistic organisms and is characterized by relatively simple, vertical to subvertical forms. The opportunistic suite represents dwelling structures of suspension feeders (or possibly passive carnivore for *Skolithos*) of the *Skolithos* ichnofacies. *Planolites*, *Palaeophycus*, *Skolithos*, *Arenicolites*, *Cylindrichnus*, *Teichichnus*, and *Ophiomorpha* within the burrowed zones are interpreted to represent the activities of equilibrium organisms. The equilibrium suite, whose burrows are seen to cross-cut the those of the opportunistic suite (Fig. 17e), represents the dwelling structures of suspension and deposits feeding organisms, as well as passive and mobile carnivores. It is characteristic of the mixed *Skolithos/Cruziana* assemblage of brackish water deposits. The trace fossil assemblage found in F12 is more diverse than previously discussed facies and represents a greater marine water influence. Fugichnia (escape structures) represent the disturbance of laminations as organisms escape to the sediment-water interface. Locally, the escape trace is seen to extend through the laminated interval to overlying burrows of the burrowed zone. This reflects the organism's "escape" through the event bed and establishing itself at the sediment/water interface during the subsequent fairweather conditions.

The characteristic laminated to burrowed successions of Facies 12 is interpreted to represent tempestite (storm) deposition within an estuarine environment. Howard (1972) interprets similar sharp-based 'parallel to burrowed' beds deposited within the lower shoreface environment to be the result of periodic storms or strong tidal action. Facies 12 contains the features identified by MacEachern (1994) as those representing tempestite deposition, including: 1) a sharp erosional base; 2) a main sand interval with low angle laminations (HCS, SCS, or QPL); 3) common escape structures; 4) waning flow deposits towards the top of the beds; 4) dwelling burrows of opportunistic organisms near the top of the beds representing initial colonization; 5) gradational burrowed tops with fairweather suites cross-cutting the opportunistic assemblage; passing into 6) thoroughly burrowed fairweather deposits containing an equilibrium trace fossil suite.

In their study of a wave-dominated shoreline, Pemberton *et al.* (1992b) provide a useful discussion of the associated trace fossil assemblage. This discussion includes potential depositional environments associated with the trace fossils. While assigning a single trace fossil to a single environment can be problematic, *Arenicolites* is reported to be generally associated with low energy shorefaces or sandy tidal flats and *Ophiomorpha*, common in shoreface environments, can also be found within tidal shoal deposits (Pemberton *et al.*, 1992b).

The relative abundance of physical structures to biogenic structures is useful in interpreting the frequency of these storm deposits. Assuming constant biologic activity (constant rate of biogenic reworking and consistent nature of burrowing organisms), the frequency and magnitude of the storm events control the relative abundance of physical and biogenic structures. Higher frequency, greater magnitude events will result in a predominance of physical structures. Less frequent, lower magnitude events allow thorough bioturbation and a predominance of biogenic structures. The interplay of these variables results in the varying intensity of burrowing preserved within facies 12.

Facies 12 is interpreted to represent shallow estuary mouth deposition. The precise nature of this sand body is difficult to define. Greer (1975) reported the inlet shoal of the Ogeechee River-Ossabaw Sound estuary as having laminated and current rippled sands as the dominant sedimentary structures. The laminated sands were interpreted as upper flow regime plane bed deposition resulting from breaking waves. Greer (1975) also noted that the preservation of physical structures is limited to those areas where wave and current energies were sufficiently high to rework the substrate. Goldring *et al.* (1978) interpreted their "fine sand facies", as an estuarine sand bank. The fine sand was characterized by plane- to cross-laminated fine sands with colonization by infaunal animals at the rippled tops of the sequences. A coarse-grained sand facies with similar physical structures to those of F12 was interpreted by Yang and Nio (1989) as a component of an ebb-tidal delta at the mouth of an estuary. Archer *et al.* (1994) interpreted their "sheet-like sandstone facies" as lower estuary sandflats and bars. The facies was characterized by horizontal lamination and bioturbation in the upper portion of the sequence.

With only rare exceptions, large-scale cross-stratification was not observed F12. Many researchers have identified large-scale cross-stratification (or the bedforms resulting in that stratification type) as a common and significant component of estuarine sand bodies (Boersma and Terwindt, 1981; Homewood and Allen, 1981; Yang and Nio, 1989). The paucity of large-scale cross-stratification observed within F12 may be the result of its relatively fine-grained (very fine to fine sand) nature. Dunes (megaripples) generally do not form in fine-grained sediments (Harms *et al.*, 1982). Greer (1975) reports that large-scale cross-beds are primarily found within tidal channels of the Ogeechee River-Ossabaw Sound estuary. The tidal channels have a limited areal extent relative to other estuarine sand bodies. The lack of observed large-scale cross-stratification within F12 may be the result of limited areal extent of these deposits within the estuary mouth.

Facies 13 (F13) - Well burrowed sand

Description:

Facies 13 is found within the upper member of the McMurray Formation. It is characterized by well bioturbated very fine sands with rare sand and mud interbeds (Fig. 18a, b). The high degree of bioturbation results in a thorough mixing of mud within the sands with few preserved physical structures. The facies could be described as a muddy sand. This facies, when present, is always found in the upper portions of FA3 and was only observed within core taken from the northern half of the study area. Rare sand interbeds are low angle parallel laminated and ripple cross-laminated.

The lower contacts of F13 are commonly burrowed, but the facies appears to gradationally overlie laminated to burrowed sand (F12) and have a distinct contact with sand-dominated inclined heterolithic stratification (F3a) and flat-lying, thinly interbedded sand and mud (F6). The sharp, undulatory upper contact of F13 is either the top of the McMurray Formation or the contact with Facies Association 4.

Ichnology:

Discrete trace fossils are difficult to identify due to the high degree of burrowing (Fig. 18a, b). *Planolites*, *Palaeophycus*, *Terebellina*, *Teichichnus*, possible *Rosselia*, small *Conichnus*, *Cylindrichnus*, simple inclined shafts, small *Skolithos* and small *Arenicolites* are visible.

Interpretation:

Facies 13 is interpreted to have been deposited as shallow sand bodies within the estuary mouth, similar to Facies 12. The difference between this facies (F13) and the laminated to burrowed sand (F12) is the higher degree of burrowing characteristic of the former. The two facies were always found in gradational contact with one another. The burrowing intensity of F13 indicates sufficient time was available for complete bioturbation of the sand with correspondingly low flow conditions to prevent reworking of the substrate. The muddy component of this facies most certainly represents mud interlaminated with the sand that had been thoroughly bioturbated into a muddy sand. This suggests that Facies 13 was deposited within a portion of the estuary exposed to less frequent depositional events than Facies 12.

The trace fossil assemblage of F13 is interpreted to represent stressed marine assemblage. That is, lower diversity and smaller sizes than their marine counterparts, but with high abundances. This is consistent with other facies within this facies association that show a greater diversity of forms than the facies of Facies Associations 1 and 2. The increased prevalence of marine conditions within this depositional environment is responsible for the increased diversity of forms but not the increased intensity of burrowing. Sufficient protection from physical reworking is responsible for the increased intensity of burrowing.

Greer's (1975) description of portions of the tidal flat deposits at the estuary-marine transition of the Ogeechee River-Ossabaw Sound estuary are similar to those of Facies 13. Bioturbated muddy sand was found on two portions of the tidal flat: the tidal channel margin and the tidal sand flat. Within the tidal sand flats, protected on the leeward side of the swash bar, the thoroughly burrowed muddy sand is interpreted to have been the result of bioturbation of interbedded fine-grained sand and mud (Greer, 1975). Horizontal laminations and ripple cross-bedding are the remnant sedimentary structures.

Archer *et al.* (1994) interpreted their Carboniferous "bioturbated sandstone facies" to have been deposited within the lowermost portion of the estuary or even outside the estuarine embayment. The physical structures found within the facies include small-scale cross-stratification and various ripple structures. The facies displayed the highest diversity of trace fossils and the most marine conditions (including body fossil interpretation) of the all the facies examined in the succession.

Facies 14 (F14) - Well burrowed interbedded sand and mud

Description:

This facies is found within the upper McMurray member and rarely within the upper portion of the middle McMurray member. It is characterized by well burrowed, medium-scale interbedded sand and mud and lacks the inclined nature of sand-dominated IHS (F3a) (Fig. 18c, d). Interbed thickness is greater than that observed in the flat-lying, thinly interbedded sand and mud (F6). The facies, when present, is always found at the base of FA3 and was observed predominantly within core taken from the southern portion of the study area.

Due to the well burrowed nature of this facies few sedimentary structures are visible and only remnant contacts between interbeds are discernible. The sand within F14 is lower very fine to lower fine, with upper very fine being most common. Rare sand interbeds or mud interlaminae are present. The sand interbeds are commonly current and climbing ripple laminated.

The lower contacts of F14 are sharp and typically represent the lower contact of this facies association (FA3). The facies beneath these contacts may be any of those that make up Facies Association 1. The upper contacts of F14 are commonly burrowed, but it appears to gradationally overlain by flat-lying, thinly interbedded sand and mud (F6) or well burrowed sand (F13). Locally, F14 has a sharp upper contact with laminated to burrowed sand (F12).

Ichnology:

The trace fossil assemblage of F14 is similar to that of F13. Discrete trace fossils are difficult to identify due to the high degree of burrowing (Fig. 18c, d). *Planolites*, *Palaeophycus*, *Terebellina*, *Teichichnus*, *Cylindrichnus* and small *Skolithos* and *Arenicolites* are visible.

Interpretation:

Facies 14 is interpreted to have been deposited as shallow interbedded sand and mud within the estuary mouth, similar to Facies 12 and 13. Facies 14 has a higher mud content, including remnant mud laminae, than the laminated to burrowed sand (F12) and the well burrowed sand (F13). Facies 14 also has a higher intensity of bioturbation than laminated to burrowed sand (F12). The three facies may be considered members of a continuum that has high energy, sand deposition with less burrowing (F12) as one end member and lower energy, sand and mud deposition with more burrowing (F14) as the other end member.

Facies 14 represents sand and mud deposition within a sheltered portion of the estuary mouth. Fluctuating energy conditions are indicated by the sand and mud interbedding. Sufficient time for thorough bioturbation is indicated by the high degree of burrowing. Interbedded sand and mud in equal proportions constitutes the most abundant facies within the modern estuaries of Georgia (Howard and Frey, 1973). Visher and Howard (1974) reported that mud and silt deposition occurred within shoal areas sheltered from ocean waves and strong currents within in the modern Altamaha estuary in Georgia.

Facies Association 4 (FA4) - Coarsening-upward sandy association

This facies association is found within the upper member of the McMurray Formation. It is characterized by dark grey mud and heavily bitumen saturated fine sand. Where present FA4 represents the uppermost portion of the upper member. The association is limited to the northern half of the study area, forming a northward thickening wedge of sediments. Where this facies association is preserved, the constituent facies occur in a predictable, coarsening-upward succession.

FA4 is made up of three facies: poorly sorted fine to coarse sand (F15); interbedded sand and dark grey mud (F16); and fine-grained sand with dark grey mud interlaminae (F17) (Fig. 19). The lower contact of this facies association is sharp with evidence of scour. Contacts between F15 and F16 are sharp, while F16 grades upward into F17. The upper contact of the facies association is similar to the lower contact.

Facies 15 (F15) - Poorly sorted fine to coarse sand

Description:

This facies is present as a thin veneer and consistently the lowermost facies of this association. It is 2 - 10 cm thick and has a sharp lower contact with evidence of scour (Fig. 19a). Grain size is typically fine sand with thin, medium to coarse sand interbeds and coarse sand to granule dispersed quartz grains. Mud laminae are rarely present. The sands are small-scale cross-stratified (small-scale trough cross-stratification) and have carbonaceous debris drapes. Other features include shale intraclasts, coal or wood fragments, small (less than 1 cm) pyrite nodules, and typically a low degree of bitumen staining.

Ichnology:

This facies is rarely burrowed, but *Planolites* and possible *Lockeia* are locally present and are associated with mud interlaminae.

Interpretation:

Facies 15 is interpreted to represent the transgressive lag associated with erosional shoreface retreat (Reinson, 1992) as the result of a marine transgression. F15 is clearly the result of erosive conditions. The lower contact is sharp and undulatory. The abundance of intraclasts, wood fragments, and carbonaceous debris within this unit indicates the incorporation of underlying sediments. Intraclasts and wood fragments are eroded from the underlying sediments and incorporated in F15. The source of the dispersed coarser grained quartz sands is problematic. One possibility is that the coarser grains are the result of winnowing of the finer grains from facies making up the overlying shoreline deposits (*e.g.* upper shoreface, backshore). Another possibility is that the coarser grains are transported basinward by storms, submarine debris flows, and/or sediment gravity flows during erosional shoreface retreat (MacEachern, 1994). Mud interlaminae indicate deposition during low energy conditions. *Planolites* and the small surface resting trace of *Lockeia* were formed during these low energy periods.

Facies 16 (F16) - Interbedded sand and dark grey mud

Description:

This facies is distinctive for its heavily bitumen saturated sand, dark grey mud interbeds, and robust trace fossils (Fig. 19b, c). The facies is typically sand dominated, but may be mud-dominated and displays wavy and lenticular bedding. Sand interbeds vary from lenses that do not extend across the width of the core to beds 15 cm thick. Mud interbeds vary from 0.5 to 4 cm, but are typically 1 cm thick. Convolute bedding occurs within this facies.

The sand is upper very fine- to lower fine-grained with rare dispersed coarse quartz sands. The sand typically has a very high degree of bitumen saturation. Examples of flaser and lenticular bedding are present, but the facies is dominated by wavy bedding. The sand interbeds are sharp-based and have oscillation ripple and combined flow ripple laminations as well as low angle parallel laminated intervals.

Mud interbeds within this facies are often discontinuous. This is the result of disturbance by burrowing and convolute bedding. Large burrows, greater than the thickness of the mud interbeds, are common. The mud interbeds typically have fine interlaminae of very fine sand to silt, but may also be structureless.

Facies 16 has a sharp lower contact with poorly sorted fine to coarse sand (F15) and grades upward into fine-grained sand with dark grey mud interlaminae (F17).

Ichnology:

Trace fossils of this facies show the same low diversity as those facies found lower in the McMurray Formation, but are distinctive for the larger sizes. The degree of burrowing is typically rare with some moderately burrowed horizons. Robust examples of *Teichichnus*, *Asterosoma*, and *Planolites* are common (Fig. 19b, c). *Teichichnus* are up to 2.5 cm wide and have vertical components of up to 10 cm. *Planolites* may reach up to 1 cm in diameter. Smaller, more typical for the McMurray Formation, examples of *Planolites*, *Palaeophycus*, *Lockeia*, and *Skolithos* are also present.

Interpretation:

Facies 16 is interpreted to represent deposition within the upper offshore environment of a shallow marine shoreline. Its interpretation is clearly tied to the rest of the facies comprising Facies Association 4. The interpretation of FA4 to follow will provide a better understanding of this specific facies interpretation. This facies is sufficiently distinct to allow correlation to previous studies that interpreted the facies as marine in origin (Flach, 1984; Flach and Mossop, 1985; Rennie, 1987). Flach and Mossop (1985) used sedimentology, palynology, and the presence of glauconite to interpret open marine conditions for their upper McMurray "marine unit". Facies 16 corresponds to the lower portion of their "marine unit".

Sand interbeds are interpreted to be the result of distal storm event deposition. Their sharp-based, rippled to low angle parallel laminated nature supports this interpretation. The low angle parallel laminated sands are interpreted as HCS, SCS, or QPL (see interpretation of laminated to burrowed sand (F12)). These stratification types are commonly interpreted as storm deposits (Walker and Plint, 1992; Arnott, 1993; MacEachern, 1994). Oscillation and combined flow ripple laminations represent waning flow conditions. Mud deposition occurred during low energy fairweather conditions. The majority of bioturbation occurred under these fairweather conditions.

The trace fossil assemblage of F16 provides a curious contradiction of the indicator trends interpreted to represent brackish to marine water transition. These trends include higher diversity and larger forms as one approaches the fully marine realm. Trace fossils of this facies are larger than those found in underlying facies (suggesting marine conditions) yet their diversity remains low. Indeed the diversity is lower than some of the underlying facies, as in the case of the outer estuary facies (FA3). The upper offshore environment of some Cretaceous shorelines is commonly burrowed by a higher diversity of forms (Pemberton *et al.* 1992b; MacEachern and Pemberton, 1992). The lower diversity of forms observed in this facies may represent a stressed environment as the result of its proximity to an estuary. The flow from the estuary could have in some way been stressing the depositional environment. The lower diversity may also reflect deposition of a shoreface in a restricted embayment rather than an open, fully marine environment.

Facies 16 has a lower intensity of bioturbation than other upper offshore examples. The facies has a lower bioturbation intensity than some of the estuarine facies. Howard and Reineck (1972) reported bioturbated muddy sands within the upper offshore and Greer (1975) reported muddy, fine-grained bioturbated sand within the equivalent "inner-shelf facies" along the modern Georgia coast. Pemberton *et al.* (1992) and MacEachern and Pemberton (1992) reported higher intensities of bioturbation within

Cretaceous upper offshore deposits than those found in F16. Insufficient time for bioturbation within a somewhat stressed environment may explain the low level of bioturbation within F16. Reworking of the substrate by physical processes (storms?) may have prevented sufficient colonization of the substrate. MacEachern *et al.* (1992a) reported a paucity of visible trace fossils in a Cretaceous facies interpreted as a lower offshore deposit associated with an overall transgressive succession.

The offshore zone lies below fairweather (minimum) wave base and above storm (maximum) wave base (MacEachern and Pemberton, 1992; Walker and Plint, 1992). Sand deposition is associated with storm event deposition. Mud deposition results from suspension occurs during waning flow conditions. The high frequency of storm events may prevent the preservation of fairweather deposits.

Facies 17 (F17) - Fine-grained sand with dark grey mud interlaminae

Description:

Facies 17 is a continuation of the coarsening-upward cycle that distinguishes Facies Association 4. The sands have a very high degree of bitumen saturation with thin (typically less than 1 cm) dark grey mud drapes. Due to high degree of the bitumen saturation physical structures are difficult to discern.

F17 is well sorted upper very fine- to lower fine-grained sand, with rare medium- to coarse-grained intervals near the top of the unit. Flat to low angle parallel lamination and oscillation ripple cross-lamination are the most common physical structures. Large-scale cross-stratification is locally present within medium- to coarse-grained sand at the top of the facies unit. Dark grey mud intraclasts are present. The intraclasts are the same lithology as the mud drapes.

Facies 17 has a gradational contact with the underlying interbedded sand and dark grey mud (F16). The upper contact is sharp and undulatory and marks the top of the McMurray Formation. F17 is overlain by facies of Facies Association 5 (Wabiskaw Member).

Ichnology:

The trace fossil assemblage within this facies is similar to that of the underlying F16. The degree of burrowing is typically rare with some moderately to abundantly burrowed horizons. Large *Teichichnus* and *Planolites* as well as smaller *Planolites*, *Teichichnus*, *Skolithos*, and *Lockeia* are present. *Asterosoma*, not present in the underlying facies, is locally present. Horizons of abundantly burrowed, monospecific *Teichichnus* assemblages are locally present (Fig. 19d).

Interpretation:

Facies 17 is interpreted to represent deposition within the lower to middle shoreface environment of a shallow marine shoreline. The contact where interbedded sand and mud passes into the overlying sand can be used to define the base of the shoreface (Walker and Plint, 1992). Its interpretation is clearly tied to the rest of the facies comprising Facies Association 4. The interpretation of FA4 to follow will provide a better understanding of this specific facies interpretation. This facies is sufficiently distinct to allow correlation to previous studies that interpreted the facies as marine in origin (Flach, 1984; Flach and Mossop, 1985; Rennie, 1987). Flach and Mossop (1985) used palynology and the presence of glauconite to interpret open marine conditions for their upper McMurray "marine unit". Facies 17 corresponds to the uppermost portion of their "marine unit".

The sand of Facies 17 is interpreted to represent amalgamated storm bed deposits. The sand beds are low angle parallel laminated to ripple cross-laminated. The low angle parallel laminated sands are interpreted as HCS, SCS, or QPL (see interpretation of laminated to burrowed sand (F12)). These stratification types are commonly interpreted to be the result of storm deposition (Walker and Plint, 1992; Arnott, 1993; MacEachern, 1994). Oscillation ripple laminations represent waning flow conditions or fairweather conditions. Rare mud deposition occurred during low energy fairweather conditions.

The trace fossil assemblage of F17 is more consistent with other reported shoreface deposits. Howard and Reineck's (1972) upper and lower shoreface environments and Greer's (1975) equivalent inlet shoal environment of the Georgia coast have low levels of bioturbation. MacEachern and Pemberton (1992) reported Cretaceous lower-middle shoreface deposits with low levels of bioturbation.

Relatively high energy conditions are interpreted to be responsible for the low intensity of bioturbation observed in Facies 17. Greer (1975) accredits reworking of the substrate by physical processes as being responsible for low levels of bioturbation observed in the inlet shoal environment. MacEachern and Pemberton (1992) attribute variations of storm events to be responsible for the variability of lower and middle shoreface deposits of the Cretaceous Interior Seaway. Storm intensity, storm frequency, and relative water depth affect the shoreface deposits (MacEachern and Pemberton, 1992). High intensity and high frequency storm events rework the substrate frequently and do not allow for significant preserved bioturbation. Strongly storm-dominated lower-middle shoreface complexes can be recognized by amalgamated storm deposits (tempestites) with minimal preserved biogenic structures (MacEachern and Pemberton, 1992). Whether or not the paucity of trace fossils within F17 is the result of a storm-dominated lower-middle shoreface is uncertain, it is clearly a high energy environment with physical reworking limiting biogenic structure preservation.

The trace fossil assemblage of F17 has a lower diversity than one would might expect for a fully marine deposit. Howard *et al.* (1975) reported the least amount of bioturbation within the most marine point bar of their study of animal-sediment relationships in point bar deposits of the Ogeechee River-Ossabaw Sound estuary. It should be noted, as it was by the authors, that this most marine bar was actually a shoal margin of a tidal flat within the estuary mouth. The 'point bar' had the least bioturbation and only traces resulting from the activity of amphipods. Yet the 'point bar' had the highest number of species of any point bar within the study. This anomaly was accredited to physical reworking of the substrate by wave action and tidal currents.

The lower and middle shoreface lies above fairweather (minimum) wave base (MacEachern and Pemberton, 1992; Walker and Plint, 1992). The low angle parallel laminations are interpreted to represent amalgamated storm events while oscillation ripple lamination is interpreted to represent waning flow conditions. The oscillation ripple lamination may also be the result of fairweather wave action. The lack of significant amounts of bioturbation suggest frequent high energy conditions. This may be the result of a strongly storm-dominated environment.

Facies Association 5 (FA5) - Fining-upward, well burrowed sandy association

This facies association represents the Wabiskaw Member of the Clearwater Formation within the study area. Other than those locations where glacial erosion has removed the upper McMurray member and the Wabiskaw Member, FA5 is present throughout the study area. The facies association is characterized by well burrowed interbedded sand and mud to sandy mud. The trace fossil assemblage is more diverse and has larger trace fossils than the underlying McMurray Formation. Glauconite is a common accessory mineral within FA5. The entire facies association is relatively thin. Within the cores examined, it did not exceed 3 m. The contact with the underlying McMurray Formation is sharp with evidence of scour. The upper contact with the overlying shale of the Clearwater Formation is sharp or distinct.

FA5 is made up of three facies: chaotically bedded sand with dark grey mud (F18); dark grey mud with sand interbeds (F19); and well burrowed glauconitic sandy mud (F20) (Fig. 20). Contacts between the constituent facies are sharp or gradational.

Facies 18 (F18) - Chaotically bedded sand with dark grey mud

Description:

This facies represents the lowermost facies of the Wabiskaw Member and is present in almost all core examined within the study area. It is characterized by chaotically interbedded sand and dark grey mud with common burrowing (Fig. 20a). Interbedding occurs on a centimetre to decimetre scale. The trace fossils are larger than those observed within the underlying McMurray Formation. The facies typically has a low degree of bitumen saturation and is typically sand-dominated.

The sands of F18 are upper very fine- to lower fine-grained with dispersed medium to coarse sand grains, except where medium to coarse sand infill large vertical burrows. The lower portions of this facies, immediately above the Wabiskaw/McMurray contact, may have dispersed coarse quartz grains. Wavy and lenticular bedding represent the few sedimentary structures that are rarely preserved within this facies. Glauconite is present as an accessory mineral.

The lower contact with the underlying McMurray Formation is always sharp and commonly uneven. The upper contact with dark grey mud with sand interbeds (F19) is typically sharp.

Ichnology:

The trace fossil assemblage within this facies displays the larger burrows and higher degree of burrowing distinctive of the Wabiskaw Member. The facies is commonly to abundantly burrowed resulting in the chaotic nature of the facies' sedimentary structures.

Trace fossils present include: *Planolites*, *Palaeophycus*, *Teichichnus*, *Skolithos*, *Arenicolites*, and *Asterosoma*. Burrows are commonly larger than those of the underlying McMurray Formation. Locally, there are large (approximately 1 cm in diameter), unlined and sharp-walled *Arenicolites* or *Skolithos* with infills that are coarser grained than the surrounding sand and mud (Fig. 20a). These traces are typically found near the top of the facies.

Interpretation:

Facies 18 is interpreted to represent deposition in the upper offshore environment. Sand interbeds are interpreted to reflect distal storm event beds. Mud deposition and burrowing occurred during fairweather conditions. The high intensity of bioturbation suggests deposition within a weakly storm-affected shoreface (MacEachern and

Pemberton, 1992). The paucity of discrete storm beds suggests nearly continuous fairweather conditions and therefore sufficient time for bioturbation.

The facies has a close affinity to a facies interpreted by MacEachern *et al.* (1992a) as representing Cretaceous transgressive deposits. Their "Facies C: Interbedded fine sandstone and shale" was interpreted as lower shoreface to upper offshore deposits of short-lived stillstand shorefaces within an overall transgressive succession. F18 lacks the discrete sandstone storm beds found in "Facies C".

The distinctive large, unlined and sharp-walled *Arenicolites* or *Skolithos* are interpreted to represent the *Glossifungites* ichnofacies. The large burrows are excavated into firmground substrates that have been exhumed (MacEachern *et al.*, 1992b). The substrate is interpreted as firmground since softground substrates could not support such large unlined burrows. The *Glossifungites* assemblage of F18 indicates a firmground surface associated with the top of this facies. Exhumation was the result of transgressive ravinement. The burrows are finally passively infilled by deposition of the overlying unit. MacEachern *et al.* (1992a) reported an abundance of ichnologically demarcated transgressive surfaces of erosion (TSE) within the transgressive deposits of the Cretaceous Viking Formation.

Facies 19 (F19) - Dark grey mud with sand interbeds

Description:

Facies 19 is characterized by dark grey muds with sand interbeds and a lower degree of burrowing than other facies within this association (Fig. 20c, d). Interbedding occurs on a centimetre scale.

The nature of the bedding is lenticular with thick lenses of silt to upper fine sand. The thick lenses of silt and sand may be starved ripples but sedimentary structures are difficult to discern. The ripples are assumed to be oscillation or combined flow ripples. The sands have a very low degree of bitumen saturation. Carbonaceous debris is locally present. Glauconite is a visible accessory mineral. The mud interbeds are typically massive with rare dispersed medium sand grains.

Contacts with the underlying chaotically bedded sand with dark grey mud (F18) are sharp. Contacts with the overlying well burrowed glauconitic sandy mud (F20) or the silty shale of the Clearwater Formation are typically sharp, but may be gradational.

Ichnology:

Facies 19 displays the diversity of trace fossils lacking in the underlying McMurray Formation. The degree of burrow intensity varies from rare to common, but is typically moderate. The trace fossils appear to be most abundant in association with sandier portions of F19. Trace fossils include: *Planolites*, *Teichichnus*, *Palaeophycus*, *Skolithos*, *Arenicolites*, *Thalassinoides*, *Asterosoma*, *Terebellina*, *Helminthopsis*, and possible *Chondrites*. None of the large, unlined *Arenicolites* or *Skolithos*, distinctive of the underlying F18, were observed.

Interpretation:

Facies 19 is interpreted to represent deposition in the lower offshore environment. Sand interbeds are interpreted to reflect distal storm event beds. Mud deposition and burrowing occurred during fairweather conditions. The paucity of discrete storm beds suggests nearly continuous fairweather conditions.

The facies has a close affinity to a facies interpreted by MacEachern *et al.* (1992a) as representing Cretaceous-aged transgressive deposits. Their "Facies D: Pinstripe bedded sandstone, siltstone, and shale" was interpreted as lower offshore deposits of short-lived stillstand shorefaces within an overall transgressive succession.

The paucity of trace fossils within "Facies D" was addressed by MacEachern *et al.* (1992a). The same conclusions apply to F19. Firstly, the lack of traces may reflect an environment unsuitable for infaunal organisms. Cooler temperatures, high turbidity, reduced salinity, and periodic euxinic conditions may have prevented colonization (MacEachern *et al.*, 1992a). The increased bioturbation associated with sandier intervals likely represents colonizers transported to the environment with the sand by storm events or gravity flows. Secondly, the lack of visible burrows may be the result of the lack of lithologic contrast (MacEachern *et al.*, 1992a). Trace fossils are often recognized by the contrasting lithologies of the burrow fill and the surrounding sediment.

Glauconite develops mainly in marine environments where there is some turbulence, low rates of sedimentation, and some organic matter (Reineck and Singh, 1980). As well as indicating a marine environment, the low sedimentation rates suggested by the glauconite is consistent with the low energy (fairweather) conditions interpreted for this facies.

Facies 20 (F20) - Well burrowed glauconitic sandy mud

Description:

Facies 20 is a well burrowed sandy mud with glauconite as a distinctive accessory mineral (Fig. 20b). Distinct bedding features are difficult to discern within this facies. The texture of the facies is best described as diffuse. Wispy mud interbeds are visible. Dispersed sand grains are locally present.

Contacts with the underlying dark grey mud with sand interbeds (F19) are typically sharp, but may be gradational. Contacts with the overlying silty shale of the Clearwater Formation are also typically sharp.

Ichnology:

The degree of burrowing within F20 varies from common to abundant. Discrete trace fossils are difficult to discern due to diffuse nature of this facies' texture. Visible trace fossils include: *Planolites*, *Skolithos*, *Asterosoma*, *Arenicolites*, *Thalassinoides*, *Terebellina*, possible *Zoophycos*, and possible *Chondrites*. Glauconite appears to be concentrated within the burrows of this facies and especially noticeable in the vertical shafts of *Skolithos* or *Arenicolites*.

Interpretation:

Facies 20 is interpreted to represent deposition in the upper offshore environment, similar to chaotically bedded sand with dark grey mud (F18). Facies 20 differs from F18 by its higher degree of bioturbation and significant glauconite content. Sand interbeds are interpreted to reflect distal storm event beds. Mud deposition and burrowing occurred during fairweather conditions. The paucity of discrete storm beds and high intensity of the bioturbation suggests nearly continuous fairweather conditions. The presence of glauconite indicates marine conditions with low sedimentation rates. Similar to F18, this facies has a close affinity to "Facies C: Interbedded fine sandstone and shale" of MacEachern *et al.* (1992a). Facies C was interpreted as lower shoreface to upper offshore deposits of short-lived stillstand shorefaces within an overall transgressive succession.

Facies 20 is interpreted to reflect lower sedimentation rates than chaotically bedded sand with dark grey mud (F18). This is reflected in the higher degree of bioturbation and higher glauconite content.

Figure 8. Large-scale cross-stratified sand (F1). **A)** High angle cross-stratification. 13-17-95-8w4 (63.0 m). **B)** Cross-stratified sand with possible double mud/carbonaceous debris drapes and dispersed coarse sand. 4-3-95-8w4 (102.7 m). **C)** Cross-stratified sand with subrounded mud intraclast. 9-17-94-8w4 (97.1 m). **D)** Mud intraclast breccia (Subfacies 1a). Intraclast breccia with angular clasts with lithologies similar to mud-dominated inclined heterolithic stratification (F4). 2-13-95-8w4 (108.8 m). Numbers in parentheses after well locations indicate depth.

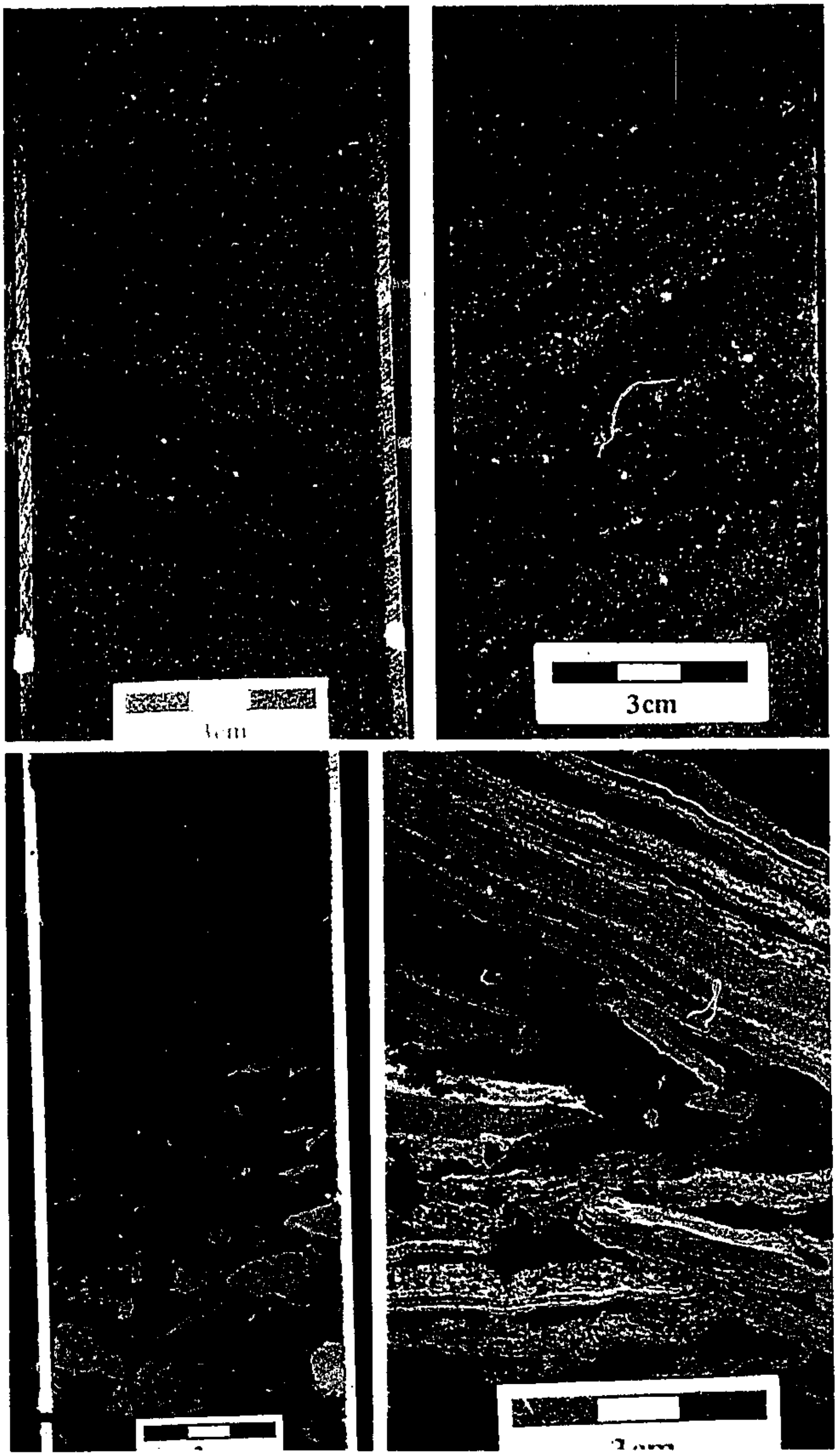
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Figure 9. Small-scale cross-stratification (F2) and grey mud (F5). **A)** Small-scale cross-stratification (F2) (climbing ripples) from a vertical section parallel to flow and wavy bedding. 13-14-95-8w4 (77.8 m). **B)** Small-scale cross-stratification (F2) (climbing ripples) with wavy bedding (below) and flaser bedding (above). 13-14-95-8w4 (75.0 m). **C)** Grey mud (F5) with *Gyrolithes* Type II. 8-9-95-8w4 (34.7 m). **D)** Grey mud (F5) with rooting. 14-10-95-8w4 (32.0 m).

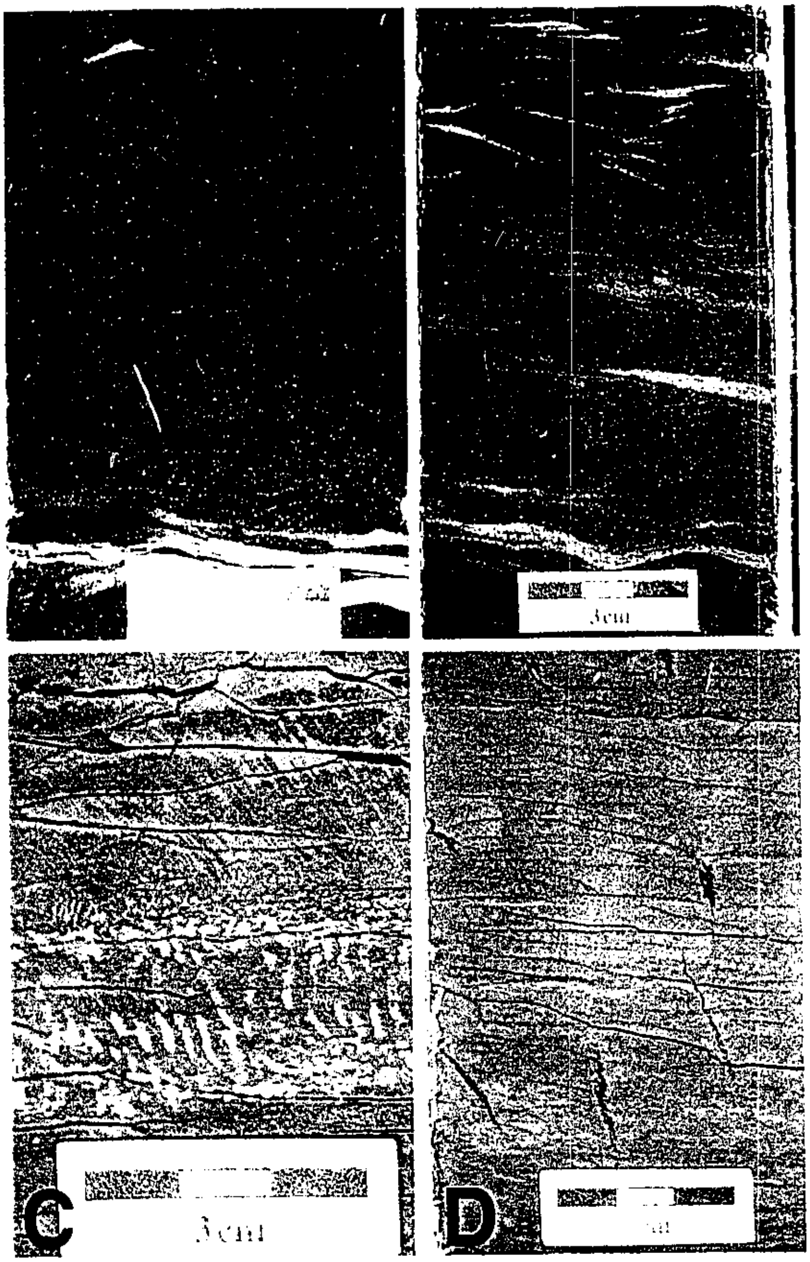
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Figure 10. A) Poorly burrowed mud-dominated IHS. 14-21-94-8w4 (72.8 - 81.8 m). **B)** Burrowed sand-dominated IHS overlying burrowed mud-dominated IHS. 11-29-9-8w4 (60.5 - 69.5 m). Note: "t" denotes the top of the core; "b" denotes the base of the core. Scale bars are 15.0 cm.

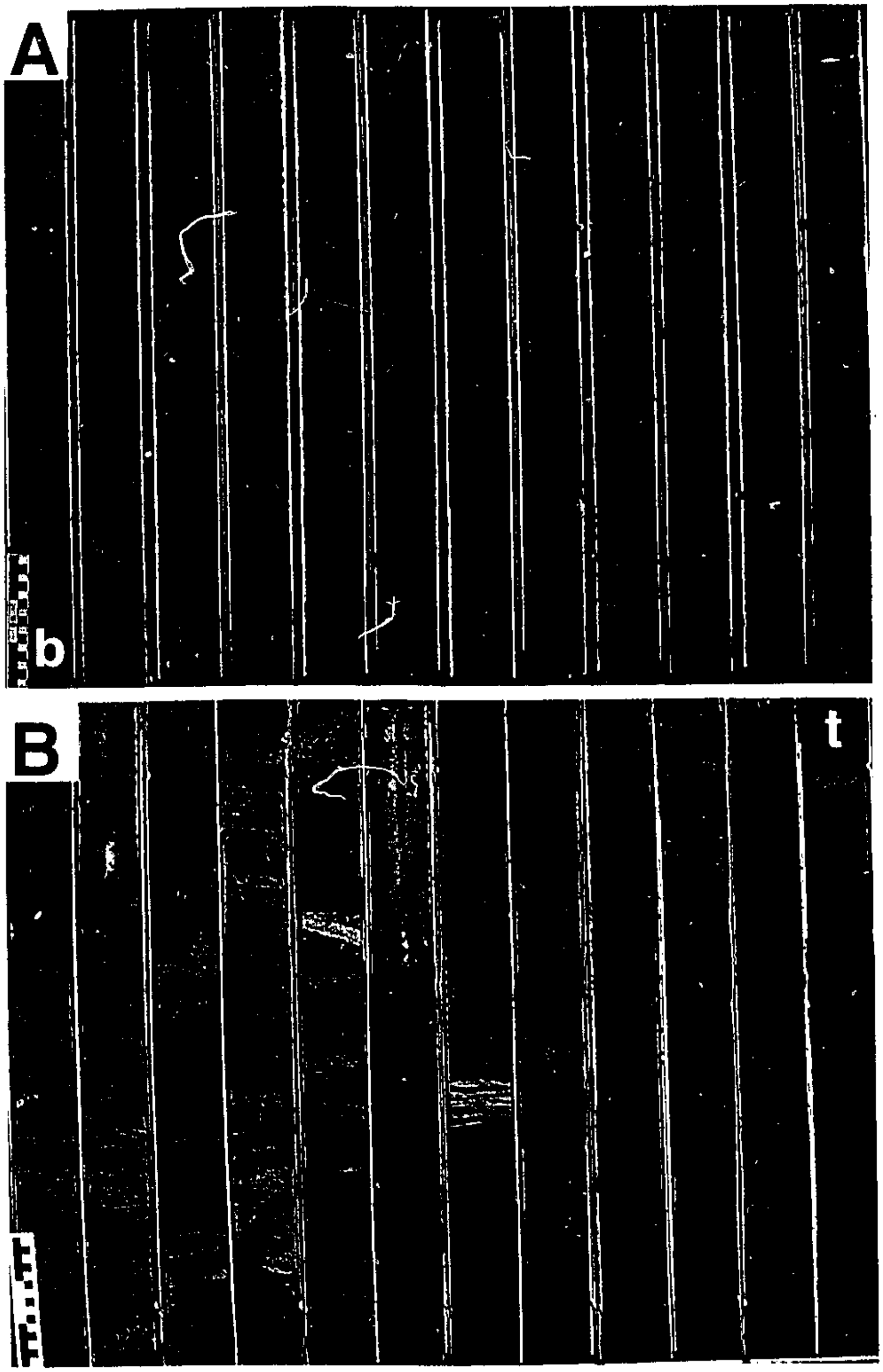
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Figure 11. Sand-dominated IHS (F3). **A)** Scales of cyclic deposition. Interlaminated sand and carbonaceous debris displaying centimetre-scale fluctuations in the debris content. A upward-decrease in the debris content through the bed. Interbedded sand and mud at the decimetre scale. 11-33-94-8w4 (71.4 m). **B)** Interlaminated sand and mud example of the fine layer of an IHS couplet with *Planolites* and possible *Conichnus* (Co). 6-30-94-8w4 (47.3 m). **C)** *Gyrolithes* Type I (Gy) demarcating the burrowed fine layer of an IHS couplet. Note sharp contact with overlying coarse layer. 11-29-95-8w4 (61.8 m). **D)** *Cylindrichnus* (Cy) dominated fine layer of IHS couplet. Note the concentric laminae; a distinctive feature of this trace fossil. 9-17-94-8w4 (65.5 m). **E)** Sharp-walled *Planolites* (P) subtending into muddy fine layer filled with sand from overlying coarse layer. 4-3-95-8w4 (83.7 m). **F)** Monospecific assemblage of *Gyrolithes* Type I in burrowed fine layer. 11-29-95-8w4 (66.0 m).

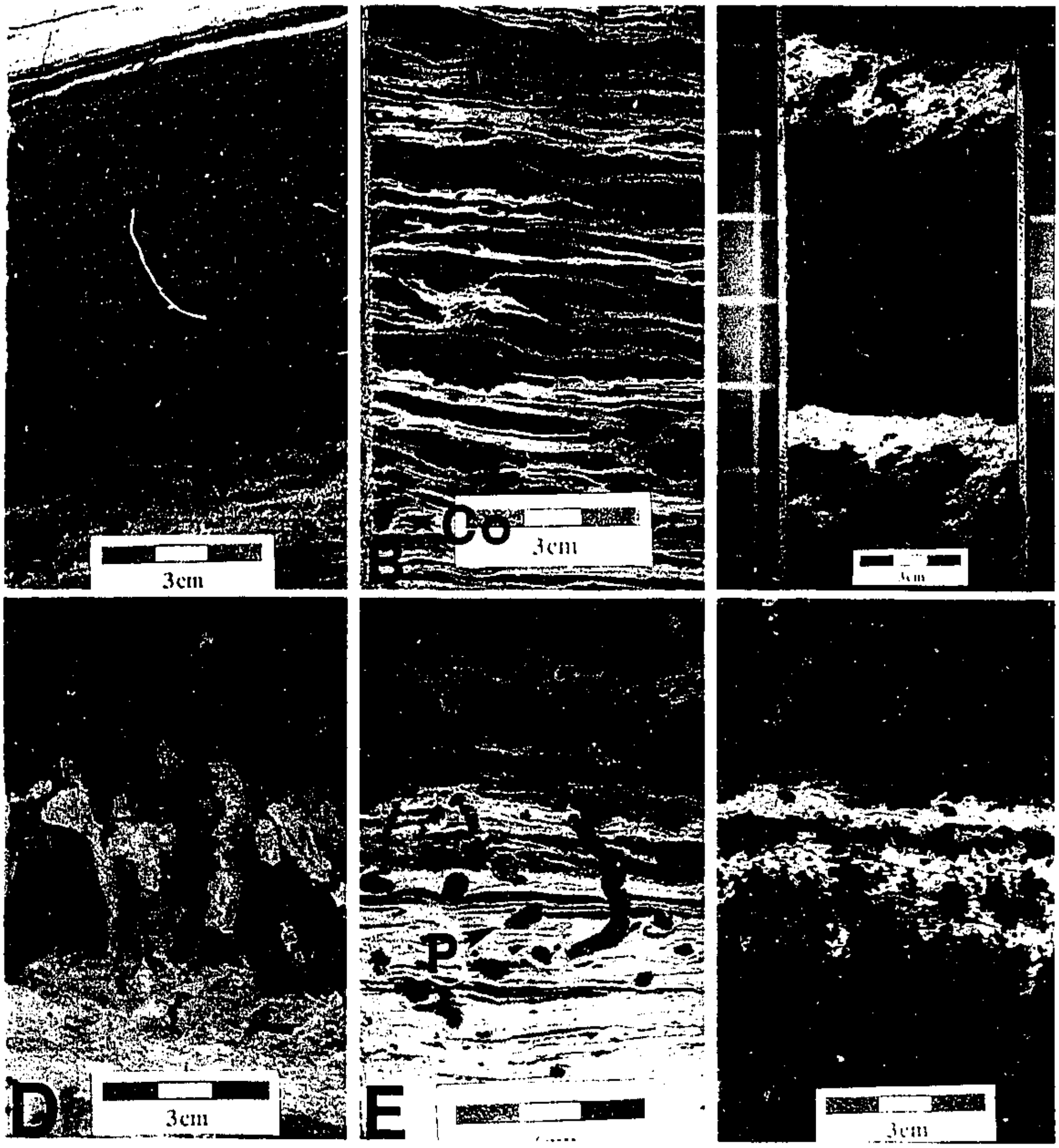
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Figure 12. Mud-dominated IHS (F4). **A)** *Arenicolites* (Ar), *Planolites* (P), and *Skolithos* (Sk) in abundantly burrowed fine layer sharply overlain by poorly burrowed interlaminated sand and mud coarse layer. 11-15-94-8w4 (96.2 m). **B)** Monospecific assemblage of *Gyrolithes* Type II. 16-10-95-8w4 (52.8 m). **C)** Interbedding of burrowed and unburrowed beds. Beds "a" and "b" are abundantly burrowed by *Teichichnus*, small *Arenicolites*, and *Skolithos*. 14-21-94-8w4 (89.1 m). **D)** *Teichichnus* (Te) and inclined shaft (sh). 14-21-94-8w4 (89.9 m).

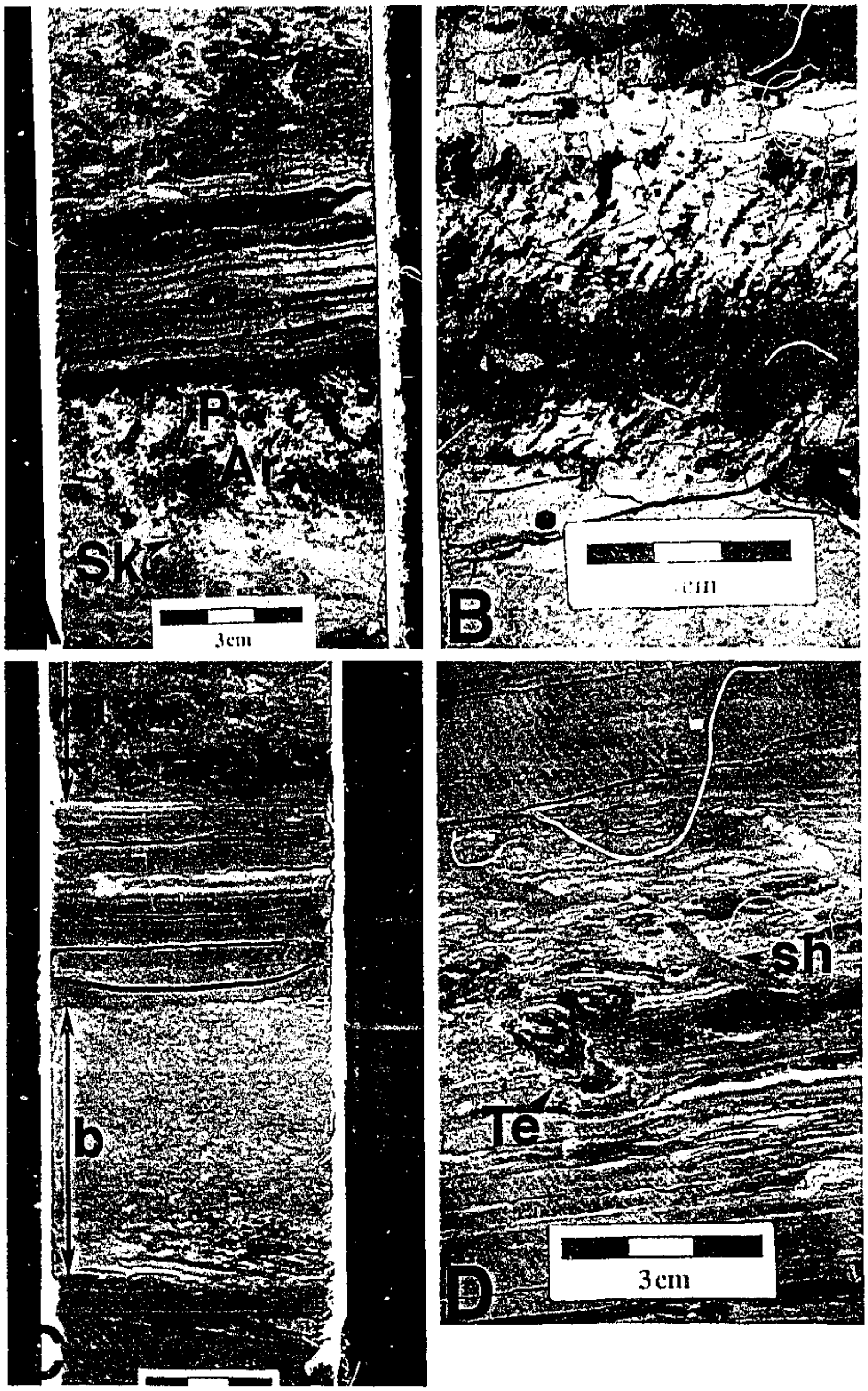
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Figure 13. Flat-lying, interbedded sand and mud (F6). **A)** *Skolithos* (Sk), *Palaeophycus* (Pa), *Teichichnus*, *Planolites*, and a synaeresis crack (sy). 13-14-95-8w4 (50.5 m). **B)** Mud-dominated examples of F6 with lenticular bedding. 16-28-94-8w4 (59.2 m). **C)** Small-scale cross-stratification with indication of multidirectional flow with a synaeresis crack. 11-33-94-8w4 (48.5 m). **D)** *Cylindrichnus* (Cy), *Skolithos* (Sk), and *Teichichnus* (Te). 14-21-94-8w4 (60.2 m). **E)** *Ophiomorpha* (O) and *Planolites* in well burrowed example of F6. 13-14-95-8w4 (72.5 m). **F)** *Skolithos* (Sk) with possible gas escape deformation structures above burrows. Rhythmic interlaminated sand and mud/carbonaceous debris. 11-15-94-8w4 (72.4 m).

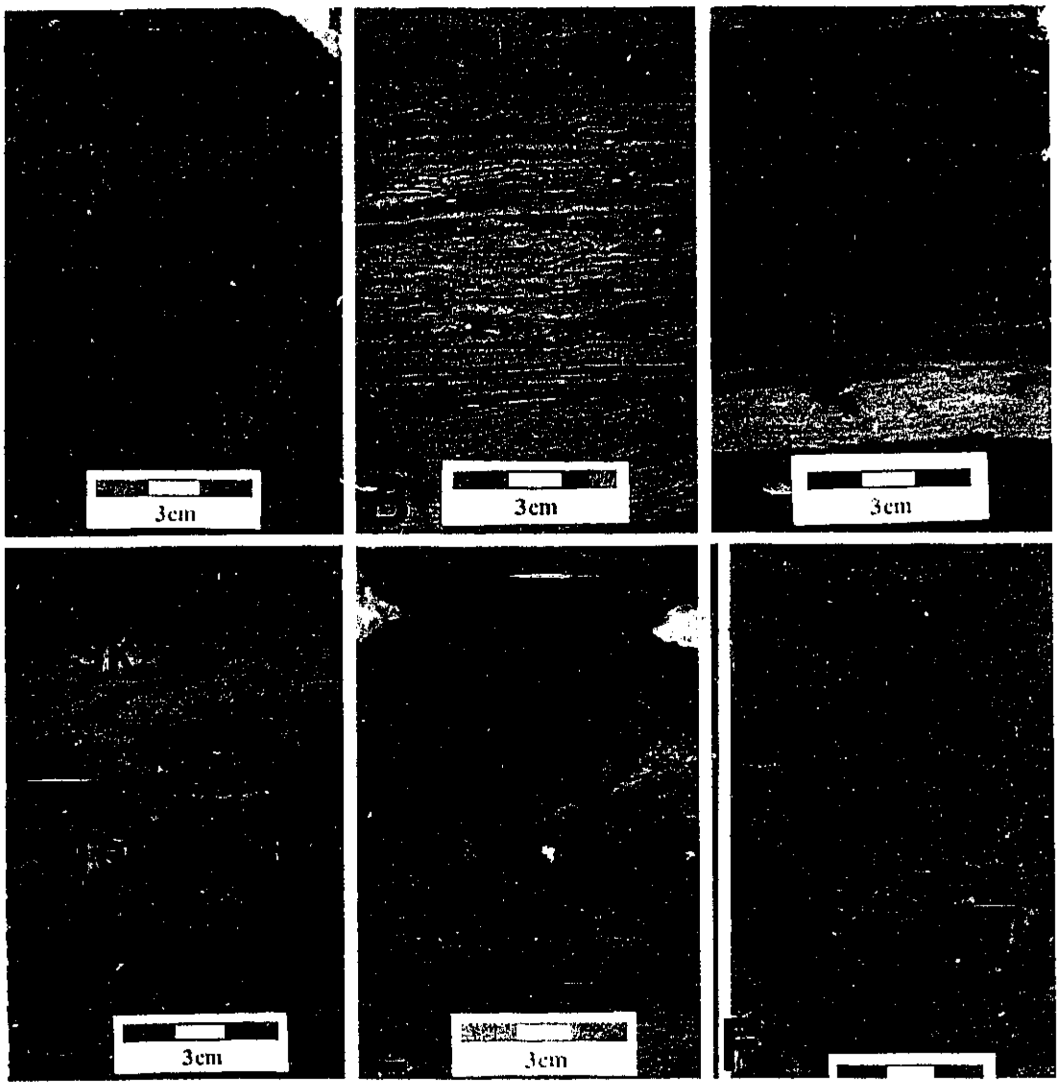
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Figure 14. Massive white to light grey mud (F7), dark grey carbonaceous mud (F8), and coal (F9). **A)** Massive white to light grey mud (F7) with rooting (r). 2-13-95-8w4 (97.6 m). **B)** Dark grey carbonaceous mud (F8) with coal fragments, dispersed sand, and pyrite nodules. 11-29-95-8w4 (103.2 m). **C)** Dark grey carbonaceous mud (F8) with rooting (r). 1-27-95-8w4 (110.0 m). **D)** Rooted contact between dark grey carbonaceous mud (F8) and the underlying massive white to light grey mud (F7). 14-17-95-8w4 (110.6 m). **E)** Coal (F9) with pyrite nodules. 1-27-95-8w4 (109.0 m). **F)** Coal (F9) with grey mud interlaminae. 13-14-95-8w4 (109.0 m).

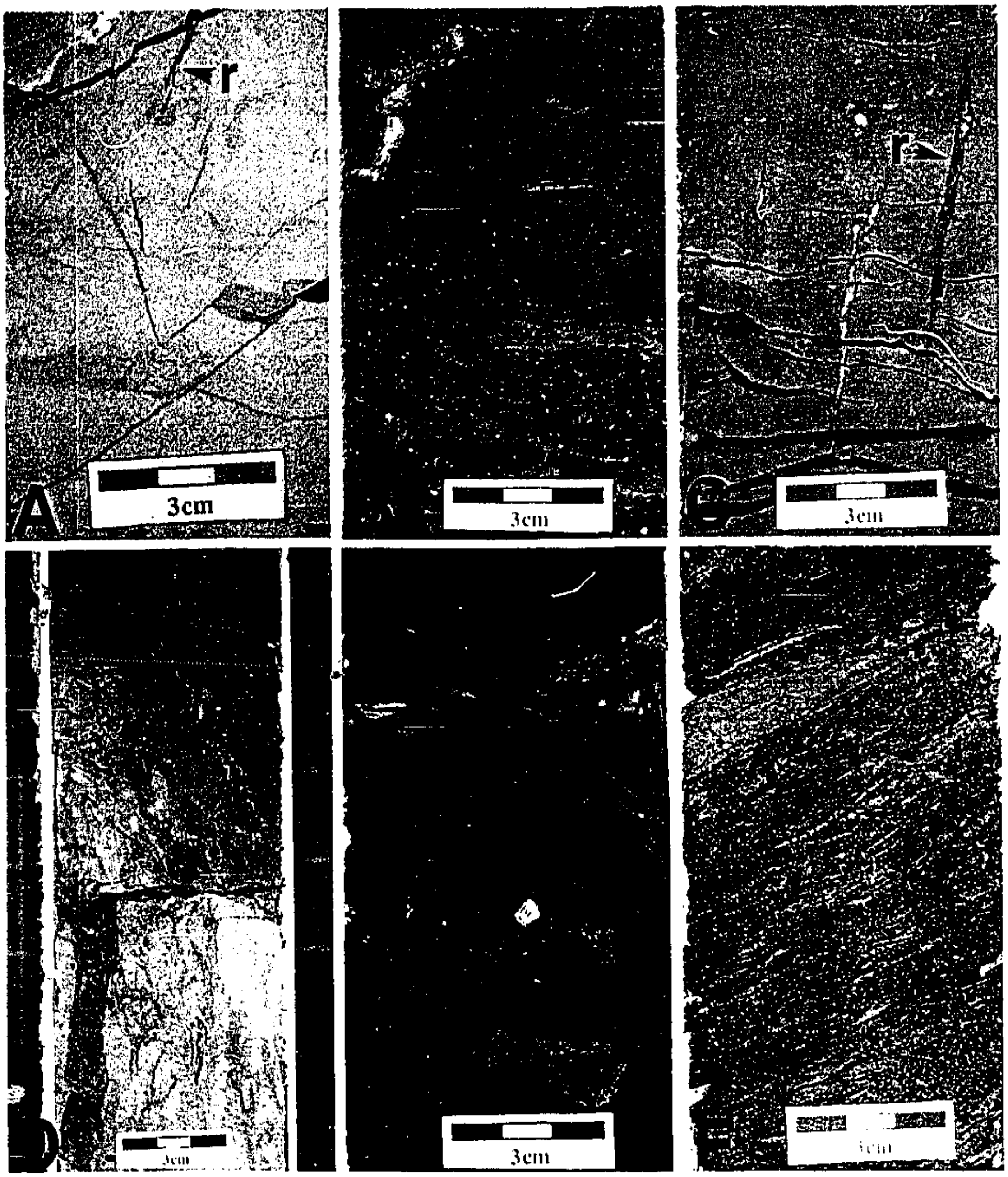
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Figure 15. Chaotic, interbedded sand and mud (F10) and Siltstone (F11). **A)** Chaotic bedding with abundant carbonaceous debris in F10. 14-17-95-8w4 (93.9 m). **B)** Interbedded very fine sand, mud, and carbonaceous debris with *Skolithos* (Sk) and *Planolites* (P) in F10. 1-27-95-8w4 (103.3 m). **C)** Interbedded siltstone and very fine sand with lenticular bedding and possibly large *Planolites* (P). 5-15-95-8w4 (85.7 m). **D)** Inclined small-scale cross-stratification (note inclination of burrows). 13-14-95-8w4 (104.5 m).

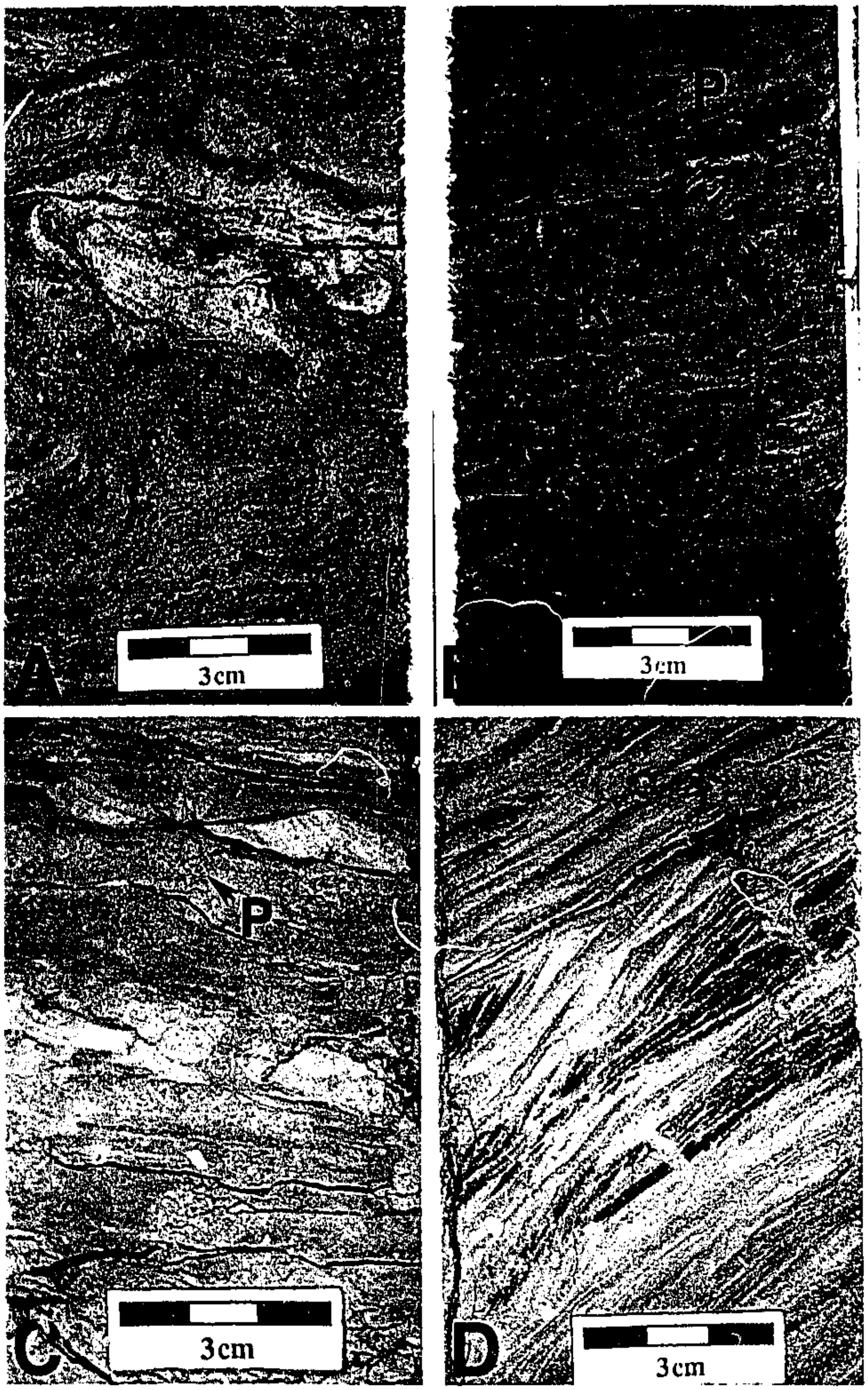
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Figure 16. FA3 examples of sand-dominated IHS (F3a). **A)** Possible *Rosselia* (Ro) and *Palaeophycus* (Pa). 4-23-95-8w4 (39.6 m). **B)** *Ophiomorpha* (O) in inclined stratification. 13-14-95-8w4 (69.1 m). **C)** Microfaulting and rhythmic interlaminated sand and mud/carbonaceous debris. 2-15-95-8w4 (32.5 m). **D)** Small-scale cross-stratification with mud/carbonaceous debris drapes. 8-9-95-8w4 (37.7 m).

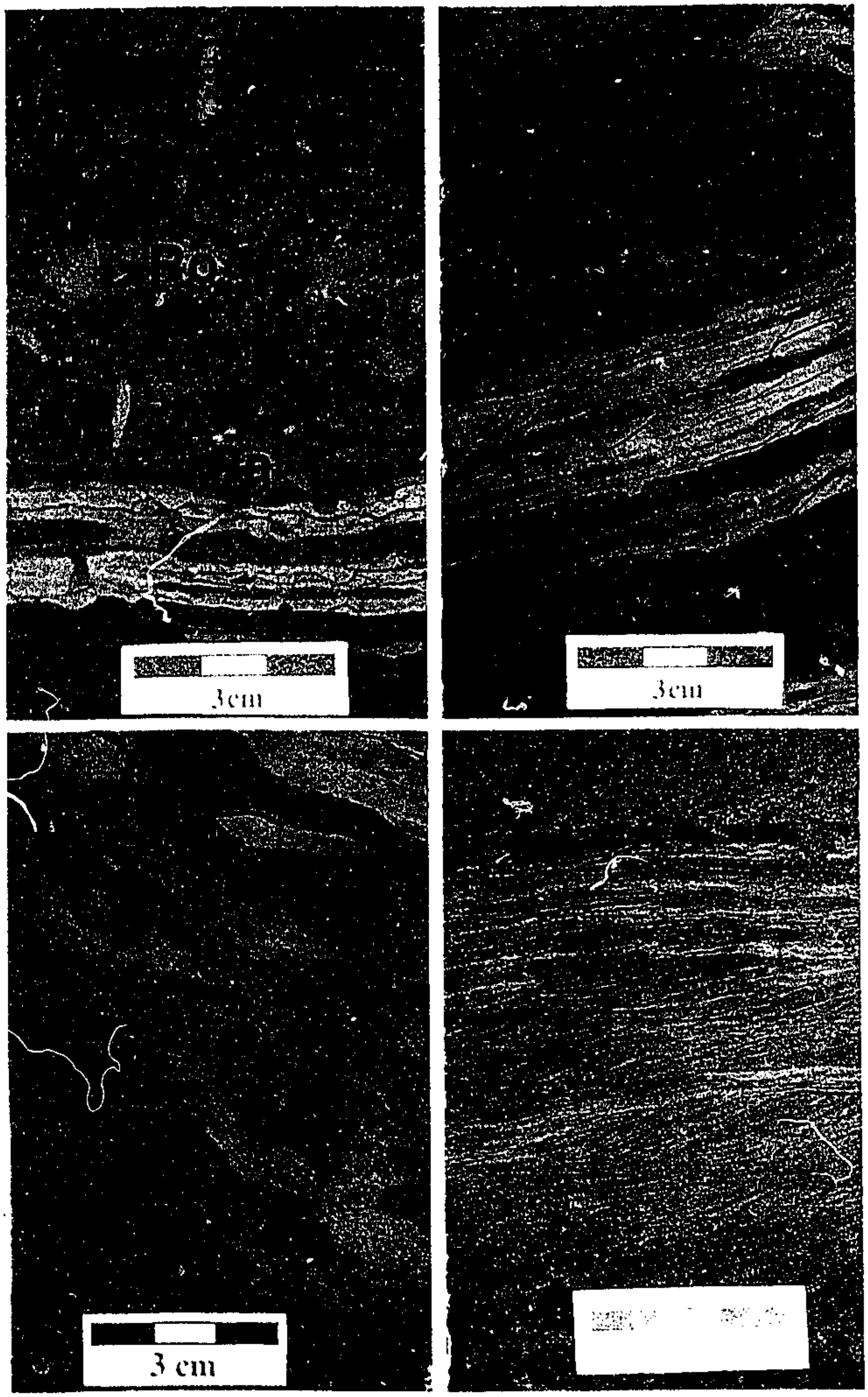
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Figure 17. Laminated to burrowed sand (F12). **A)** Abundantly burrowed bed truncated by low angle parallel laminations. 14-22-94-8w4 (74.2 m). **B)** Ripple cross-stratified sand interbedded with abundantly burrowed beds. 14-21-94-8w4 (57.6 m). **C)** Fugichnia (escape trace) (f) in small-scale cross-stratified sand. 9-17-94-8w4 (61.7 m). **D)** *Arenicolites* (Ar) and *Teichichnus* (Te) in abundantly burrowed interval. 14-9-95-8w4 (21.6 m). **E)** *Gyrolithes* (Gy), *Ophiomorpha* (O), *Skolithos*, and *Planolites* within burrowed interval that is truncated by parallel laminated sand. 9-17-94-8w4 (62.4 m). **F)** *Gyrolithes* (Gy) and *Cylindrichnus* (Cy) within burrowed interval above two escape traces (small arrows) that may reflect readjustment after event bed deposition. 14-22-94-8w4 (73.2 m).

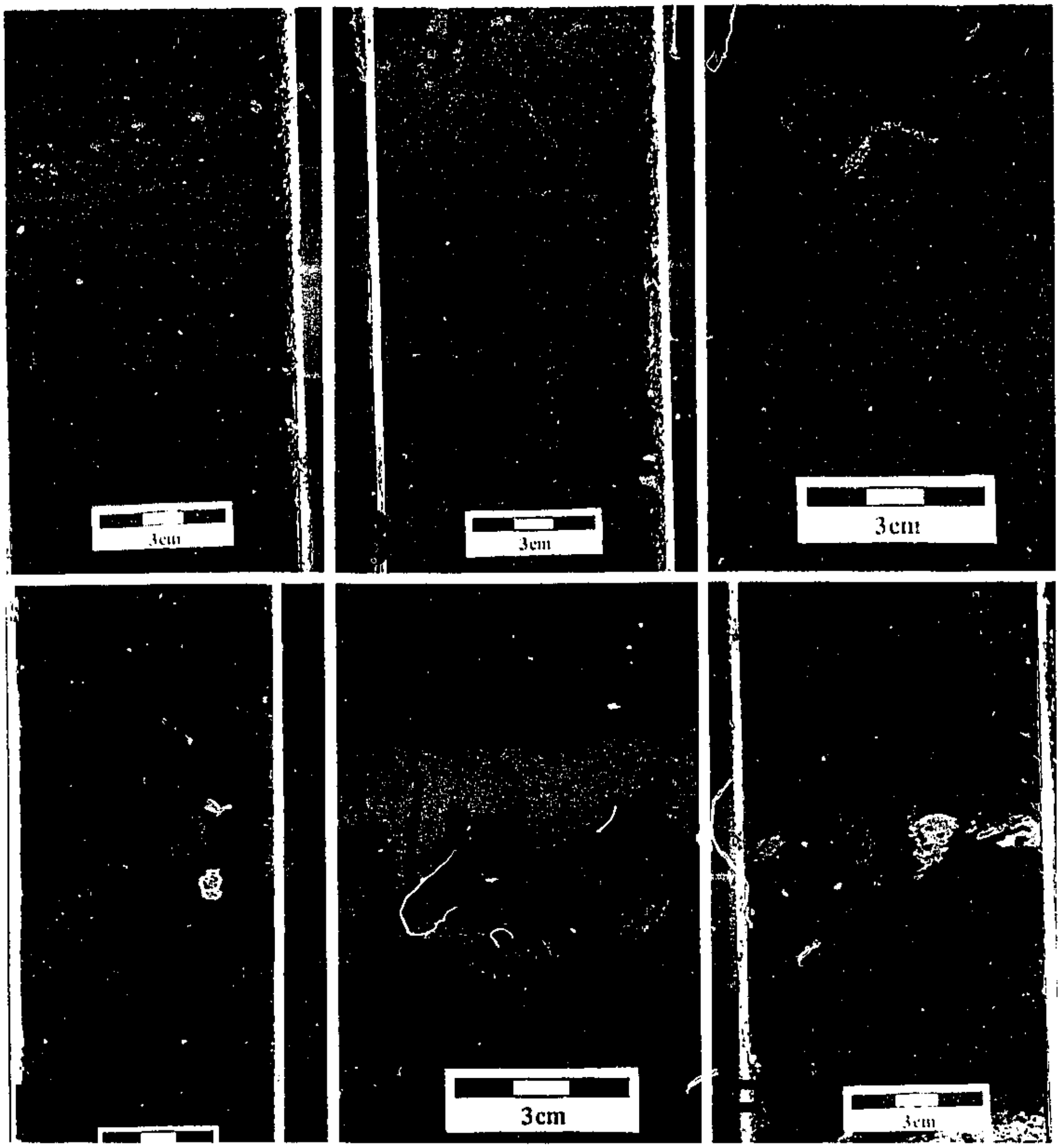
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Figure 18. Well burrowed sand (F13) and well burrowed interbedded sand and mud (F14). **A)** Well burrowed muddy sand (F13). 11-15-94-8w4 (75.2 m). **B)** Well burrowed muddy sand (F13) with possible *Cylindrichnus* (muddy streaks). 14-22-94-8w4 (71.2 m). **C)** *Cylindrichnus* (Cy) and *Skolithos* in well burrowed interbedded sand and mud (F14). 12-12-95-8w4 (77.4 m). **D)** *Skolithos* (Sk) and *Planolites* (P) in well burrowed interbedded sand and mud (F14). 13-17-95-8w4 (8.44 m).

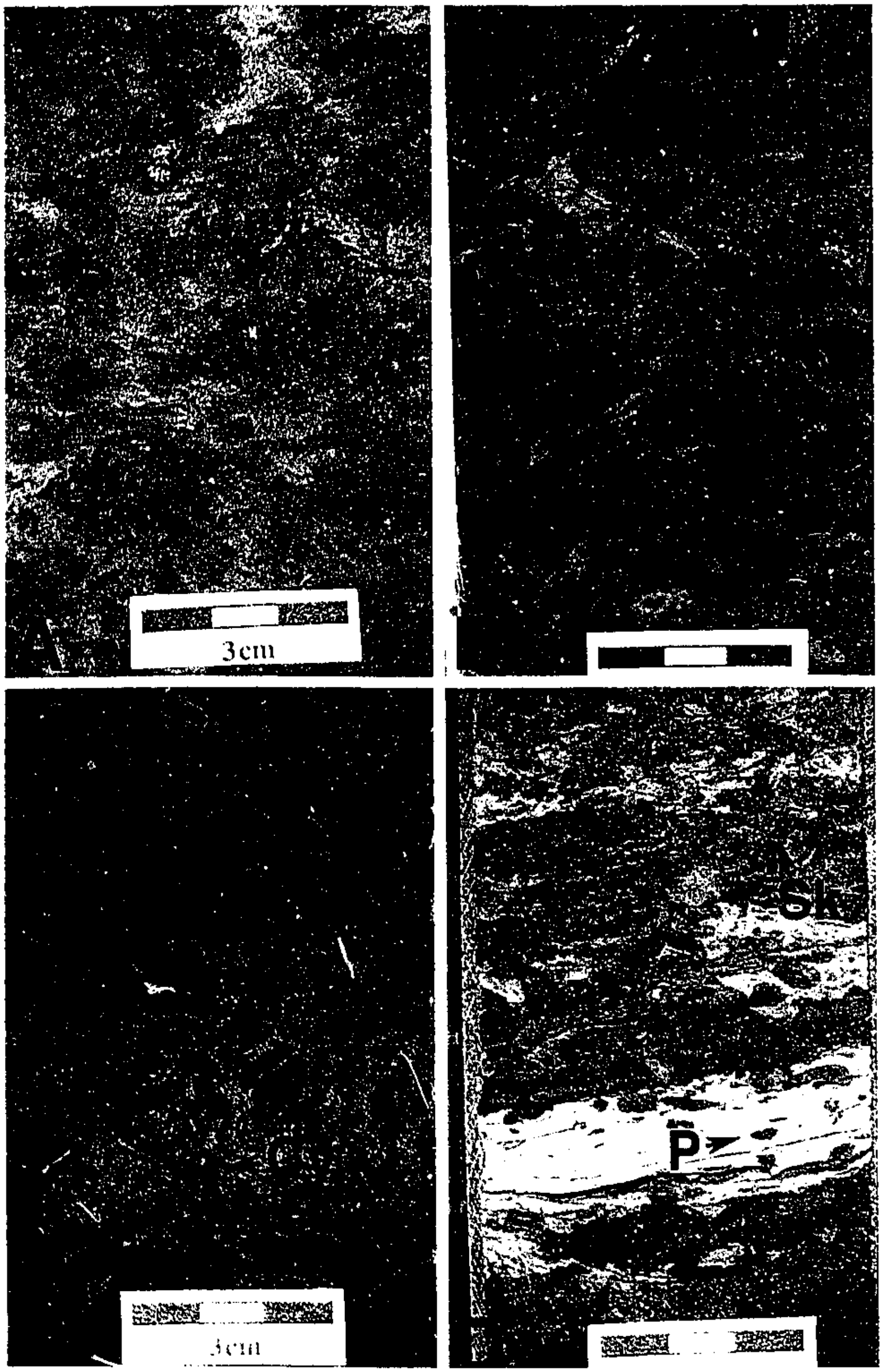
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Figure 19. Facies Association 4. **A)** Poorly sorted fine to coarse sand (F15) with dispersed sand grains and carbonaceous debris. 12-12-95-8w4 (72.0 m). **B)** Large *Asterosoma* (A) in interbedded sand with dark grey mud (F16). 12-12-95-8w4 (70.9 m). **C)** Robust *Teichichnus* in interbedded sand with dark grey mud (F16). 2-22-95-8w4 (19.0 m). **D)** Abundant *Teichichnus* with *Palaeophycus* in fine-grained sand with dark grey mud interlaminae (F17). 2-22-95-8w4 (16.4 m).


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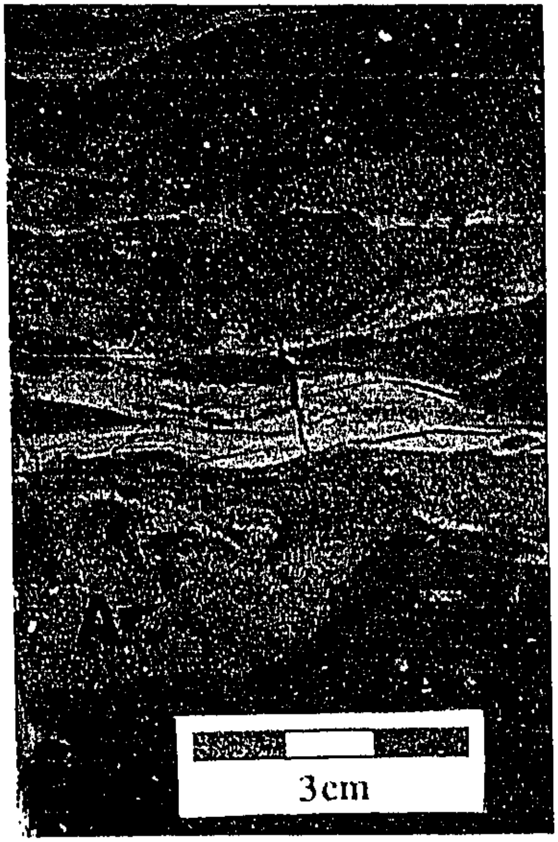
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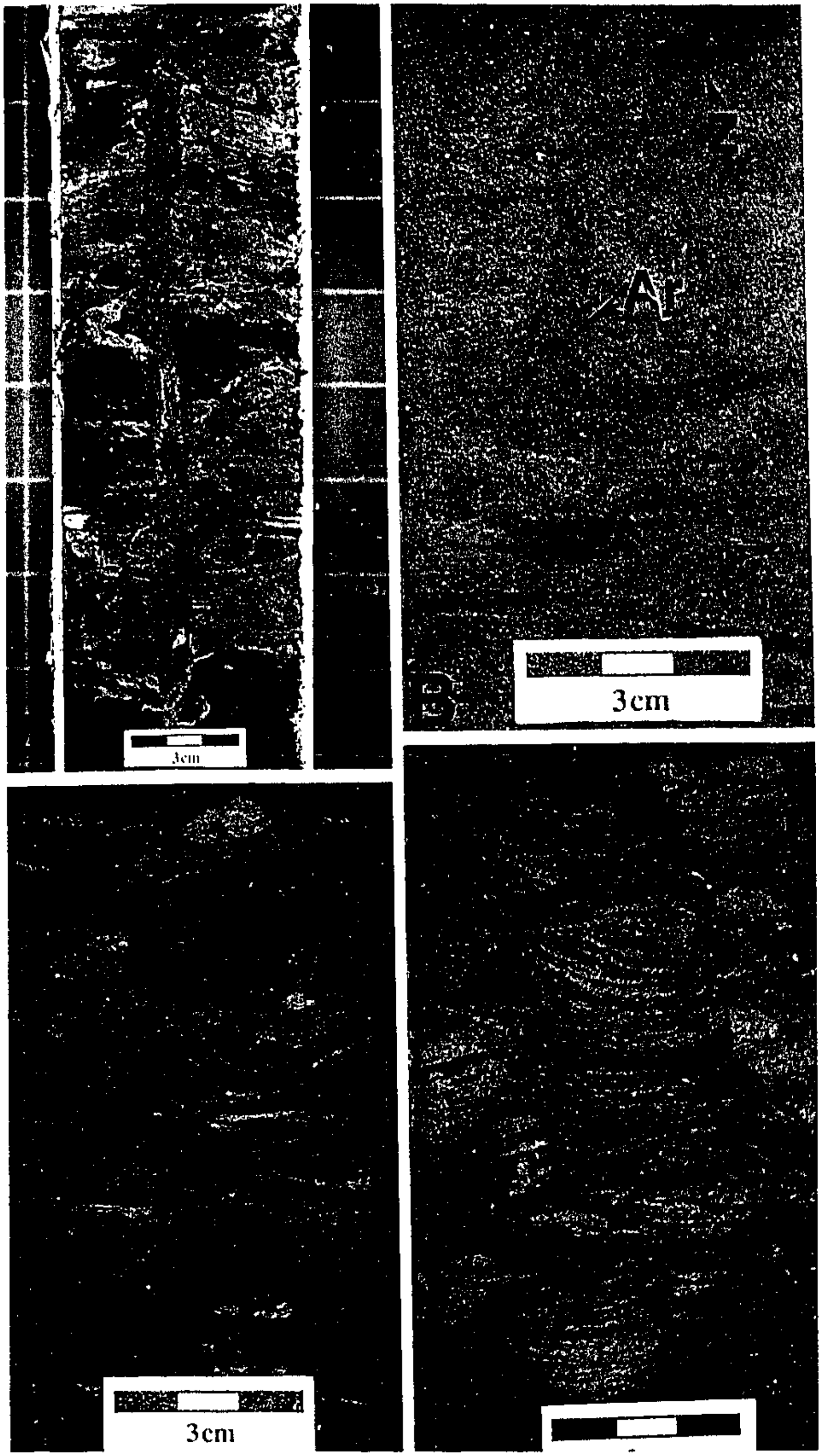
Figure 20. Facies Association 5 (Wabiskaw Member). **A)** Large *Arenicolites* with coarse-grained fill. Possibly an example of the *Glossifungites* ichnofacies. 5-15-95-8w4 (16.4 m). **B)** *Zoophycos* (Z) and *Arenicolites* (Ar) in well burrowed glauconitic sand (F20). 2-13-95-8w4 (78.1 m). **C)** Poorly burrowed dark grey mud with sand interbeds (F19) with lenticular bedding. 6-30-95-8w4 (17.9 m). **D)** Large *Teichichnus* within sand interbed of Facies 19. 11-15-94-8w4 (69.1 m).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Chapter 3 - Stratigraphic Interpretation

Facies Association Interpretation

The facies defined for this study have been grouped into facies associations to provide a useful scale for interpretation of the McMurray Formation and Wabiskaw Member. It is useful to group closely related facies into facies associations for interpretation (Walker, 1992). The high variability of the McMurray Formation and Wabiskaw Member requires this approach to provide a clear understanding of the depositional environments.

Interpreting the vertical succession of the McMurray Formation and Wabiskaw Member as viewed in core requires careful application of Johannes Walther's *Law of the Correlation of Facies* (*Walther's law*). Walker (1992) succinctly paraphrased the law as "in a vertical succession, a *gradational* transition from one facies to another implies that the two facies represent environments that were once adjacent laterally". Grouping the facies of this study into facies association is an attempt to recognize genetically related deposits for application of Walther's law. Clearly an understanding of discontinuities that bound these facies association units is necessary for a complete interpretation of the succession.

This chapter will interpret the facies associations as genetically related units with a clear understanding of the bounding discontinuities. The facies associations will be related to the informal lithostratigraphic terminology of lower, middle, and upper members of the McMurray Formation with sequence stratigraphic terminology applied where applicable. Figure 21 is a stratigraphic cross-section of the McMurray Formation that displays the vertical succession of facies associations and their bounding discontinuities. The sections also relates the facies association to the established lithostratigraphy of the McMurray Formation. Facies Association 1 is found within both the lower and middle members of the McMurray. For a clearer understanding of the sedimentary succession that makes up the McMurray Formation discussion of FA1 will be subdivided into two parts. The lower McMurray examples of the association will be discussed in relation to the genetically related Facies Association 2 and therefore, separately from the middle McMurray examples.

Sub-Cretaceous unconformity

The McMurray Formation unconformably overlies Devonian carbonates (Fig. 21). During this hiatus the top of the Devonian was subjected to periods of subaerial exposure (Carrigy, 1963; Stewart, 1963). The unconformity is a high relief surface with gradients as high as 75.0 m/km (Fig. 5).

This surface marks the lowermost bounding discontinuity of the McMurray/Wabiskaw succession. It is the unconformity that represents the sequence boundary and the lower boundary of the lowstand systems tract (LST) in sequence stratigraphic terms.

Lower McMurray Formation examples of Facies Association 1 (FA1) - Fining-upward sandy association

Facies Association 1 is characterized by a fining-upward succession with sandy facies at its base fining to muddy facies in the upper portions. It makes up the lower portion of the lower member of the McMurray and the entire middle member of the McMurray Formation (Fig. 21). The lower McMurray examples of FA1 are genetically related to the facies of Facies Association 2. The two associations make up the lower member of the McMurray Formation and are differentiated by their distinct textures. FA1 is sand-dominated; FA2 is mud-dominated.

The lower McMurray examples of FA1 can be differentiated from middle member examples. Lower McMurray FA1 units are limited to structural lows on the sub-Cretaceous unconformity. The typical lower McMurray succession of facies within this association occurs in a predictable order. Large-scale cross-stratified sand (F1) overlies a sharp erosional lower contact. This facies grades upward into small-scale cross-stratified sand (F2). Locally, sand-dominated IHS (F3) overlie small-scale cross-stratified sand. The succession is typically capped by grey mud (F5) or another muddy facies of Facies Association 2. Bioturbation is rare to absent within the lower member of the McMurray Formation.

The succession represents deposition within a channel environment. The sharp lower contact of FA1 represents channel erosion and incision. The large-scale cross-stratified sand was deposited as subaqueous dunes within the channel. Small-scale cross-stratified sand was deposited under waning flow conditions on larger channel bedforms and/or on point bar surfaces. The limited examples of sand-dominated IHS were deposited as lateral accretion deposits of a meandering point bar. Grey mud is the result of suspension deposition from the extremely low flow conditions associated with channel abandonment.

The overall succession of the lower McMurray examples of FA1 indicates deposition within a fluvial meandering channel environment. The overall fining-upward successions, paucity of burrowing, general lack of IHS cycles, and association with rooted and coal horizons of FA2 suggest a fluvial origin. Palynological evidence indicates fresh water conditions with rare brackish water influences for the lower member of the McMurray Formation (Flach, 1984).

Previous work and the results of this study agree on this interpretation. Previous studies have assigned a fluvial interpretation to the lower member of the McMurray Formation (Carrigy, 1971; Stewart and MacCallum, 1978; Flach, 1984; Flach and Mossop, 1985; Rennie, 1987; Fox, 1988; Yuill, 1995). Most of these interpretations include the muddy intervals assigned to FA2. Only Rennie (1987) separated the muddy facies for interpretation.

The typical lower McMurray examples of FA1 are characterized by sand units that fine-upwards from medium- or coarse-grained, large-scale cross-stratified sand to fine-grained small-scale cross-stratified sand and then pass abruptly into a silty or muddy facies. This is consistent with all three depositional facies (fully developed, intermediate, and transitional facies) for a meandering fluvial river presented by Jackson (1976). A distinctive variation between the three models is the relative amount of mud capping the fining-upward succession; the mud is thickest within the fully developed facies model (Jackson, 1976).

Smith (1987) presented a point bar lithofacies model for different meandering river conditions. Based on a combination of previous work and his own, Smith (1987) identified a threefold lithofacies classification that represented the variations that occur within point bars as the result of increased tidal influence (Fig. 22). The three point bar types, sequentially downriver, are: 1) fluvial sandy point bar facies; 2) low-energy fluvial and microtidally-influenced (upper estuary) point bar facies; and 3) mesotidally-influenced point bar facies deposited in upper and middle estuary settings. Using this classification, the profile of the lower McMurray FA1 would correspond to the fluvial sandy point bar facies. Allen (1991) presented a section of five sedimentological logs at the fluvial-tidal facies transition of the Gironde estuary. Similar to Smith's model, the textural profile of the fluvial examples compares with those of lower McMurray examples of FA1. The fluvial deposits of the Gironde are coarser-grained (coarse sand to gravel) than those of this study. This likely simply reflects the grain size of sediments available for transport by the fluvial system.

Facies Association 1 represents the fluvial channel deposits that make up the lowermost portion of the lowstand systems tract (LST). The channel sands commonly sharply overlie the sequence boundary (Sub-Cretaceous unconformity) and they occupy structural lows of that surface.

Facies Association 2 (FA2) - Muddy association

Facies Association 2 is characterized by various muddy and coal facies. It constitutes the upper portion of the lower member of the McMurray Formation (Fig. 21). The facies of Facies Association 2 are genetically related to the lower McMurray examples of FA1 and typically have sharp contacts with those underlying facies. The two associations make up the lower member of the McMurray Formation and are differentiated by their distinct textures. FA2 is mud-dominated while FA1 is sand-dominated. FA2 has a sharp, erosive contact with the overlying middle McMurray examples of FA1. The typical FA2 succession of facies lacks any predictable order of facies. Though some associations are discernible, the facies are typically irregularly intercalated with each other.

Previous studies have assigned a fluvial interpretation to the entire lower member of the McMurray Formation (Carrigy, 1971; Stewart and MacCallum, 1978; Flach, 1984; Flach and Mossop, 1985; Rennie, 1987; Fox, 1988; Yuill, 1995). Most of this interpretations include both lower McMurray examples of FA1 and FA2. Only Rennie (1987) separated the muddy facies (FA2) for interpretation. Rennie (1987) used sedimentological and micropaleontogical evidence to interpret a deltaic marsh environment. A wide variety of pollens, including cypress and ferns species, within "overbank muds" and mud drapes within the channel sediments indicate a fresh water input. His "bay-fill" muds contain a few algal species and dinoflagellates indicating occasional influxes of saltwater. Flach (1984) provides palynological evidence that indicates fresh water conditions with rare brackish water influences for the lower member of the McMurray Formation.

The overall succession of FA2 indicates deposition on the channel banks and within the flood basin of a fluvial environment. Reineck and Singh (1980) subdivided the fluvial environment into three major groups: channel deposits, bank deposits, and flood basin deposits. Chaotic, interbedded sand and silty mud (F10) and siltstone (F11) represent bank deposits. Grey mud (F5), massive white to light grey mud (F7), dark grey carbonaceous mud (F8) and coal (F9) represent flood basin deposits. Flood basin deposits are only well developed within fluvial systems where the channel does not migrate actively laterally (Reineck and Singh, 1980). This premise in combination of the paucity of IHS (point bar) deposits within lower McMurray examples of FA1 suggests that the lower McMurray Formation channels did not migrate significantly. This would seem to fit the interpretation that the lower McMurray was confined to the lows of the sub-Cretaceous unconformity.

Crevasse-splay deposits represent the most channel (FA1) proximal facies. The deposits thin and fine away from the channel. Produced by breaches in the channel levee during flood conditions the deposits are the result of decelerating flow with coarser grains and thicker beds being deposited near the channel and finer grains and thinner beds being deposited away from the channel. Chaotic, interbedded sand and silty mud and siltstone represents these depositional conditions. Crevasse-splay deposits are clearly related to levee deposits. While not identified as part of this study, levee deposits should also be present within the lower member of the McMurray Formation. As a positive relief surface feature, levees may have a low preservation potential. In addition, distinguishing levee deposits from other interbedded sand and mud deposits of this association would be difficult. Therefore, some of the interbedded units within the lower McMurray Formation may in fact be levee deposits.

The flood basin deposits are found in a channel (FA1) distal position. Grey mud, massive white to light grey mud, dark grey carbonaceous mud and coal represent this depositional environment. Rooting, indicative of vegetated conditions, is a common feature. The variety of grey muds were deposited within standing bodies of water within the flood basin. Periodic flooding inundates the flood basin and provides the coarser grained sediments. The light colored, well cemented muds may represent pedogenesis within a humid environment. Reducing conditions associated with this environment allows for the formation of pyritic and sideritic nodules and preservation of organic matter. The dark grey carbonaceous muds and coal indicate the increasing organic content of facies deposited further away from the channel. These marsh and peat marsh environments are formed within portions of the flood basin that are protected from marine inundations and fluvial floods under continuously rising ground water conditions. This is another indicator of the transgressive conditions that dominated deposition of the McMurray Formation. Rising sea levels may provide the increasing water tables necessary for swampy conditions (Ainsworth, 1994).

The TSE above FA2 represents the top of the lowstand systems tract (LST) and the base of the transgressive systems tract (TST). Facies Association 2 and the underlying lower McMurray examples of Facies Association 1 represent the fluvial lowstand systems tract (LST).

Transgressive surface of erosion (TSE 1)

The contact between the lower and middle members of the McMurray Formation is interpreted as a transgressive surface of erosion (TSE) (Fig. 21). The contact is sharp and uneven and typically separates the muddy facies of FA2 of the lower McMurray from the sandy facies of FA1 of the middle McMurray. Locally within the study area middle member examples of FA1 directly overlie lower member examples of the same association. Differentiating between the two associations at this sand-on-sand contact is difficult, especially on well logs. In this situation distinction between the two associations is made through correlation with other wells. As the contact is at the base of a channel succession it could be attributed to normal channel incision (autocyclic) processes, but the differing nature of FA1 above and below this contact suggests transgressive (allocyclic) processes. The middle McMurray examples of FA1 have numerous indicators of tidal and marine influence. This suggests that a transgression deposited estuarine sediments over underlying fluvial deposits. Rennie (1987) concluded that a transgression resulted in deposition of the estuarine sediments above his lower McMurray "delta marsh" facies (equivalent to FA2).

The surface is equivalent to the *Transgressive Surface* of Allen and Posamentier (1994). Within the Gironde estuary deposits estuarine point bar, tidal flat, and marsh sediments are separated from the underlying fluvial sediments by this stratigraphic discontinuity. The transgression is the result of a Holocene sea-level rise that converted the alluvial valley to the modern Gironde estuary (Allen and Posamentier, 1994).

The TSE beneath the middle McMurray deposits, like Allen and Posamentier's (1994) transgressive surface, represents the top of the lowstand systems tract (LST) and the base of the transgressive systems tract (TST). Lower McMurray examples of Facies Association 1 and the entire Facies Association 2 represent the fluvial lowstand systems tract (LST).

Definition of an estuary

The definition of an estuary is variable (Fox, 1988; Dalrymple, 1992). Dalrymple *et al.* (1992) provide a definition based on criteria recognizable within the geologic record; a estuary is "the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial processes. The estuary is considered to extend from the landward limit of tidal facies at its head to the seaward limit of coastal facies at its mouth.". In addition, the authors note that estuaries can only form as the result of a relative sea-level rise (transgression). Dalrymple *et al.* (1992) provide a schematic representation of the definition of an estuary and the distribution of physical processes operating in an estuary (Fig. 23).

An understanding of the morphological zonation of an estuary is necessary for interpretation of an estuarine deposit. Previous authors have used variety of terms to describe the various parts of an estuary (Dörjes and Howard, 1975; Smith, 1987; Allen, 1991; Dalrymple *et al.*, 1992; Allen and Posamentier, 1994) (Fig. 24). Dalrymple *et al.* (1992) suggested a classification scheme and standardized terminology for estuarine systems. They proposed that estuaries be classified within a continuum that has wave-dominated and tide-dominated estuaries as its end-members. The classification reflects the dominant energy source (wave or tidal currents) at the marine end of the estuary (Zaitlin *et al.*, 1994). Recognizing the tripartite zonation of an estuary it can be divided into three zones: 1) an inner, river-dominated zone; 2) a relatively low energy central zone where marine energy is approximately balanced with river currents; and 3) an outer zone dominated by marine processes (Dalrymple *et al.*; 1992; Zaitlin *et al.*, 1994). Figure 24 shows the correlation of estuarine morphology terms used by authors referenced in this study. The wave-dominated and tide-dominated facies models of Dalrymple *et al.* (1992) are used as end members in the diagram.

Middle McMurray Formation examples of Facies Association 1 (FA1) - Fining-upward sandy association

The middle McMurray examples of FA1 can be differentiated from lower member examples. The typical middle McMurray facies within this association occur in a predictable order. Large-scale cross-stratified sand (F1) overlies a sharp erosional lower contact. This facies grades upward into small-scale cross-stratified sand (F2). Sand-dominated (F3) and/or mud-dominated IHS (F4) commonly overlie the small-scale cross-stratified sand. Mud intraclast breccia (F1a) is commonly found in association with the IHS. The succession is typically capped by grey mud (F5) or, in the upper portions of the middle McMurray, flat-lying, thinly interbedded sand and mud (F6). Bioturbation is a significant component of the middle McMurray FA1 intervals. The succession of facies is often repeated vertically within the middle McMurray with both complete and incomplete successions being preserved.

The overall succession of the lower McMurray examples of FA1 indicates deposition within an estuarine channel environment. The overall fining-upward successions, abundance of burrowing indicative of brackish water conditions, and abundance of IHS cycles suggest an estuarine channel origin. The sharp lower contact of middle McMurray examples of FA1 (TSE 1) represents channel erosion and incision during transgression and as the result of channel meandering. The large-scale cross-stratified sand was deposited as subaqueous dunes with the estuarine channel. Small-scale cross-stratified sand was deposited under waning flow conditions on larger channel bedforms and/or on point bar surfaces. The sand- and mud-dominated IHS reflects lateral accretion deposition associated with tidally-influenced point bars. The mud-intraclast breccia was deposited as the result of erosion of point bar deposits. Examples of this subfacies found at the bottom of the channel succession represent channel lag deposits with the lag sediments being sourced from the cutbank of the meandering channel (commonly point bar deposits of previous channel positions). Examples of this subfacies higher in the succession, commonly in association with the IHS, represent erosion of the point bar during higher energy tidal conditions and short distance transport within the channel. The grey mud deposits are the result of suspension deposition from the extremely low flow conditions associated with channel abandonment. Flat-lying, thinly interbedded sand and mud reflects deposition within tidal flats flanking an estuarine channel and point bar complex. This tidal flat environment is topographically higher than the point bar and represents the vertical accretion deposits of a meandering channel succession.

Flach (1984) summarized the characteristics of the middle McMurray successions that indicate a channel origin: 1) a scour base; 2) a fining-upward of sand grain size and a fining-upward increase in the number and thickness of mud beds; 3) an upward decrease in the scale of cross-bedding from large-scale trough cross-beds to small-scale current ripples; 4) continuity of bedding from the IHS to the cross-bedded sands, indicating that deposition of the two facies was synchronous; and 5) unidirectional paleocurrent indicators. With the exception of the unidirectional paleocurrent indicators (not measured as part of this core study), the succession demonstrated by the FA1 strongly suggests a channel origin. In addition, the intensity of bioturbation increases upward as observed by Smith (1987) in successions containing mesotidally-influenced IHS deposits. Figure 25 is a litholog and gamma ray log for a single fining-upward succession.

The interpretation of the middle McMurray channel successions is the most contentious issue in understanding the depositional history of the McMurray Formation. Previous interpretations have included fluvial with periodic marine incursions (Flach, 1984; Flach and Mossop, 1985), mesotidally-influenced meandering estuarine channels (Smith, 1987), deltaic (Carrigy, 1971), and estuarine (Stewart and MacCallum, 1978; Fox, 1988; Ranger and Pemberton, 1992; Yuill, 1995). Both ancient and modern examples of tidally-influenced IHS have been reported (Howard *et al.*, 1975; Clifton, 1983; Smith, 1987, 1988a; Rahmani, 1988; Ainsworth and Walker, 1984).

The evidence of tidal influence is clearly represented by the characteristics of the middle McMurray examples of FA1. Ichnological evidence suggests that the facies association had a marine influence. Trace fossils are more abundant and more diverse than the underlying fluvial examples of this association. The trace fossils found within the estuarine examples of the association include: *Planolites*, *Palaeophycus*, *Cylindrichnus*, *Skolithos*, *Arenicolites*, *Gyrolithes*, *Teichichnus*, *Conichnus*, *Lockeia*, and *Terebellina*. The small size of the burrows, the simple morphology of the forms, low diversity, high abundances, and a combination of traces from both the *Skolithos* and *Cruziana* ichnofacies indicate a brackish water environment (Pemberton *et al*, 1982; Wightman *et al*, 1987; Benyon and Pemberton, 1992; Ranger and Pemberton, 1992).

The cyclic nature of the deposits that comprise the middle McMurray examples of FA1 is the strongest evidence for tidal influence. Chemical and physical variations resulting from tidal fluctuations had a significant influence on deposition of facies of FA1. Chemical variations, especially salinity changes, resulted in the production of synaeresis cracks, alternating burrowed and unburrowed zones within the same facies, and burrows by opportunistic (r-selected) organisms that are able to tolerate the unpredictable physiological stresses associated with the estuarine environment. Variations in the physical regime of the estuarine environment are also reflected in the sedimentological and ichnological features of FA1. The characteristic sand-mud couplets of the IHS units demonstrate the cyclic energy levels. Sharp-based sand layers deposited during high flow velocities grade into overlying muds deposited during slack water periods. With vertical successions of IHS measured in metres, the rhythmic deposition of the sand-mud couplets is interpreted to be the dominant feature of these estuarine channels. A similar rhythmic deposition is interpreted for the flat-lying, thinly interbedded sand and mud. Regular fluctuations within the tidal flat environment resulted in deposition of the wavy and lenticular bedding with indications of flow-reversals.

Other features of the facies that constitute FA1 provide evidence of fluctuating energy conditions. Angular mud rip-up clasts are the result of short distance transport of muds allowed to dewater and desiccate during low water level conditions (low tide). Escape traces demonstrate rapid deposition of sand beds. Monospecific assemblages of trace fossils represent colonization of the substrate following an episodic depositional event. Passively infilled inclined shafts (?*Planolites*) within muddy intervals may represent exposure and dewatering of the mud prior to subsequent submergence and infill. Many of the features of the flat-lying, thinly interbedded sand and mud indicate intertidal deposition.

Mud is a characteristic constituent of Facies Association 1. Not only is it a distinctive feature of many of the facies, but it also dominates the upper portions of the middle McMurray examples of FA1. Mud deposition is a significant component of the estuarine system (Dalrymple *et al.*, 1992) and the mud content of estuarine sediments have been used to identify geomorphologic boundaries within estuaries (Dörjes and Howard, 1975; Allen, 1991). Allen's (1991) sedimentological logs of the Gironde estuary demonstrate the increased mud content of estuarine point bars downstream of the fluvial-tidal facies transition. These estuarine point bars contain crossbedded to rippled sand, with abundant mud laminae and flasers (Allen, 1991). The high mud content of middle or central portions of estuaries is the result of the presence of the turbidity maximum. The turbidity maximum acts as a sediment trap of suspension sediments. Density currents (estuarine circulation), tidal current asymmetry, and flocculation contribute to the maintenance of the maximum. The upper, mud-dominated portions of the middle McMurray are interpreted to have been deposited within the turbidity maximum of an estuarine system. This represents the continued transgression of the muddy, central portion of the estuary over the sandy, inner reaches of the estuary. Ainsworth and Walker (1994) suggest changes in relative sea-level to explain the juxtaposition of sand-filled and mud-filled estuarine channels within the Cretaceous Bearpaw Formation-Horseshoe Canyon Formation transition.

In outcrop exposures of the middle McMurray, mud layers drape the entire point bar surfaces with the IHS grading at its base into the underlying large-scale cross-stratified sand (Flach, 1984; Flach and Mossop, 1985). This provides further evidence of tidal processes. Under high tide conditions bankfull stage is achieved with very low flow velocities during the post-flood slack water. Within fluvial systems, bankfull stage is achieved during high discharge flood stage. Flow velocities are at a maximum and mud deposition from suspension seems unlikely.

The succession of facies within FA1 indicates a vertical progression from subtidal to intertidal facies. The lowermost facies of FA1 (F1 - F5) are interpreted to have been subtidally deposited. Features common to FA1 and Clifton's (1983) criteria for subtidal deposits include: 1) extensive lag deposits; 2) units of inclined strata (IHS) more than 2 m thick; 3) laterally persistent thin layers of mud (from reported outcrop evidence); and 4) medium- to large-scale crossbedding. Smith (1988b) interpreted tidal bundles and mud couplets observed in outcrop as evidence of subtidal channel deposition within the McMurray Formation. The 'mud couplets' are composed of mud and/or carbonaceous debris. The tidal bundles and mud couplets were observed within the cross-stratified sands beneath the IHS. Similar bundles were observed as part of this study, but due to limited suitable exposures (requires specific bitumen saturation conditions), these features have not been dealt with in detail. The uppermost facies (F6) of FA1 has evidence of intertidal deposition. The criteria found within F6 that indicate intertidal deposition include: 1) lack of medium- and large-scale crossbedding; 2) directionally inconsistent (not unidirectional) ripple lamination; 3) locally present rooting; and 4) thin, regular alternations of clay, silt, and fine sand.

The middle McMurray examples of FA1 are interpreted to have been deposited within the inner to central zones of the estuary. Similarly, Fox (1988) and Yuill (1995) assign the middle McMurray to the upper (inner) to middle (central) estuary. More specifically, poorly burrowed sand-dominated examples of the association likely reflect inner estuary deposition where river currents dominate. The sparse trace fossils may be the result of periodic incursions of the higher salinity waters during low river discharge and/or spring tides. Studies of the Ogeechee River-Ossabaw Sound estuary support this interpretation. The inner estuarine facies of Dörjes and Howard (1975) is characterized by large-scale cross-stratification with absent to rare bioturbation.

Well burrowed, sand-dominated examples of FA1 likely reflect deposition near the boundary between the inner (upper) and central (middle) zones of the estuary. The increased bioturbation reflects a greater influence by marine water. The occurrence of mud interbeds marks the boundary between fluvial and estuarine channel deposits. In Smith's (1987) threefold lithofacies classification of point bars for different meandering river conditions, the mesotidally-influenced deposits are distinctive for their higher mud content and are interpreted to have been deposited within upper and middle estuary settings (Fig. 22). Mesotidally-influenced point bar facies are characterized by IHS (Smith, 1987). Smith (1987, 1988a) notes the similarity between mesotidally-influenced point bars of the modern Willapa, Daule, and Babahovo Rivers and the middle McMurray Formation IHS deposits. In the Gironde Estuary tidal estuarine point bars (interbedded sand and mud) are assigned to the upper portion of the inner estuary (Allen and Posamentier, 1994).

Well burrowed, mud-dominated examples of FA1 likely reflect deposition within the central (middle) zone of the estuary. Mud deposition is the result of the high suspended sediment concentrations associated with the turbidity maximum of the estuary. Density currents and tidal current asymmetry, clay flocculation , and low energy associated with the central estuary allow for mud deposition. Dörjes and Howard (1975) described their upper-middle and lower-middle estuarine facies as interbedded sand and mud with moderate to abundant bioturbation. Point bars within the middle estuary displayed abundant bioturbation (Howard *et al.*, 1975). In the Gironde Estuary mud deposition dominates the lower portion of the inner estuary (Allen and Posamentier, 1994).

The middle McMurray examples of Facies Association 2 represent the lowermost portion of the transgressive systems tract (TST). The association is the result of continuing transgression placing estuarine deposits in erosional contact with the underlying fluvial lowstand systems tract (TST).

Tidal ravinement surface (TR 1)

The contact between Facies Association 2 and the overlying Facies Association 3 represents a significant stratigraphic horizon. It is sharp, erosional and has significant relief (Fig. 21). Resulting from continued transgression, the contact marks the base of estuary mouth deposits. Therefore, at this surface outer estuary deposits overlie central estuary muddy deposits.

The surface is equivalent to the *tidal ravinement surface* of Allen and Posamentier (1994). Within the Gironde estuary tidal channel, estuary mouth, and tidal delta sand deposits are separated from the underlying inner estuarine sediments by this stratigraphic discontinuity. This irregular surface that scours deeply into the underlying inner estuary deposits is limited to the incised valley. The Gironde tidal ravinement surface commonly has a gravel lag not observed within McMurray Formation of the present study.

Facies Association 3 (FA3) - Flat-lying, sand and mud association

Facies Association 3 is characterized by various flat-lying, relatively laterally extensive, often well burrowed sand and interbedded sand and mud facies. It constitutes the lower portion of the upper member of the McMurray Formation. The flat-lying nature of the upper McMurray has been used to distinguish it from the inclined stratification of the middle McMurray (Mossop, 1980; Flach and Mossop, 1985). FA3 marks the top of the McMurray Formation where FA4 is not present. FA3 has a sharp, erosive lower contact with the underlying middle McMurray examples of FA1. From outcrop studies, Stewart and MacCallum (1978) report that the flat-lying upper McMurray beds truncate the inclined middle McMurray stratification. The upper contact with FA4 or FA5 is sharp.

The constituent facies of FA3 typically do not occur in a predictable vertical order though some general observation may be made. The association is floored by flat-lying, thinly interbedded sand and mud (F6), laminated to burrowed sand (F12), well burrowed interbedded sand and mud (F14), or sand-dominated inclined heterolithic stratification

(F3a). Grey mud (F5) may be found at any stratigraphic level above these facies. Well burrowed sand (F13) was observed exclusively as capping the association.

Locally, recognition of the lower contact of the upper member of the McMurray Formation is difficult. Therefore, correlation of the upper McMurray in this study to those from previous studies is difficult. In addition, the irregular erosion surface at the base of the FA3 suggests that it is an anomalous deposit and may not be correlative to other upper McMurray deposits. Previous studies have assigned a range of interpretations to the upper McMurray Formation. Carrigy (1971) interpreted the interval as deltaic topset beds. The lower portions of the upper McMurray have also been interpreted as off-channel facies such as crevasse-splay, marsh, and brackish bay (Mossop, 1980; Flach, 1984; Flach and Mossop, 1985; Keith *et al.*, 1988; Yuill, 1995). Portions of the upper McMurray have been interpreted as marine deposits such as offshore bars or shorefaces (Stewart and MacCallum, 1978; Fox, 1988; Fox and Pemberton, 1989; Yuill, 1995). Few of the above studies appear to have facies similar to those of the FA3. Well burrowed sand and flat-lying, thinly interbedded sand and mud may be present in some of the previous studies. Pemberton *et al.* (1982) described the upper McMurray sediments exposed in outcrops along the Athabasca River as commonly intensely bioturbated with physical sedimentary structures and discrete trace fossils indistinct. The ichnology of these upper McMurray deposits suggest marine deposition (Pemberton *et al.*, 1982). The marine upward coarsening units of Flach (1984), Flach and Mossop (1985), and reported by Rennie (1987) are the same as FA4 of this study and will be discussed with its interpretation. The deposits of FA3 appear to be anomalous and may have few previously reported counterparts. This may be the result of how the facies have been grouped into this association.

The overall succession of FA3 suggests deposition within the estuary mouth (outer estuary). The sand-dominated inclined heterolithic stratification (F3a) can be distinguished from IHS of the underlying middle McMurray Formation. The estuary mouth IHS has thinner sand and mud interbeds, possibly reflecting the effects of daily tides. Middle McMurray IHS of the central estuary has thicker beds that may represent the amalgamation of daily tidal deposits. The increased occurrence of synaeresis cracks in the F3a deposits may reflect a greater variability of salinity. The estuary mouth IHS has a higher diversity and greater abundance of trace fossils suggesting a greater influence by marine waters. Howard *et al.* (1975) reported more species on point bars in the lower estuary. The outer estuary IHS (F3a) also lacks the characteristic brackish water trace fossils (*Cylindrichnus* and *Gyrolithes*) found in the central and inner estuary examples.

The grey mud (F5) and flat-lying, thinly interbedded sand and mud (F6) deposits may also be present in the outer estuary. Grey muds could have been deposited within any standing body of water within the estuary and are therefore thought to be ubiquitous. Tidal flat deposits (F6) are indicated as fringing deposits throughout the outer zone of the tide-dominated estuary facies model of Dalrymple *et al.* (1992). Tidal flat deposits fringe the length of the mixed tide- and wave-dominated Gironde estuary (Allen, 1991).

The three facies unique to Facies Association 3 (F12, F13, and F14) may represent a continuum of facies. Figure 26 graphically displays the relationship between the facies and their interpreted depositional environment. The dominance of sand or mud and the dominance of biogenic or physical structures is used to interpret the relative nature of the depositional setting. A sand-dominated, moderately burrowed facies represents a high energy environment with significant sedimentation and reworking of substrates and thus suggests an exposed depositional setting. Greer (1975) noted that the preservation of physical structures is limited to those areas of the estuary where wave and current energies were sufficiently high to rework the substrate. A muddy, well burrowed facies represents a lower energy environment where organisms are given sufficient time to thoroughly burrow the substrate and thus suggests an sheltered setting. Visher and Howard (1974) reported that mud and silt deposition occurred within estuarine shoal areas sheltered from ocean waves and strong currents.

Facies 12 represents deposition of an outer estuary sand body with high sedimentation rates within an exposed portion (channel) of the estuary. The preservation of physical structures suggests reworking of the substrate by physical processes. Evidence suggests that F12 is the result of storm deposition. The laminated to burrowed cycles are sharp based sands passing into well burrowed intervals near the top of the beds similar to the 'parallel to burrowed' storm deposits of Howard (1972). The undulatory, parallel laminated very fine- and fine-grained sands likely represent HCS, SCS, and/or QPL, all of which may indicate storm deposition (Arnott, 1993). The trace fossil assemblage include escape traces and displays burrows of opportunistic organisms passing into burrows of the fairweather assemblage. The entire assemblage is more diverse than the underlying central estuary deposits (FA2). Specifically, *Arenicolites* may be found on sandy tidal flats and *Ophiomorpha* may be found on tidal shoal deposits (Pemberton *et al.*, 1992b).

Facies with features similar to F12 have been observed within outer (lower) estuarine deposits. Greer (1975) reported that the inlet shoal of the Ogeechee River-Ossabaw Sound estuary as having similar sedimentary structures. Goldring *et al.* (1978) interpreted their "fine sand facies" as an estuarine sand bank. A coarse-grained sand facies with similar physical structures to those of F12 was interpreted by Yang and Nio (1989) as a component of an ebb-tidal delta at the mouth of an estuary. Archer *et al.* (1994) interpreted their "sheet-like sandstone facies" as lower estuary sandflats and bars.

Well burrowed sand (F13) also represents deposition of an outer estuary sand body, although in a more sheltered area than the laminated to burrowed sand (F12). Sufficient time and protection from physical processes have resulted in a high intensity of burrowing. Thorough bioturbation of the facies has resulted in a muddy sand. The higher diversity of traces again reflects more marine conditions.

Other well burrowed facies similar to F13 have been reported from outer (lower) estuarine environments. Greer (1975) reported that bioturbated muddy sand was found on two portions of the tidal flat: the tidal channel margin and the tidal sand flat. Archer *et al.* (1994) interpreted their "bioturbated sandstone facies" to have been deposited within the lowermost portion of the estuary.

Facies 14 is interpreted to have been deposited as shallow interbedded sand and mud within the estuary mouth. It represents an end member of the continuum of facies displayed by F12, F13, and F14. It therefore is interpreted to be the result of deposition within a sheltered portion of the estuary. Flow energies were sufficiently low to allow mud deposition and intense bioturbation of the substrate.

Interbedded sand and mud constitutes the most abundant facies within the modern estuaries of Georgia (Howard and Frey, 1973). Visher and Howard (1974) reported that mud and silt deposition occurred within shoal areas sheltered from ocean wave and strong currents within in the modern Altamaha estuary in Georgia.

Variations in FA3 are present within the upper member of the McMurray Formation. Locally, poorly burrowed sand-dominated IHS and large-scale cross-stratified sand units can be identified. These may represent ephemeral channels with a significant freshwater content. These channels may have been tributary channels trending perpendicularly to the estuary axis. With only rare occurrences, the channels are not interpreted to represent a drop in sea level.

FA3 represents a continuation of the transgressive systems tract (TST). Rising relative sea levels shifted deposition of the estuary mouth complex up the paleovalley. The tidal ravinement surface was cut and outer estuarine deposits were laid down.

Classification of the Lower Cretaceous McMurray Estuary at O.S.L.O.

The middle McMurray examples of FA1 and the upper McMurray FA3 is interpreted to represent estuarine deposition. Comparison of the McMurray Formation within the study area to the facies models presented by Dalrymple *et al.* (1992) and deposits of other estuaries has allowed for a possible classification of the estuary. The McMurray estuary contains features common to both the wave-dominated and tide-dominated models. The estuary is interpreted to have an estuary mouth complex yet lacks the bay-head delta deposits of the wave-dominated model. While the central portion of the estuary is clearly mud-dominated, deposition is interpreted to have been by channel processes and therefore not part of the central basin of the wave-dominated model. The inner and central zones of the McMurray estuary are dominated by channel deposition yet lack the tidal sand bars and upper flow regime sand flats associated with the tide-dominated model. The presence of fringing tidal flat deposits is consistent with the tide-dominated model. The above evidence suggests that the McMurray estuary is a mixed tide- and wave-dominated estuary.

The facies and facies associations of the McMurray estuary have been compared to a number of other estuarine deposits, both modern and ancient (Fig. 24). The modern Ogeechee River-Ossabaw Sound, Gironde, and Willapa Bay estuaries are all mixed-energy estuaries (Dalrymple *et al.*, 1992). The similarity of facies within the McMurray estuary to those of the above estuaries suggests that it is a mixed tide- and wave-dominated estuary. The estuary of the Cretaceous Bearpaw-Horseshoe Canyon transition has been interpreted as a tide-dominated estuary (Rahmani, 1983; Ainsworth and Walker, 1994). Paleogeographic diagrams of the Bearpaw-Horseshoe Canyon estuary presented by Rahmani (1983) and Ainsworth and Walker (1994) resemble the modern Ogeechee River-Ossabaw Sound mixed-energy estuary and lack the tidal bars and upper flow regime sand flats of the tide-dominated model. Perhaps it too is a mixed tide- and wave-dominated estuary.

Through comparison to modern analogs Smith (1988a, 1988b) has interpreted a mesotidal tidal range for the McMurray Formation. The complete classification of the McMurray estuary would then be: a mesotidal, mixed tide- and wave-dominated estuary.

Wave ravinement surface (WR 1)

The contact between Facies Associations 1 and 3 and the overlying Facies Association 4 represents a significant stratigraphic horizon. It is sharp and erosional but unlike the tidal ravinement surface it is a very low relief planar surface (Fig. 21). Where FA4 is absent this contact is amalgamated with the transgressive surface of erosion beneath FA5 (Fig. 27). Therefore, the surface has regional extent either as an unique surface beneath FA4 or an amalgamated surface beneath FA5. As the result of continued transgression wave erosion associated with shoreline retreat cuts the ravinement surface.

The contact marks the boundary between the underlying estuarine deposits (FA1 and FA3) and the marine deposits of FA4.

The surface is equivalent to the *wave ravinement surface* of Allen and Posamentier (1994). Within the Gironde estuary shoreface sands and shelf muds (each a transgressive deposit) are separated from the underlying estuarine sediments by this stratigraphic discontinuity. Wave ravinement surfaces are planar and of regional extent and may be overlain by fining-upward transgressive deposits, possibly containing retrogradationally-stacked parasequences (Zaitlin *et al.*, 1994). In the Quaternary deposits of the Texas continental shelf the "marine ravinement surface" separates underlying estuarine deposits from the marine deposits (Thomas and Anderson, 1994). Wave ravinement surfaces are not present in tide-dominated settings (Zaitlin *et al.*, 1994). This is further evidence that the McMurray estuary is not simply tide-dominated.

Facies Association 4 (FA4) - Coarsening-upward sandy association

Facies Association 4 is a coarsening-upward association of facies. It is distinctive for its dark grey mud, coarsening-upward profile, and large trace fossils. Where present, it constitutes the uppermost portion of the upper member of the McMurray Formation. FA4 has a sharp, erosive lower contact with the underlying middle McMurray examples of FA1 or FA3 (Fig. 21). The upper contact with FA5 is also sharp.

The constituent facies of FA4 typically occur in a predictable vertical order. A veneer of poorly sorted fine to coarse sand (F15) rests immediately above the wave ravinement surface. Above a sharp contact with F15, interbedded sand and dark grey mud (F16) grades upward into fine-grained sand with dark grey mud interlaminae (F17).

Correlation of FA4 to other McMurray Formation studies is possible due to its distinctiveness. Flach and Mossop (1985) used sedimentology, palynology, and the presence of glauconite to interpret open marine conditions for their upper McMurray "marine unit" which is equivalent to F16 and F17. The unit was interpreted to be an offshore marine bar (Flach, 1984; Flach and Mossop, 1985).

The overall succession of FA4 represents a thin transgressive sand sheet overlain by a prograding shoreface succession. Facies 15 is interpreted to represent the transgressive sand associated with erosional shoreface retreat (Reinson, 1992) as the result of a marine transgression. The abundance of intraclasts, wood fragments, and carbonaceous debris within this unit indicates the incorporation of underlying sediments. The dispersed grains may be the result of winnowing of the finer grains and/or transportation basinward by storms, submarine debris flows, and/or sediment gravity flows. Within the Gironde estuary transgressive deposits consisting of thin veneer shoreface sands and shelf muds were found immediately above the wave ravinement surface (Allen and Posamentier, 1994).

Facies 16 and 17 represent the remnants of a prograding shoreface succession. The interbedded sand and dark grey mud (F16) represents the upper offshore deposits while the fine-grained sand with dark grey mud interlaminae (F17) represents lower to middle shoreface deposits. Sand interbeds of F16 are interpreted to be the result of distal storm event deposition. They are sharp-based and rippled to low angle parallel laminated. The low angle parallel laminated sands are interpreted as HCS, SCS, or QPL. Oscillation and combined flow ripple laminations represent waning flow conditions. Mud deposition occurred during low energy fairweather conditions. Most of the bioturbation occurred under these fairweather conditions. Facies 17 is interpreted as a increase in the predominance storm bed deposits as the lower to middle shoreface progrades into the area. The sand beds are interpreted as amalgamated HCS, SCS, or QPL. The facies include waning flow and fairweather deposits.

The trace fossil assemblage of F16 and F17 is distinctively different than the underlying estuarine deposits. The trace fossils are larger (consistent with more marine assemblages), but appear less diverse and are less abundant than the estuarine examples. The difference is most notable in the upper offshore deposits as other Cretaceous shorelines are commonly burrowed by a higher diversity of forms and in greater abundances (Pemberton *et al.* 1992b; MacEachern and Pemberton, 1992). The trace fossil assemblage of the lower to middle shoreface is more consistent with other reported shoreface deposits. Howard and Reineck's (1972) upper and lower shoreface environments and Greer's (1975) equivalent inlet shoal environment of the Georgia coast have low levels of bioturbation. MacEachern and Pemberton (1992) reported Cretaceous lower-middle shoreface deposits with low levels of bioturbation.

Energy levels and possibly chemical stresses may best explain the low diversity and low abundances of trace fossils within these shoreface deposits. The balance between physical processes and biogenic processes has already been discussed. Insufficient time for colonization and burrowing of a substrate will result in a predominance of physical structures. Howard *et al.* (1975) accredited physical reworking of the substrate by wave action and tidal currents as the reason for limited bioturbation within a zone of the estuary that had the highest species abundances. Similarly, strongly storm-dominated lower-middle shoreface complexes can be recognized by amalgamated storm deposits (tempestites) with minimal preserved biogenic structures (MacEachern and Pemberton, 1992). Flach and Mossop (1985) reported highly bioturbated shale at the base of their marine unit. Perhaps the environment in which the shoreface was deposited was capable of maintaining a diverse and abundant marine assemblage but physical processes dominated and only local assemblages display that abundance.

A contributing factor to the low trace fossil abundances may have been chemical stresses. Perhaps the proximity of the brackish estuary water influenced the depositional environment. Another possibility is that the shoreface was deposited within a broad embayment rather than an open coastline. The restriction of water in such an embayment may have influenced species abundances.

FA4 represents a continuation of the transgressive systems tract (TST). Rising sea levels deposited a transgressive sand above the wave ravinement surface. The progradation of a shoreface indicates slowing or a temporary halt to the transgression. The shoreface reflects an increased sediment supply and less subsidence in relation to *eustatic* sea level, resulting in a *relative* sea level fall. Therefore the prograding, storm-dominated shoreface of FA4 represents a stillstand event. Formation of stillstand sand bodies during an overall transgression on the Texas continental shelf has been reported by Thomas and Anderson (1994). The possibility that this shoreface is in fact the initiation of the highstand systems tract (HST) should be discussed. HST deposits have a progradational stacking pattern, whereas TST deposits have a retrogradational stacking pattern (Van Wagoner *et al,* 1990). It will be demonstrated through discussion of FA5 that the stacking pattern for these sands is in fact retrogradational and therefore a continuation of the TST.

Wave ravinement surface (WR 2)

The low-relief, erosive contact between FA4 and the overlying FA5 is another wave ravinement surface (Fig. 21). Erosion associated with transgression incised the ravinement surface. This transgressive surface of erosion (TSE) is equivalent to a high-energy flooding surfaces (HE FS). High-energy flooding surfaces are low-relief erosional surfaces over which there are indications of an abrupt increase in water depth (Pemberton and MacEachern, 1995; Van Wagoner *et al,* 1990). WR 2 may also be equivalent to the resumed transgression (RT) surface of Walker (1990). RT surfaces are produced under conditions of transgression punctuated by stillstand (Walker, 1990). The RT surface is the upper bounding discontinuity of a shoreface bounded below by the initial transgression (IT) surface. Away from shoreface incision the RT surface becomes amalgamated with the IT surface that marks the base of the shoreface (Walker , 1990). This relationship is represented by the amalgamation of WR 1 and 2 (Fig. 27). This would suggest that WR 1 below the FA4 is an IT surface. While the processes responsible for the surfaces are similar it is not suggested that WR 1 represents the initiation of transgression, but rather a continuation of a transgression recognized in the underlying estuarine deposits. WR 1 does mark the boundary between estuarine and marine deposits.

Facies Association 5 (FA5) - Fining-upward, well burrowed sandy association

Facies Association 5 is a thin, fining-upward association of facies. It is distinctive for its large trace fossils, fining-upward profile, and the presence of glauconite. FA5 represents the deposits of the Wabiskaw Member of the Clearwater Formation. The association is present throughout the study area except where glacial erosion has removed the upper part of the McMurray Formation and the Wabiskaw Member. FA5 has a sharp, erosive lower contact with the underlying FA1, FA3, or FA4. Contacts between the constituent facies are typically sharp, but may be gradational. The upper contact with the overlying shale of the Clearwater Formation is sharp or distinct.

The constituent facies of FA5 typically occur in a predictable vertical order. Chaotically interbedded sand and dark grey mud (F18) is found immediately above the McMurray/Wabiskaw contact. Dark grey mud with sand interbeds (F19) typically forms the middle of the association. Well burrowed glauconitic sandy mud (F20) is found beneath the Clearwater shales. Chaotically interbedded sand and dark grey mud (F18) is typically present whereas dark grey mud with sand interbeds (F19) and well burrowed glauconitic sandy mud (F20) may not be preserved.

Not surprisingly most previous studies of the Athabasca deposits discuss the Wabiskaw Member in only an cursory manner. The Wabiskaw in these studies is commonly only present as thin sands similar to FA5. It is commonly referred to as the indication of fully marine offshore deposits (Stewart and MacCallum, 1978; Fox and Pemberton, 1989; Yuill, 1995). Carrigy and Zamora (1968) differentiated the "McMurray sands" from the "Clearwater sands" (Wabiskaw Member) and interpreted the Wabiskaw as marine. South of the O.S.L.O. area, the Wabiskaw Member occurs in thick (exceeding 15.0 m) sand bodies (Keith *et al.* 1988; Ranger, 1994). Keith *et al.* (1988) interpreted thin bioturbated, glauconitic sands as transgressive deposits and thicker coarsening-upward burrowed sands as almost fully marine, offshore deposits.

The overall succession of FA5 represents thin transgressive deposits. Facies 18 is interpreted as upper offshore deposits. The diversity of trace fossils, abundant bioturbation, and interbedded sand and mud interpreted as distal storm event beds suggest deposition within the upper offshore. A similar facies in the Viking Formation has been interpreted to represent the distal equivalents of short-lived, moderately to highly storm-dominated stillstand shorefaces within an overall transgressive succession (MacEachern *et al.*, 1992a). F18 lacks the discrete storm beds of the Viking deposits and may therefore represent a weakly storm-affected shoreface (MacEachern and Pemberton, 1992).

Facies 19 is interpreted to represent lower offshore deposition. The high mud content and the trace fossil assemblage suggest lower offshore deposition. A similar facies from the Viking Formation has been interpreted as lower offshore deposits of short-lived stillstand shorefaces within an overall transgressive succession (MacEachern *et al.*, 1992b). F19 marks the first occurrence of *Chondrites* and *Helminthopsis*. *Chondrites* is a deposit-feeding structure and *Helminthopsis* is a grazing structure. Both trace fossils are commonly found within the *Cruziana* and *Zoophycos* ichnofacies typical of offshore deposits (Pemberton *et al.*, 1992b). The general paucity of trace fossils may reflect unsuitable conditions for infaunal organisms, with trace fossils associated with sand interbeds being the result of colonizing organisms being transported into the environment by storm events.

Facies 20 marks the return to the upper offshore setting. F20 has a higher degree of bioturbation and higher glauconite content than the similar F18, which suggests lower sedimentation rates than F18. The three facies of FA5 may represent distal equivalents to the thick Wabiskaw sand bodies observed by Keith *et al.* (1988) and Ranger (1994).

In general, FA5 represents a fluctuation in relative sea level with deposition resulting in upper offshore, lower offshore, and then a return to the upper offshore. The large *Arenicolites* or *Skolithos* burrows with coarser grained fills found within F18 have been interpreted as belonging to the *Glossifungites* ichnofacies. As transgressive ravinement is the most favorable process for firmground development and colonization (MacEachern *et al.*, 1992b) these *Glossifungites* ichnofacies trace fossils are interpreted to delineate a third wave ravinement surface (WR 3). Pemberton and MacEachern (1995) used the occurrence of the *Glossifungites* ichnofacies as an indication of the presence of a high-energy FS within the Viking Formation. Within FA5, transgression of upper offshore deposits resulted in the ravinement associated with the high-energy FS. This process exposed the firmground substrate to colonization by suspension-feeding organisms. Subsequent deposition of sediments associated with the ongoing ravinement in shallower water infills the open burrows with the coarser grained sands. Sand beds with equivalent textures as the burrow fills were not observed immediately above the TSE. The *Glossifungites* assemblage indicates a depositional hiatus between the erosional event and sedimentation of the overlying unit (Pemberton and MacEachern, 1995). The stacking of facies 19 and 20 represent progradation of the upper offshore over the lower offshore. Some of the large burrows with higher concentrations of glauconite observed in F20 may represent the *Glossifungites* ichnofacies. The top of FA5 is also interpreted to be a wave ravinement surface (WR 4) with the overlying Clearwater silty shales representing shelfal conditions. Locally, WR 4 incision has resulted in removal of the uppermost FA5 deposits and amalgamation of WR 3 and 4.

FA5 represents a continuation of the transgressive systems tract (TST). Rising sea levels were punctuated by stillstand events. FA5 represents distal equivalents to the resulting stillstand shorefaces. Therefore, FA4 and FA5 are both the result of stillstand events within an overall transgressive sequence. The succession of facies that make up these associations show a overall deepening of depositional environments: lower shoreface (F15), upper offshore (F16), lower to middle shoreface (F17), upper offshore (F18), lower offshore (F19), upper offshore (F20), and shelfal (Clearwater shales). The result is a retrogradational stacking pattern indicative of the TST. The top of the TST (base of the HST) would be marked by the maximum flooding surface somewhere in the Clearwater shales. A coarsening-upward shoreface succession was observed approximately 25.0 m above the top of the Wabiskaw Member at 11-15-94-8w4. This parasequence likely marks the lower portion of a progradational stacking pattern indicative of the highstand systems tract (HST). The maximum flooding surface would then be within the 25.0 m interval above the top of the Wabiskaw Member.

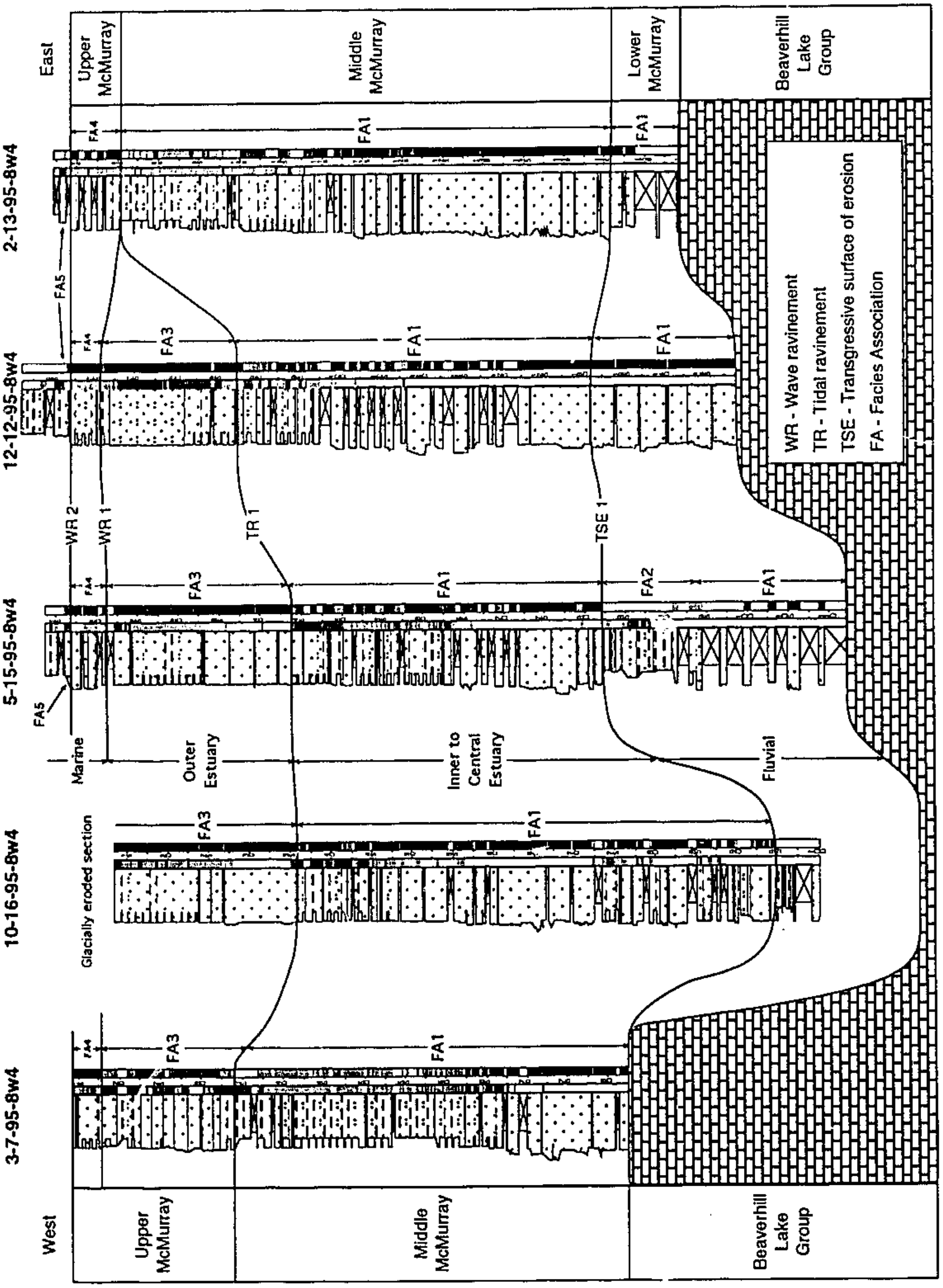
Review of the McMurray/Wabiskaw succession at O.S.L.O.

The McMurray Formation/Wabiskaw Member succession within the study area records the fill of a paleovalley incised into the underlying Devonian carbonates (Fig. 21). While the limited areal extent of the study limits one's ability to identify the margins of the paleovalley, the vertical succession clearly demonstrates the transgression responsible for its infilling. The sub-Cretaceous unconformity is a sequence boundary and marks the base of the incised-valley. Lower McMurray examples of FA1 and FA2 represent the lowstand fluvial deposits. Above the transgressive surface of erosion (TSE 1), inner to central zone sediments (middle McMurray examples of FA1) of a mesotidal, mixed tide- and wave-dominated estuary were deposited. A continued rise in relative sea level resulted in transgression of the estuary mouth complex (FA3) up the paleovalley. The tidal ravinement surface resulted from erosion associated with this transgression. A wave ravinement surface (WR 1) was incised as the result of wave erosion during erosional shoreface retreat as the shoreface transgressed the estuary (Fig. 27). Progradation of a stillstand shoreface resulted in deposition of the FA4 parasequence. Above the second wave ravinement surface (WR 2) distal equivalents to stillstand shorefaces (located to the south) representing the Wabiskaw Member (FA5) of the Clearwater Formation were deposited. Separated by WR 3, FA5 is present as two parasequences. Capped by WR 4 the three parasequences are retrogradationally-stacked. The overlying Clearwater shales marks the maximum marine transgression.

Zaitlin *et al.* (1994) have provided a stratigraphic organization of incised-valley systems. Using their terminology, the valley fill at O.S.L.O. represents the outer incised valley (segment 1) of a coastal plain incised-valley system. Segment 1 is characterized by backstepping fluvial and estuarine deposits overlain by transgressive marine sands and shelf muds (Zaitlin *et al.*, 1994). The fill of the paleovalley within the study area appears to record only a single transgressive cycle and is therefore termed "simple". The middle McMurray within the study area has multiple channel incision events that have been interpreted as possible fluctuations in the rate of transgression, but no additional lowstand events (fluvial deposits upon a sequence boundary) were observed. The complexity of the fill within the McMurray interval and observation of possible highstand systems tract parasequences elsewhere within the McMurray (Ranger and Pemberton, 1992) certainly allow for the interpretation of the McMurray as a compound fill.

The McMurray incised-valley fill at O.S.L.O. was deposited under highly aggradational conditions. Subsidence from dissolution of the Prairie evaporites and rising eustatic sea levels resulted in significant accommodation space even with abundant sediment supply. McMurray sediments had a high preservation potential as the result of the rising relative sea level. Tidal ravinement, wave ravinement, and high-energy flooding commonly remove portions of underlying deposits (Allen and Posamentier, 1994; Pemberton and MacEachern, 1995). McMurray sediments were preserved below these erosive processes as the result of sufficient accommodation space.

Figure 21. Stratigraphic cross-section of the McMurray Formation showing correlation between lithostratigraphy and the facies associations of this study (datum: top of the McMurray Formation). Lithology patterns same as lithologs in Appendix A. Left vertical bar on lithologs is the intensity of bioturbation; right vertical bar on litholog is degree of bitumen saturation. Depth scale is in metres.


West
East
3-7-95-8w4
10-16-95-8w4
5-15-95-8w4
12-12-95-8w4
2-13-95-8w4
Upper McMurray
Middle McMurray
Lower McMurray
Beaverhill Lake Group
Glacially eroded section
FA1
FA2
FA3
FA4
FA5
WR 2
WR 1
TR 1
TSE 1
Marine
Outer Estuary
Inner to Central Estuary
Fluvial
WR - Wave ravinement
TR - Tidal ravinement
TSE - Transgressive surface of erosion
FA - Facies Association

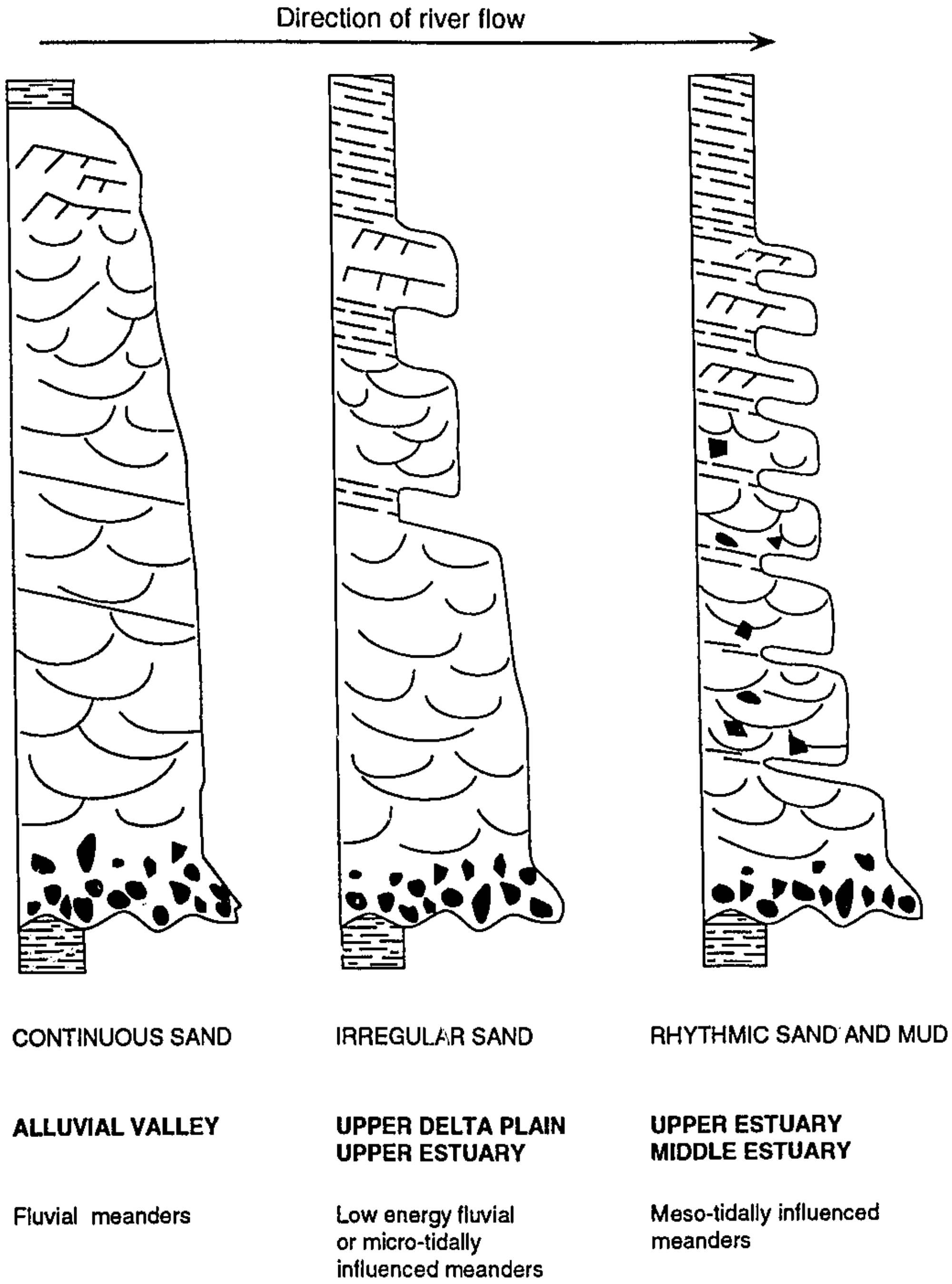


Figure 22. Lithofacies classification for meandering river-estuarine point bar deposits (modified from Smith, 1987).

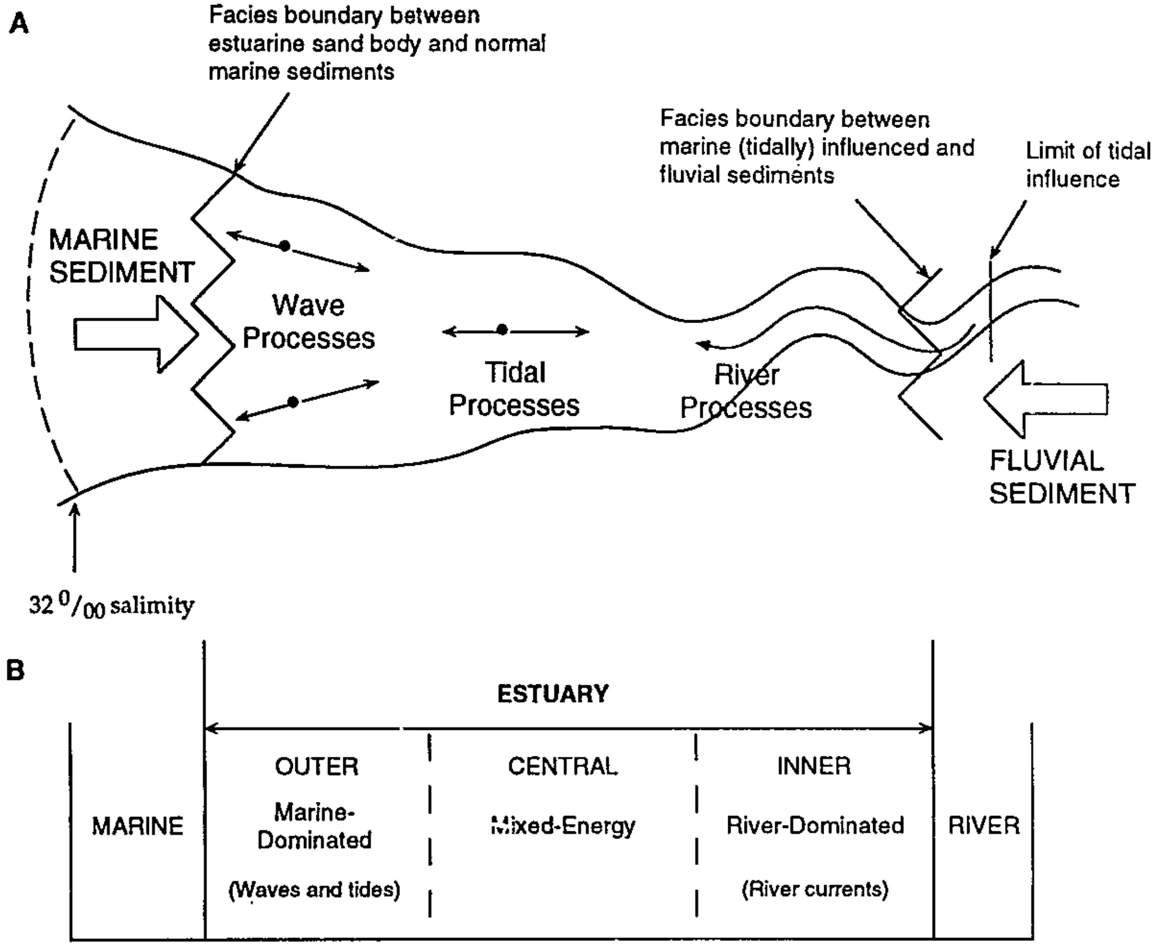


Figure 23. A) Schematic representation of an estuary. B) Tripartite zonation of the estuary. (modified from Dalrymple *et al.*, 1992).

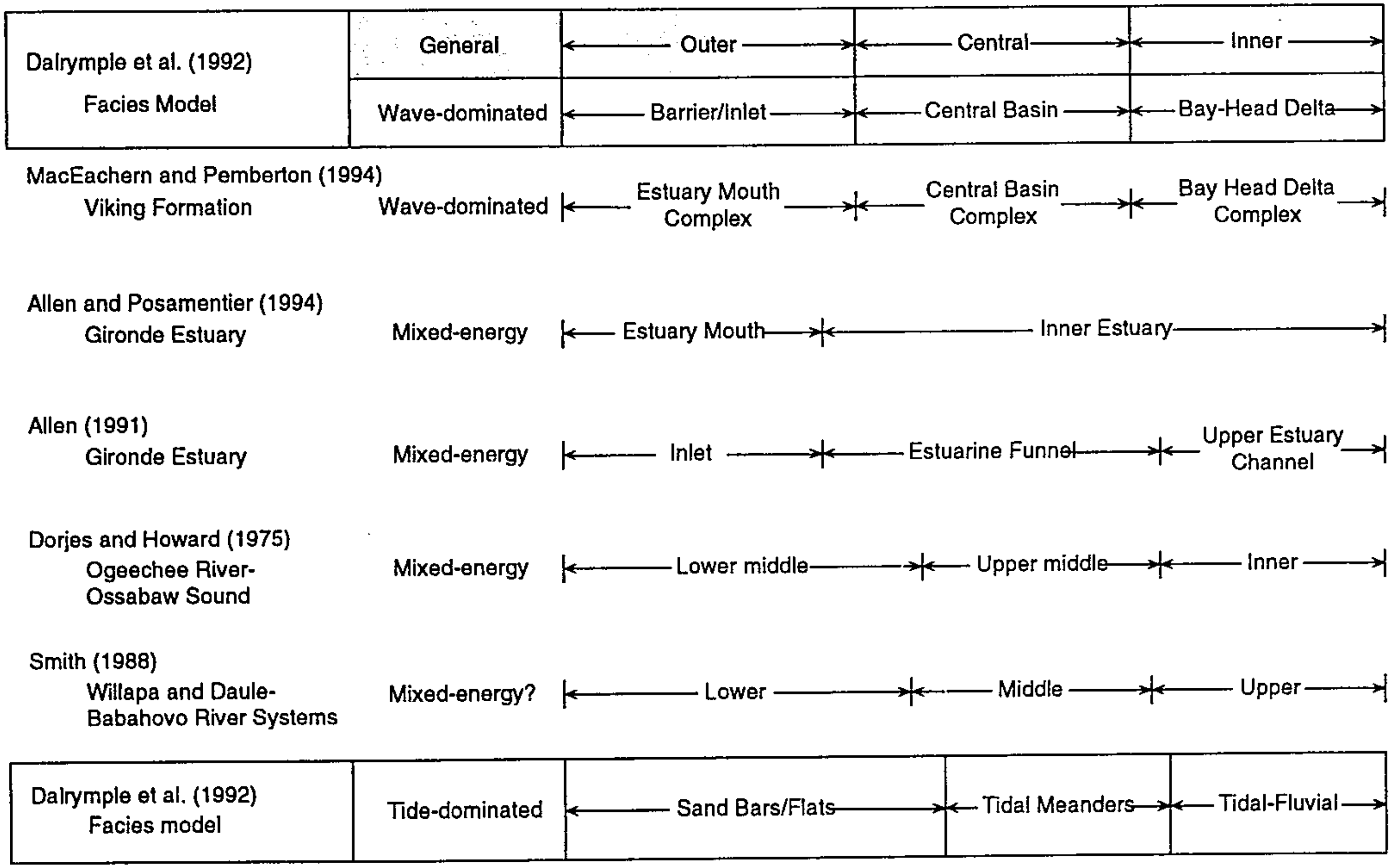
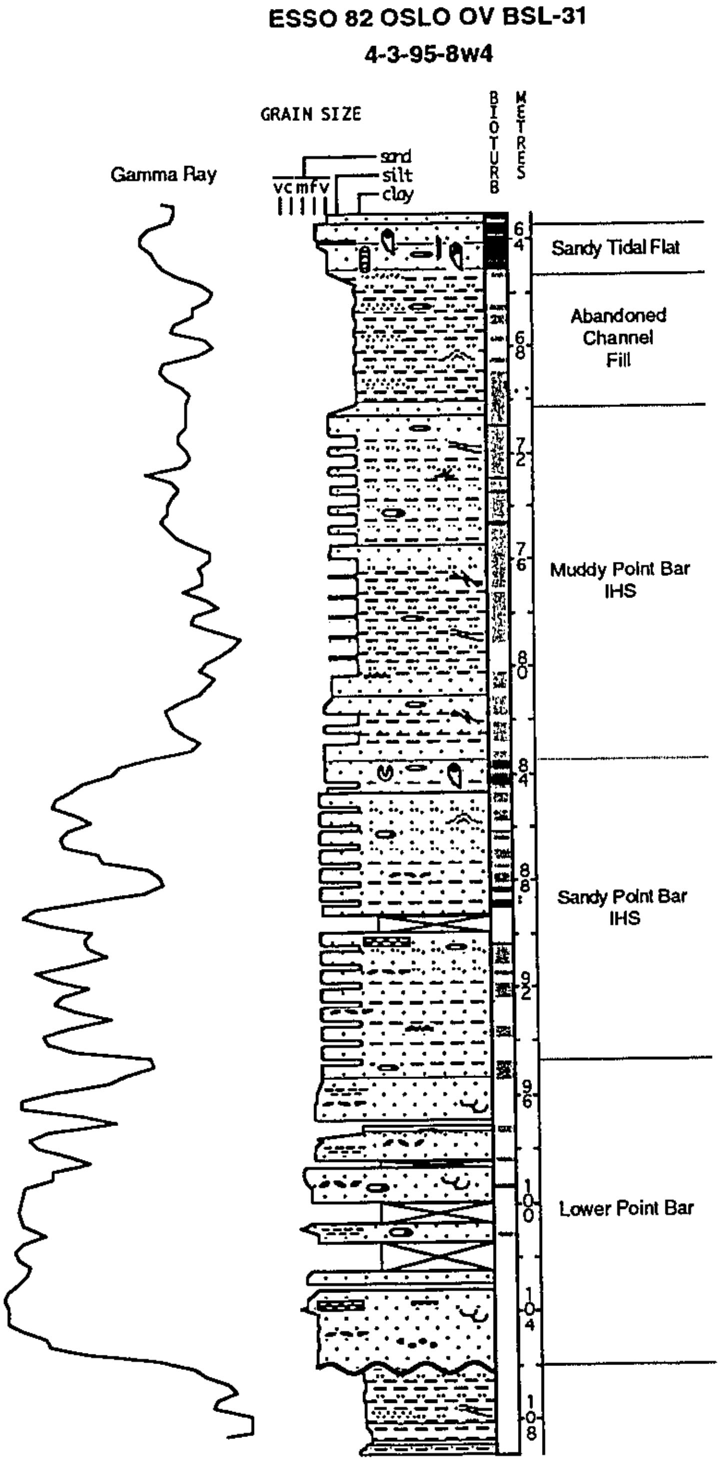


Figure 24. Summary of estuary zonation schemes used in this study. The McMurray Formation at O.S.L.O. is interpreted as a mixed-energy esturaine deposit.


ESSO 82 OSLO OV BSL-31

4-3-95-8w4

Figure 25. Interpretive strip log and gamma ray log for 4-3-95-8W4. See Appendix for legend.

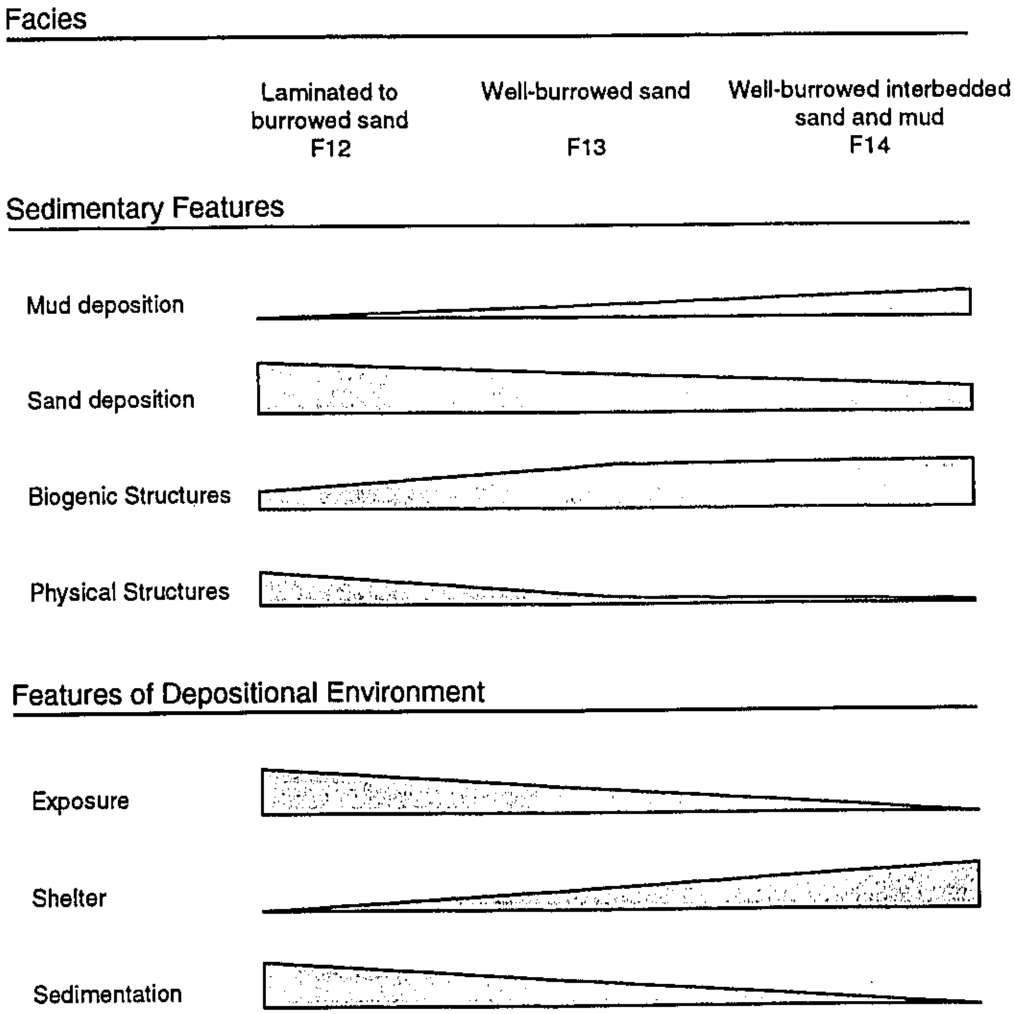


Figure 26. Relationship of Facies 12, 13, and 14.

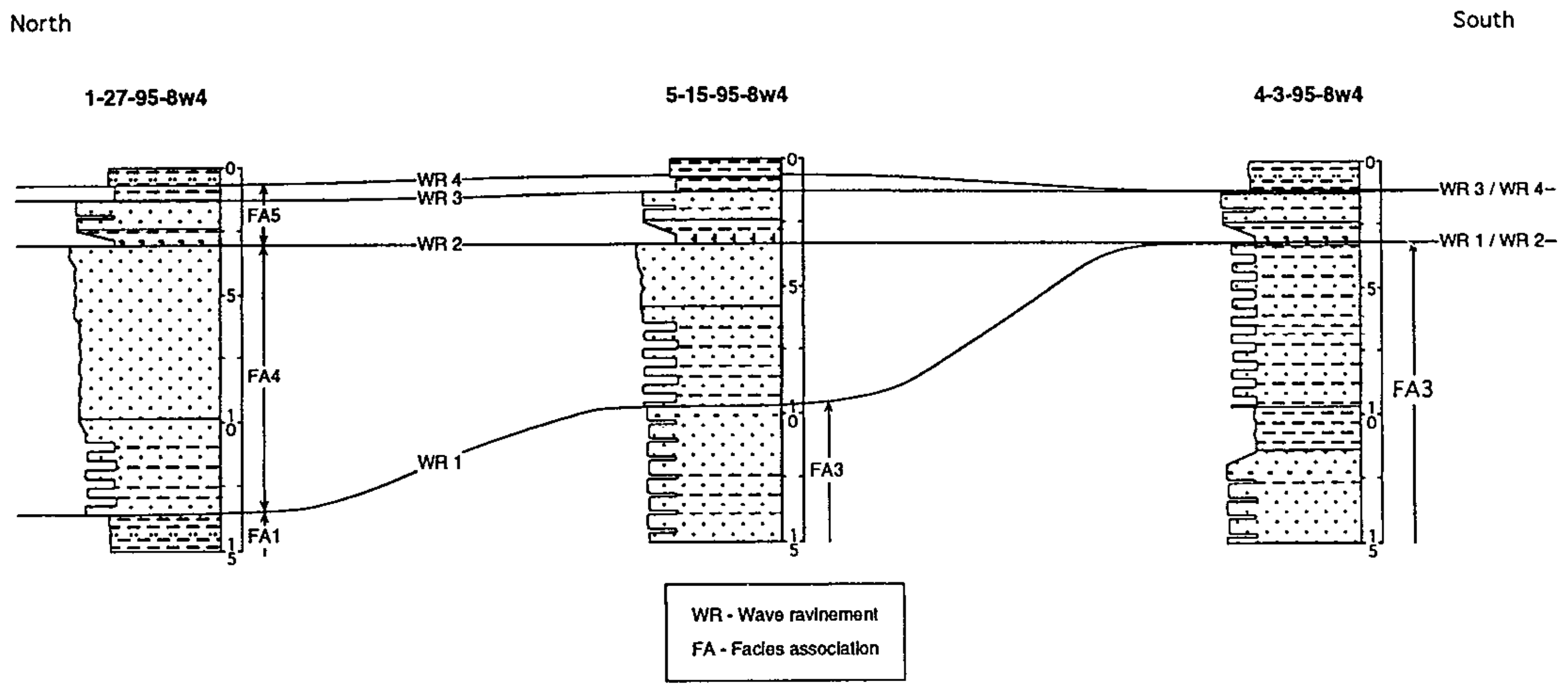


Figure 27. Schematic stratigraphic cross-section of the upper McMurray/Wabiskaw interval. WR 1 nad WR 2 are separate surfaces to the north, but erosion associated with the incision of WR 2 has amalgamated the two surfaces to the south. The same relationship is represented by WR 3 and WR 4. Vertical scale is in metres.

Chapter 4 - Conclusion

The McMurray/Wabiskaw succession in the O.S.L.O. area records a Lower Cretaceous transgression of paleovalleys incised on the sub-Cretaceous unconformity. The nature of the unconformity significantly influenced McMurray deposition. Subsidence resulting from dissolution of the Devonian Prairie Formation evaporites and erosion of Devonian carbonates produced a paleotopographic low in the area of the Athabasca oil sands deposit bounded to the east by the Canadian Shield and to the west by the Wainwright Ridge-Grosmont High (resistant Devonian carbonates). Within the northern portion of the O.S.L.O. area, high subsidence associated with salt dissolution, evident by the nearby Bitumount subbasin, resulted in a significant thickening of the McMurray Formation. The thick, well preserved sedimentary succession provides a record of a overall transgression punctuated by stillstand events.

The lower member of the McMurray Formation represents deposits of fluvial channels and flood basins that occupied the lows on the unconformity surface during early McMurray time. The lower McMurray sediments are fining-upward channel successions representing channel, point bar, and abandonment deposits often capped by crevasse-splay and flood basin deposits. The lower member of the McMurray Formation constitutes the lowstand systems tract (LST).

Middle McMurray sediments represent inner to central estuary deposits of a mesotidal, mixed tide- and wave-dominated estuary. Transgression of the McMurray paleovalley resulted in estuarine deposits erosionally overlying lower McMurray fluvial deposits. Therefore, the contact between the two members is a transgressive surface of erosion (TSE 1). The middle McMurray deposits have sedimentological and ichnological evidence of estuarine deposition. Within stacked fining-upward channel successions features that suggest subtidal conditions, inclined heterolithic stratification and rhythmically interbedded sand and mud attest to the cyclic nature of the physical processes operating within the depositional environment. The significant mud content of the deposits records the effects of the turbidity maximum within the central estuary. Burrowed/unburrowed alternations and evidence of opportunistic organism colonization reflect the cyclic nature of the chemical conditions existing within the depositional environment. The mixing of fresh water and marine water has resulted in a trace fossil assemblage that has the indicators of brackish water conditions: 1) smaller trace fossils than their fully-marine counterparts; 2) simple morphological forms; 3) low diversity, including monospecific assemblages; 4) high abundances; and 5) a combination of traces from both the *Skolithos* and *Cruziana* ichnofacies. These estuarine deposits mark the base of the transgressive systems tract (TST).

Further transgression resulted in the outer estuary and marine deposits of the upper McMurray erosionally overlying the central estuary sediments of the middle McMurray. The high-relief contact between the two members is the result of tidal channel erosion within the outer estuary and is termed the tidal ravinement surface. The outer estuary deposits are characterized by flat-lying, relatively laterally extensive, often well burrowed sand and interbedded sand and mud. Reflecting the proximity to the marine environment the deposits have abundant burrowing, an increased diversity of forms, rhythmically interlaminated sand and mud/carbonaceous debris, and evidence of storm deposition. Within the upper McMurray, the outer estuary deposits are separated from the overlying marine deposits by a wave ravinement surface. Associated with erosional shoreface retreat, this low-relief surface is the result of wave erosion during transgression. The marine deposits of the upper McMurray consist of a transgressive sand overlain by a prograding shoreface succession. Their marine nature is reflected in the trace fossil assemblage that is more diverse and contains more robust forms than the underlying estuarine deposits. This progradation of sediments records a stillstand event during the overall transgression cycle.

The overlying Wabiskaw Member sediments are transgressive deposits associated with a rise in relative sea level. These glauconitic sediments have a trace fossil assemblage indicative of nearly fully-marine conditions. The surface beneath these deposits is a wave ravinement surface (WR 2). Within the Wabiskaw Member, at least two parasequences of transgressive deposits are recognized. These parasequences may be distal equivalents to Wabiskaw shoreface sand bodies to the south of the study area and are also capped by wave ravinement surfaces (WR 3 and WR 4), the lower of the two demarcated by a *Glossifungites* assemblage. While the Wabiskaw Member caps the observed succession within the study area it does not mark the top of the transgressive systems tract. The TST continues into the overlying shales of the Clearwater Formation. With no evidence of highstand deposits within the study area, the McMurray succession at O.S.L.O. is interpreted to reflect a single overall transgressive cycle.

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APPENDIX

Core lithologs and legend used for figures in thesis.

4-3-95-8w4

3-7-95-8w4

12-12-95-8w4

2-13-95-8w4

5-15-95-8w4

10-16-95-8w4

1-27-95-8w4

LEGEND

LITHOLOGY

- SAND/SANDSTONE
- silty sand
- shaly sand
- SILT/SILTSTONE
- sandy silt
- clayey silt
- SHALE/MUDSTONE
- silty shale

- sandy shale
- clay/claystone
- organic shale
- ■ coal
- matrix supported
- grain supported
- conglomerate
- breccia

- X-stln basement
- LIMESTONE
- DOLOSTONE
- Dolomitic Lst
- Calcareous Dolst
- Oolitic Lst
- Oolitic Dolst
- Calcareous shale

- Dolomitic shale
- Cherty Lst
- Cherty Dolst
- Chert
- Gypsum/Anhyd.
- Coquina
- Halite
- ☒ Lost Core

PHYSICAL STRUCTURES

- Current Ripples
- Climbing Ripples
- Low Angle Tabular Bedding
- Lenticular Bedding
- Convolute Bedding
- Graded Bedding
- Mud Cracks
- Double Mud Drapes
- Imbrication
- Horizontal Stratfication
- Fracture

- Trough Cross-strat.
- Planar Tabular Bedding
- Flaser Bedding
- »» Herringbone Cross-strat.
- @ Chaotic Bedding
- Reverse Graded Bedding
- Synaeresis Cracks
- Load Casts
- Stylolites
- Inclined Stratification
- Syndepositional Microfaulting

- Oscillatory Ripples
- /// High Angle Tabular Bedding
- Wavy Parallel Bedding
- Hummocky Cross-strat.
- Scour
- Fault
- Reactivation Surface
- xxxxxx Tight zone
- Slickensides
- Combined Flow Ripple

LITHOLOGIC ACCESSORIES

- Sand Lamina
- Pebbles/Granules
- Organic Shale Lamina
- Sid Siderite
- Gl Glauconitic
- Wd Wood Fragments
- Q Quartz Crystals
- Carbonaceous Debris
- Dispersed Sand Grains

- Silt Lamina
- Coal Lamina
- Calcareous
- Rip Up Clasts
- Shell Fragments
- Anhydritic
- ? Question Mark

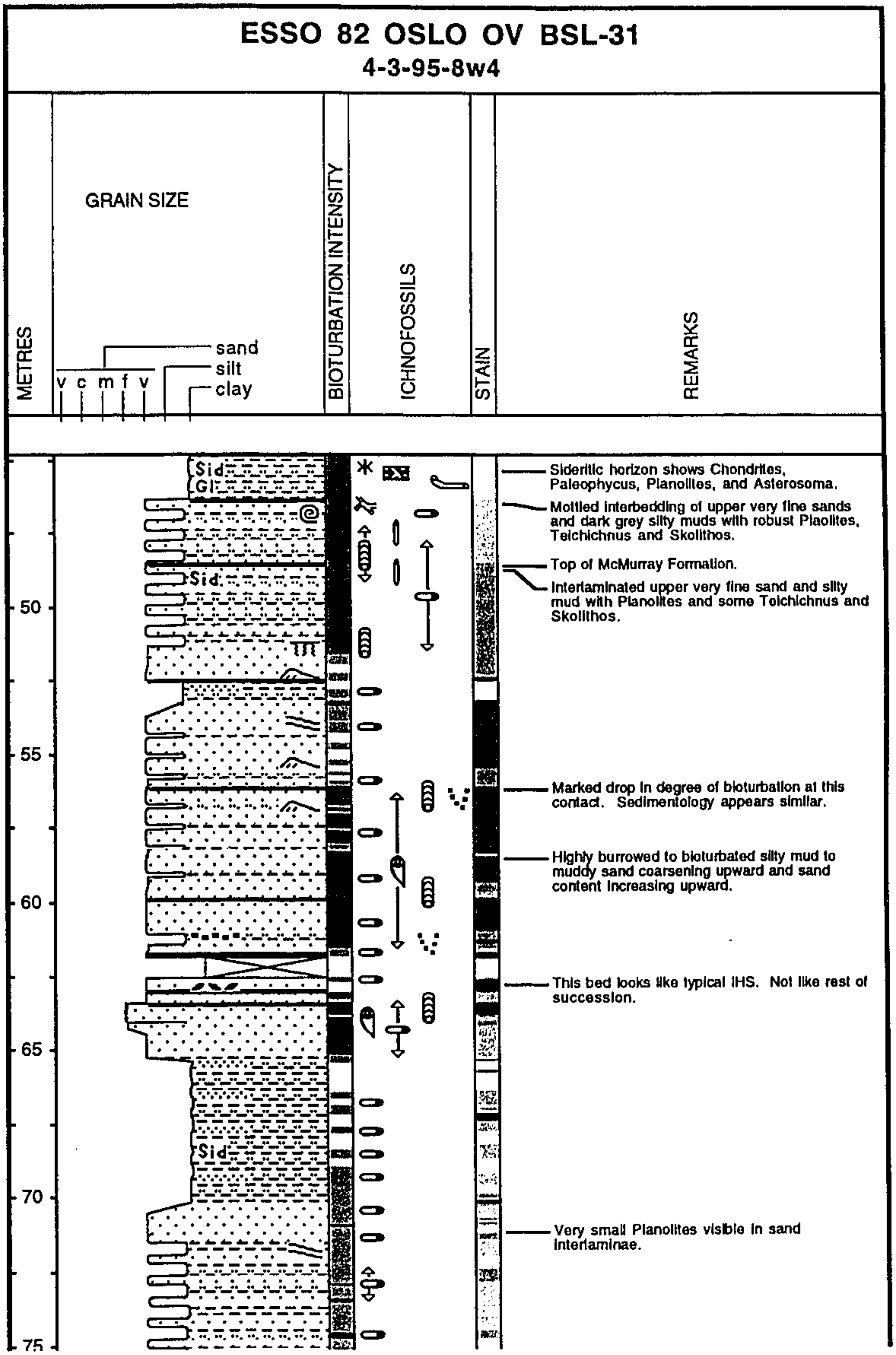
- Shale Lamina
- Breccia Horizon
- Dolomitic
- Py Pyrite
- Coal Fragments
- Pald Paleosol Horizon
- S Sulfur
- o Nodule
- OP Pyrite Nodule

ICHNOFOSSILS

- Rootlets
- Planolites
- Diplocraterion
- Ophiomorpha
- Rhizocorallium
- Conichnus
- Asterosoma
- Chondrites
- Zoophycos
- Trypanites
- Subphylachorda
- Skolithos
- Palaeophycus
- Arenicolites
- Escape Trace
- Cylindrichnus
- Conostichus
- Rosselia
- Terebellina
- Helminthopsis
- Bored HardGround
- Monocraterion
- Gyrolithes
- Macaronichnus
- Trichichnus
- Bergaueria
- Psilonichnus
- Thalassinoides
- Teichichnus
- Teredolites
- Lockeia

FOSSILS

- Gastropods



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4-3-95-8w4

Sideritic horizon shows Chondrites, Paleophycus, Planolites, and Asterosoma.

Mottled interbedding of upper very fine sands and dark grey silty muds with robust Planolites, Teichichnus and Skolithos.

Top of McMurray Formation.

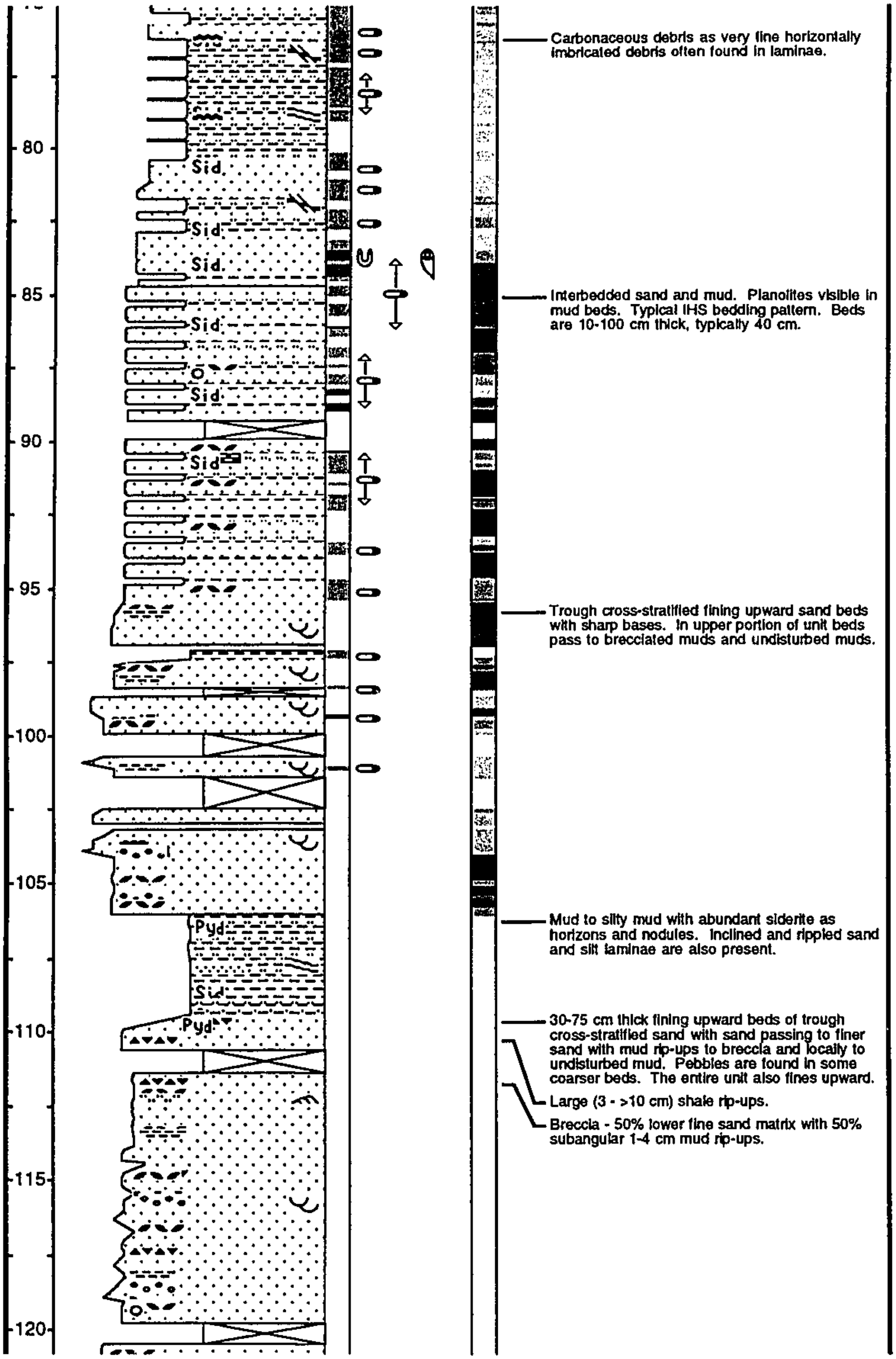
Interlaminated upper very fine sand and silty mud with Planolites and some Teichichnus and Skolithos.

Marked drop in degree of bioturbation at this contact. Sedimentology appears similar.

Highly burrowed to bioturbated silty mud to muddy sand coarsening upward and sand content increasing upward.

This bed looks like typical IHS. Not like rest of succession.

Very small Planolites visible in sand interlaminae.



Carbonaceous debris as very fine horizontally imbricated debris often found in laminae.

Interbedded sand and mud. Planolites visible in mud beds. Typical IHS bedding pattern. Beds are 10-100 cm thick, typically 40 cm.

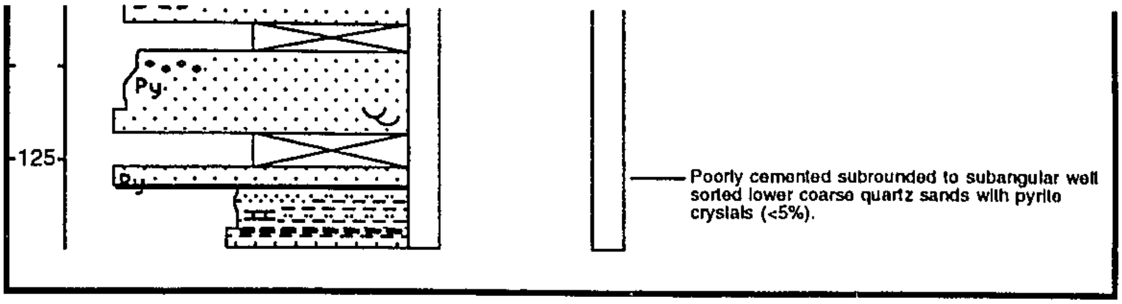
Trough cross-stratified fining upward sand beds with sharp bases. In upper portion of unit beds pass to brecciated muds and undisturbed muds.

Mud to silty mud with abundant siderite as horizons and nodules. Inclined and rippled sand and silt laminae are also present.

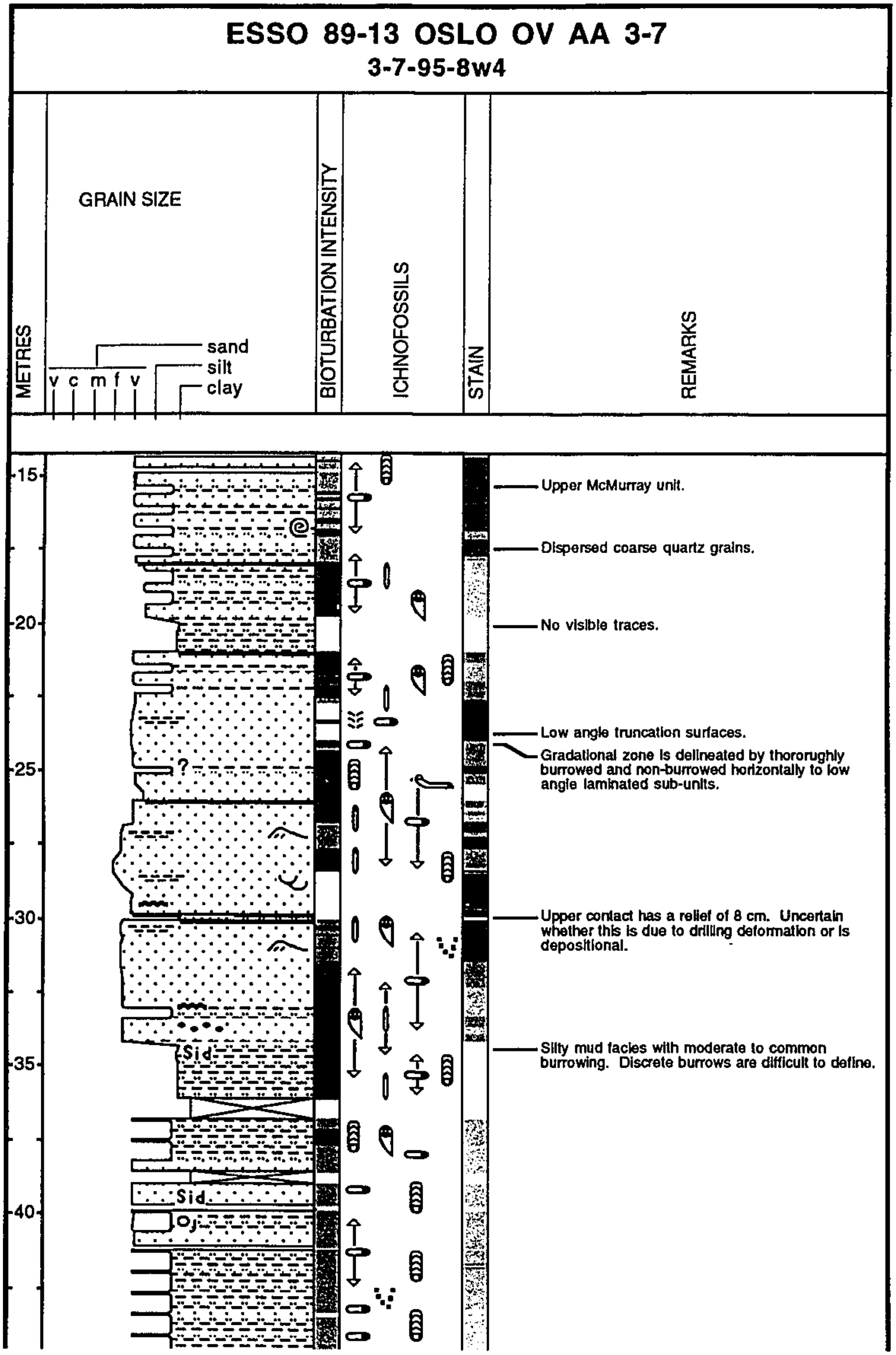
30-75 cm thick fining upward beds of trough cross-stratified sand with sand passing to finer sand with mud rip-ups to breccia and locally to undisturbed mud. Pebbles are found in some coarser beds. The entire unit also fines upward.

Large (3 - >10 cm) shale rip-ups.

Breccia - 50% lower fine sand matrix with 50% subangular 1-4 cm mud rip-ups.



Poorly cemented subrounded to subangular well sorted lower coarse quartz sands with pyrite crystals (<5%).



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Upper McMurray unit.

Dispersed coarse quartz grains.

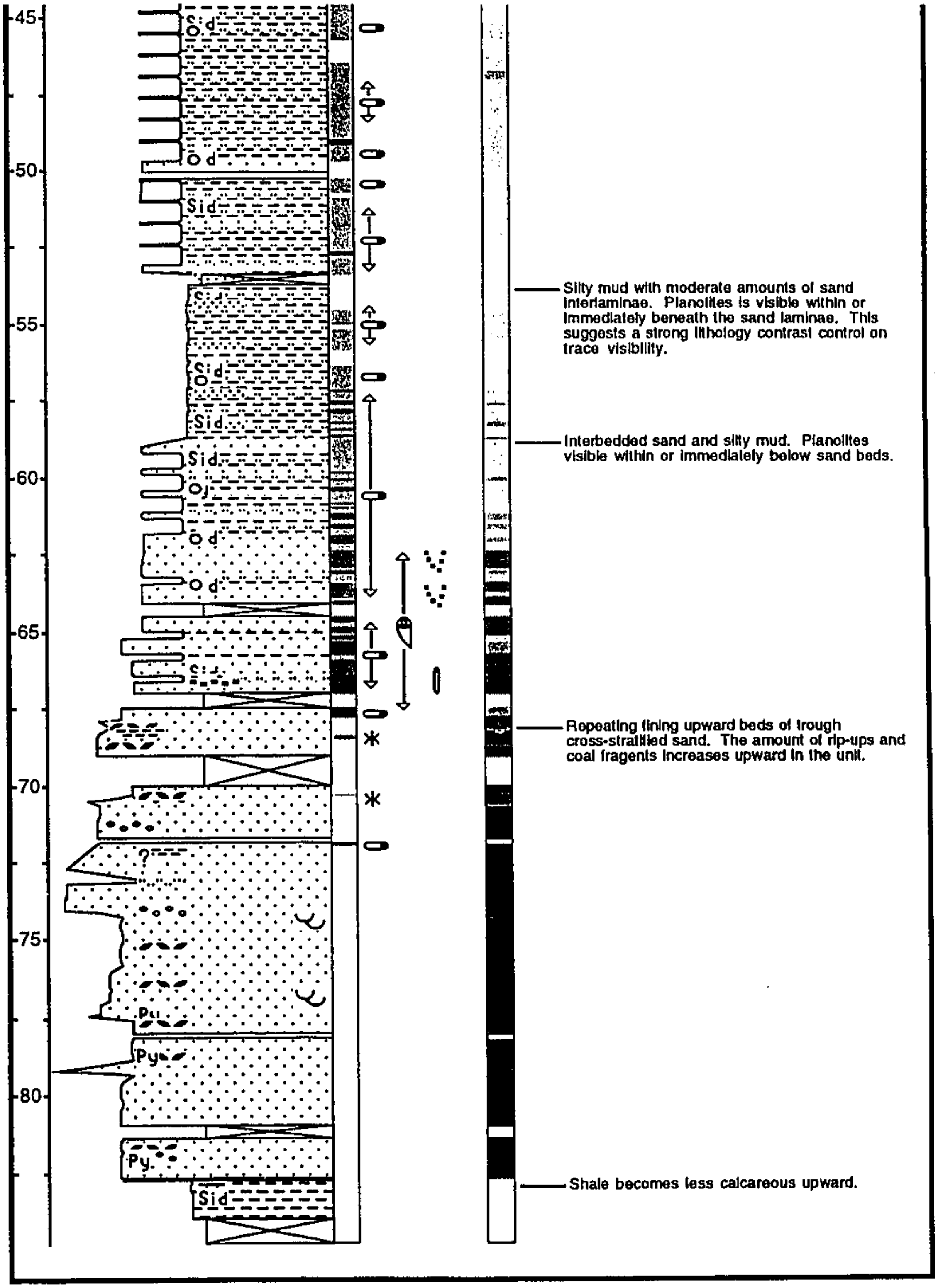
No visible traces.

Low angle truncation surfaces.

Gradational zone is delineated by thororughly burrowed and non-burrowed horizontally to low angle laminated sub-units.

Upper contact has a relief of 8 cm. Uncertain whether this is due to drilling deformation or is depositional.

Silty mud facies with moderate to common burrowing. Discrete burrows are difficult to define.



Silty mud with moderate amounts of sand interlaminae. Planolites is visible within or immediately beneath the sand laminae. This suggests a strong lithology contrast control on trace visibility.

Interbedded sand and silty mud. Planolites visible within or immediately below sand beds.

Repeating fining upward beds of trough cross-stratified sand. The amount of rip-ups and coal fragents increases upward in the unit.

Shale becomes less calcareous upward.

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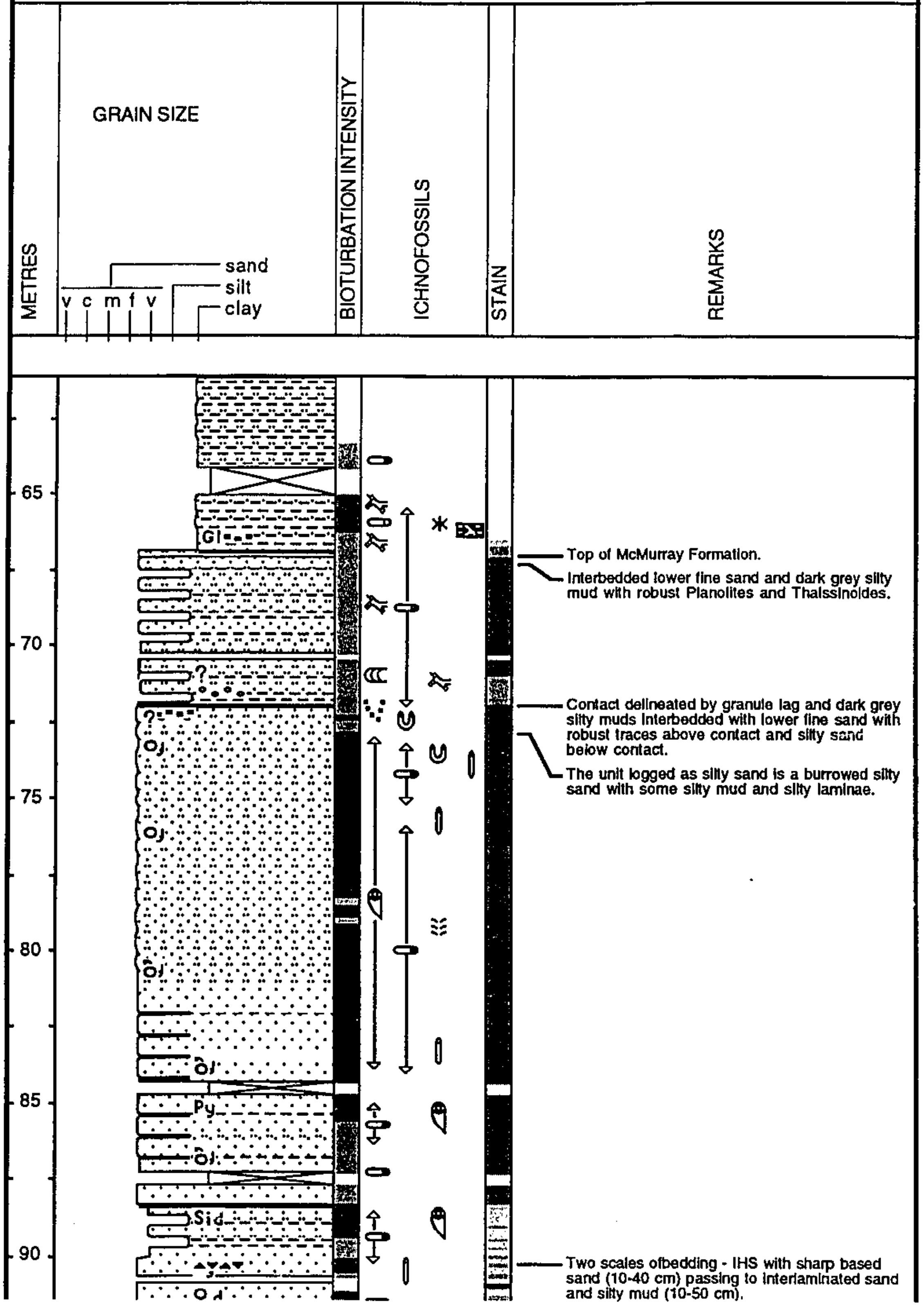


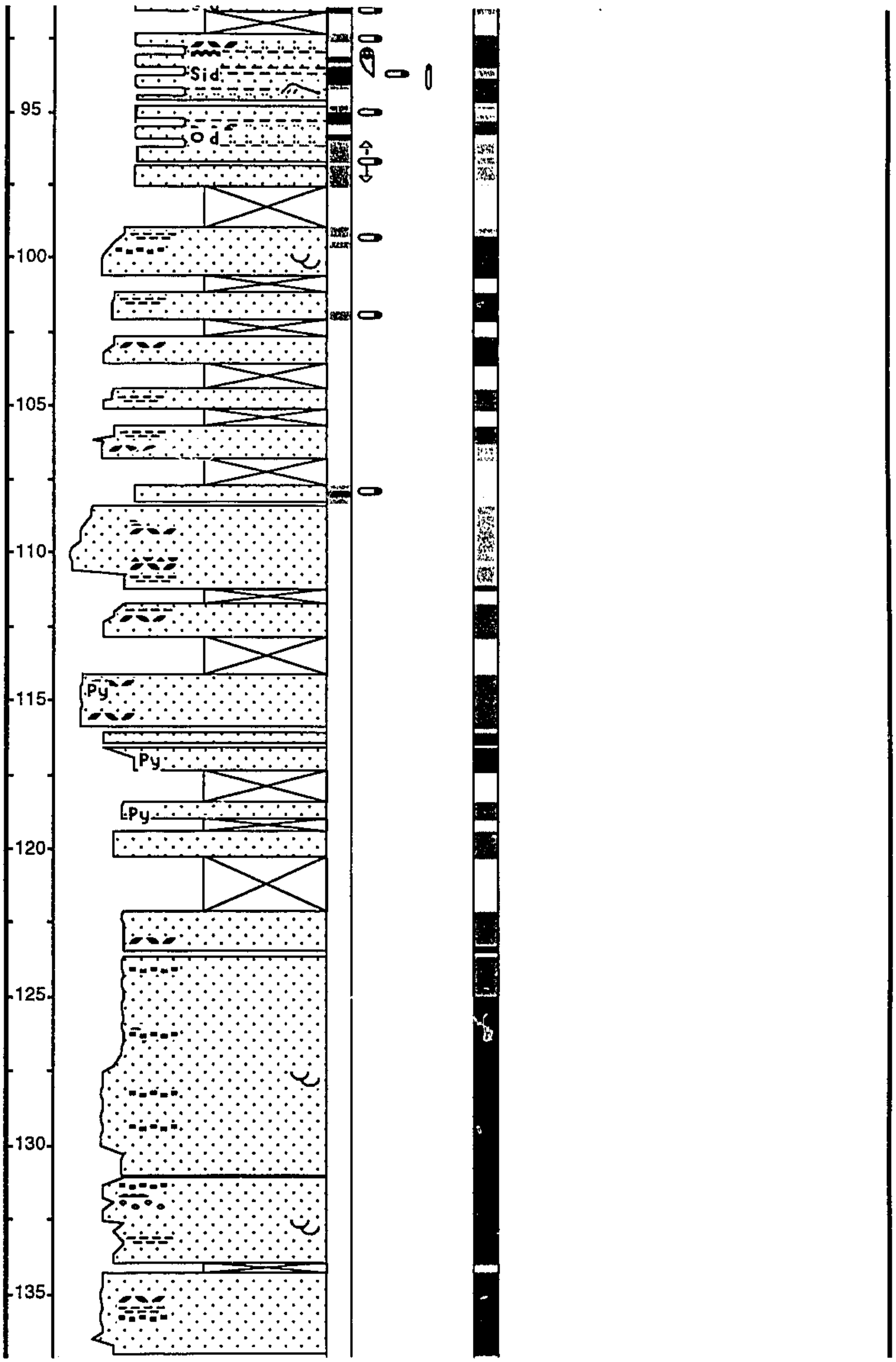
Top of McMurray Formation.

Interbedded lower fine sand and dark grey silty mud with robust Planolites and Thalssinoides.

Contact delineated by granule lag and dark grey silty muds interbedded with lower fine sand with robust traces above contact and silty sand below contact.

The unit logged as silty sand is a burrowed silty sand with some silty mud and silty laminae.

Two scales ofbedding - IHS with sharp based sand (10-40 cm) passing to interlaminated sand and silty mud (10-50 cm).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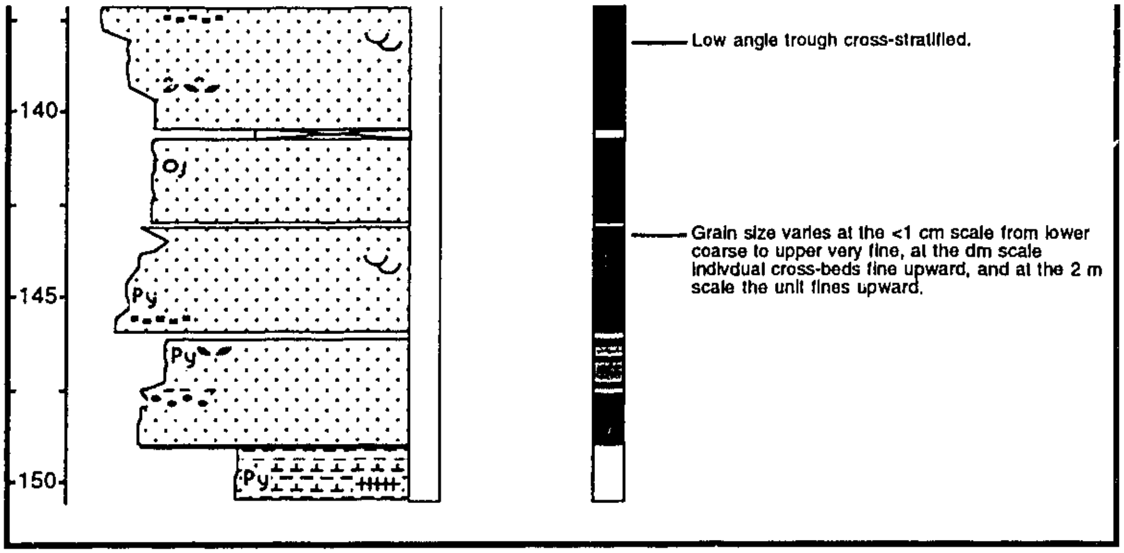
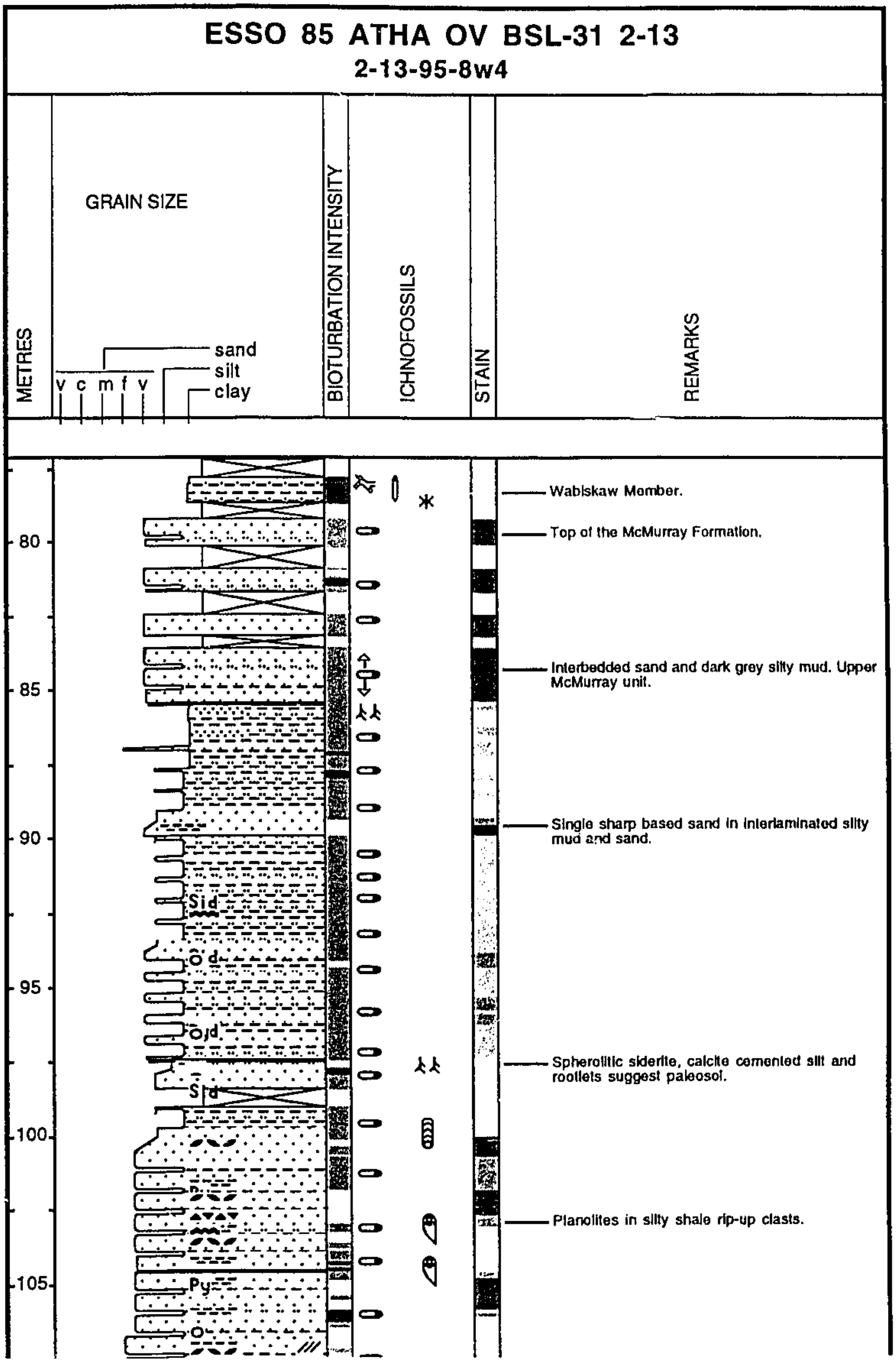


Low angle trough cross-stratified.

Grain size varies at the <1 cm scale from lower coarse to upper very fine, at the dm scale Indivdual cross-beds fine upward, and at the 2 m scale the unit fines upward.



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2-13-95-8w4

Wabiskaw Member.

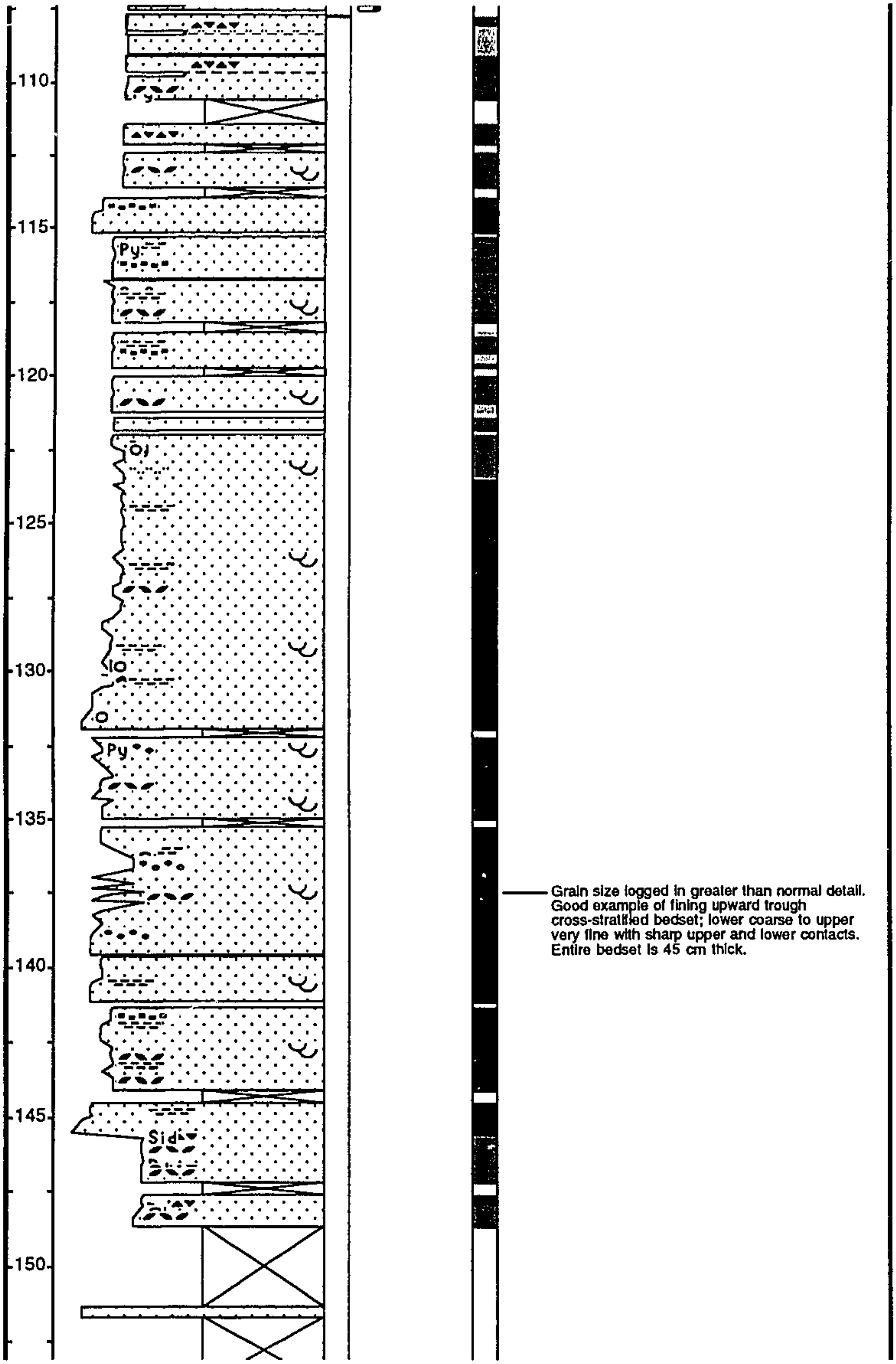
Top of the McMurray Formation.

Interbedded sand and dark grey silty mud. Upper McMurray unit.

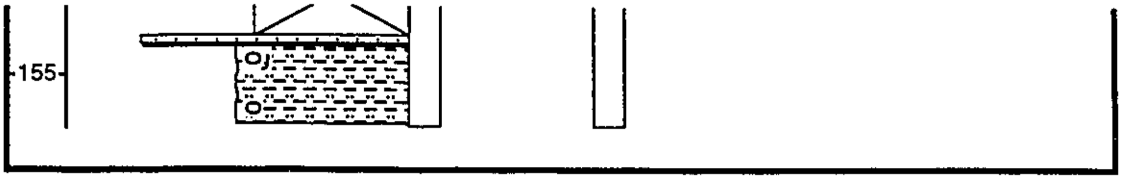
Single sharp based sand in interlaminated silty mud and sand.

Spherolitic siderite, calcite cemented silt and rootlets suggest paleosol.

Planolites in silty shale rip-up clasts.



Grain size logged in greater than normal detail. Good example of fining upward trough cross-stratified bedset; lower coarse to upper very fine with sharp upper and lower contacts. Entire bedset is 45 cm thick.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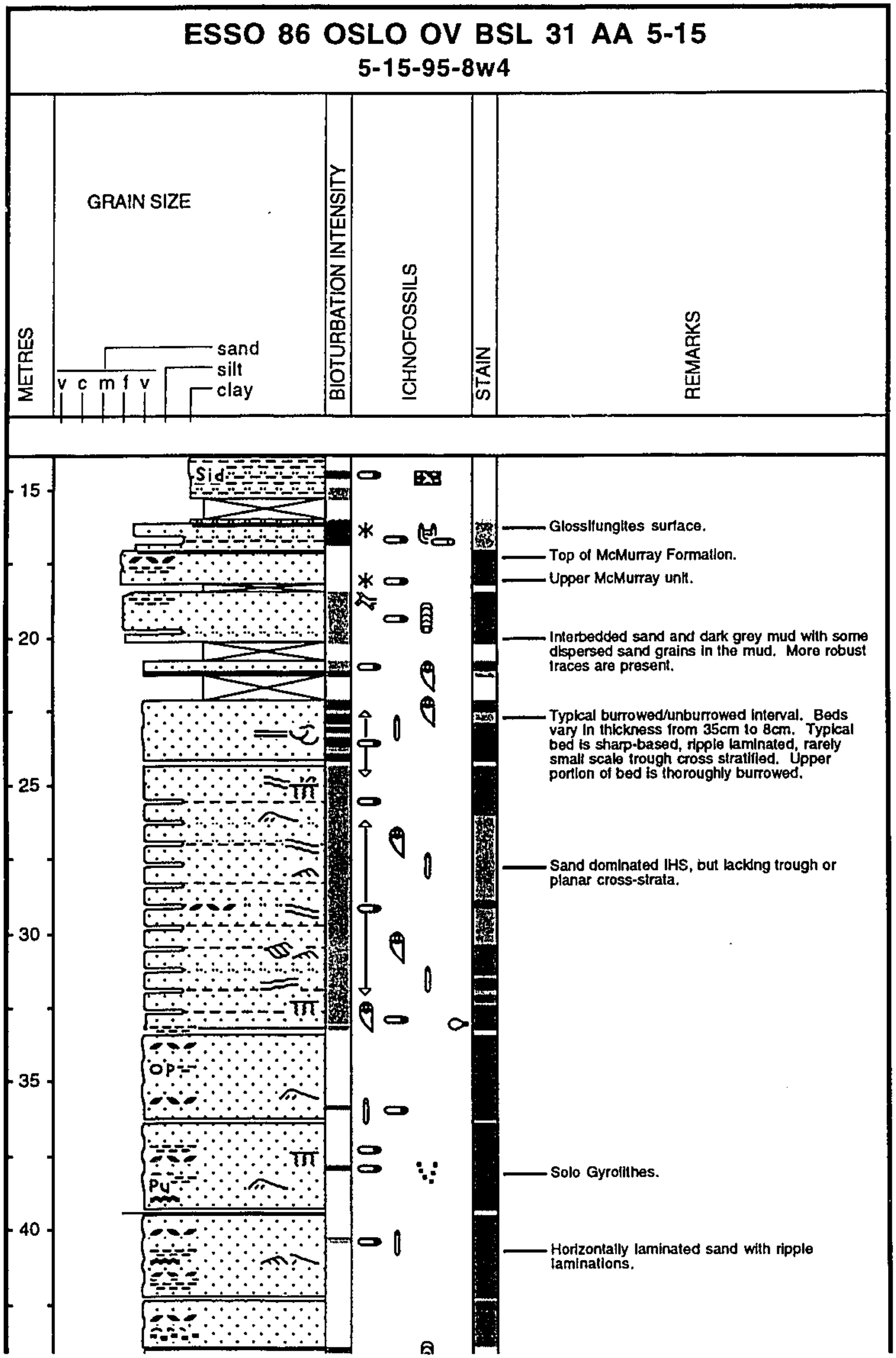

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5-15-95-8w4

Glossifungites surface.

Top of McMurray Formation.

Upper McMurray unit.

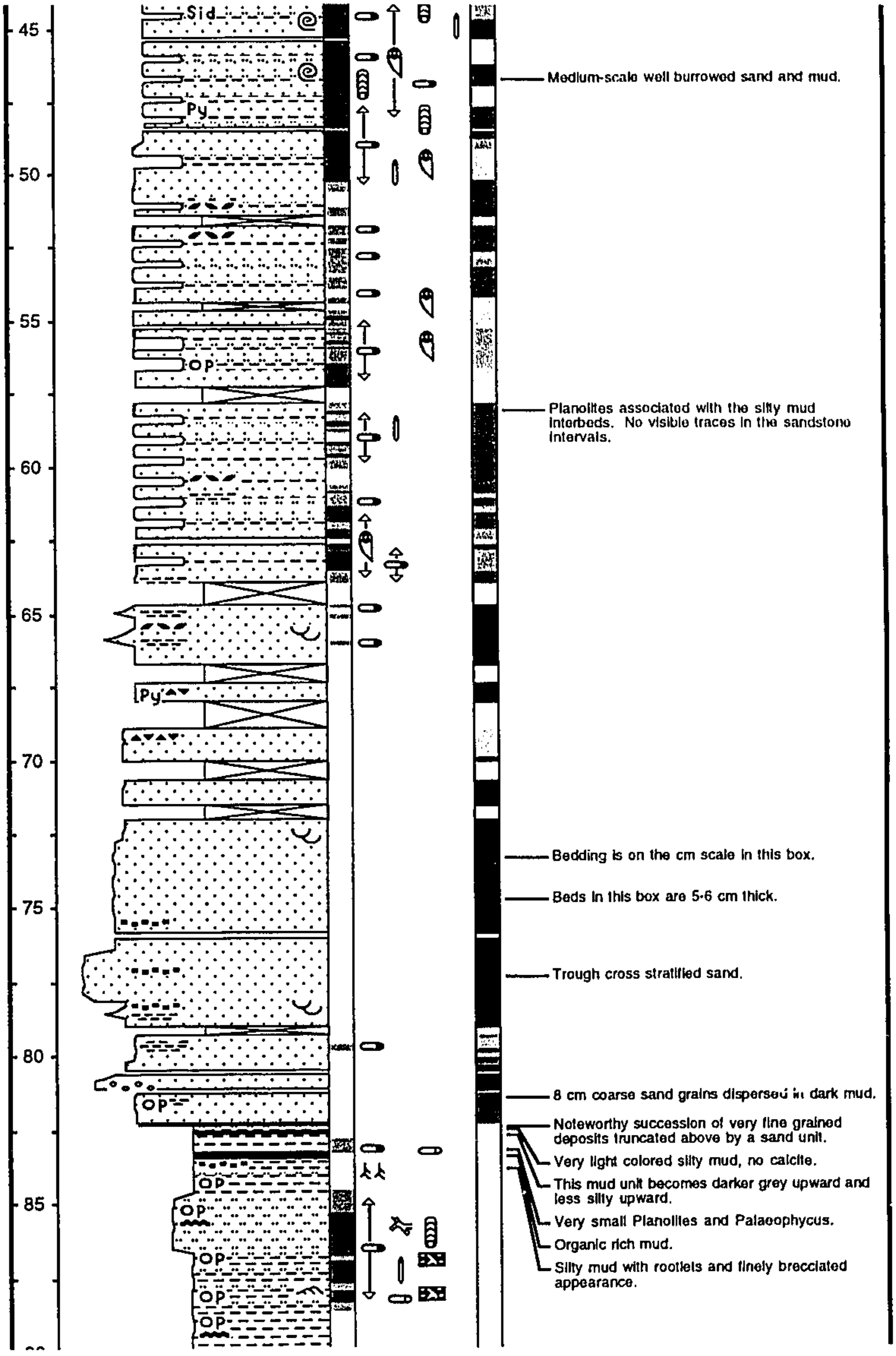
Interbedded sand and dark grey mud with some dispersed sand grains in the mud. More robust traces are present.

Typical burrowed/unburrowed interval. Beds vary in thickness from 35cm to 8cm. Typical bed is sharp-based, ripple laminated, rarely small scale trough cross stratified. Upper portion of bed is thoroughly burrowed.

Sand dominated IHS, but lacking trough or planar cross-strata.

Solo Gyrolithes.

Horizontally laminated sand with ripple laminations.



Medium-scale well burrowed sand and mud.

Planolites associated with the silty mud interbeds. No visible traces in the sandstone intervals.

Bedding is on the cm scale in this box.

Beds in this box are 5-6 cm thick.

Trough cross stratified sand.

8 cm coarse sand grains dispersed in dark mud.

Noteworthy succession of very fine grained deposits truncated above by a sand unit.

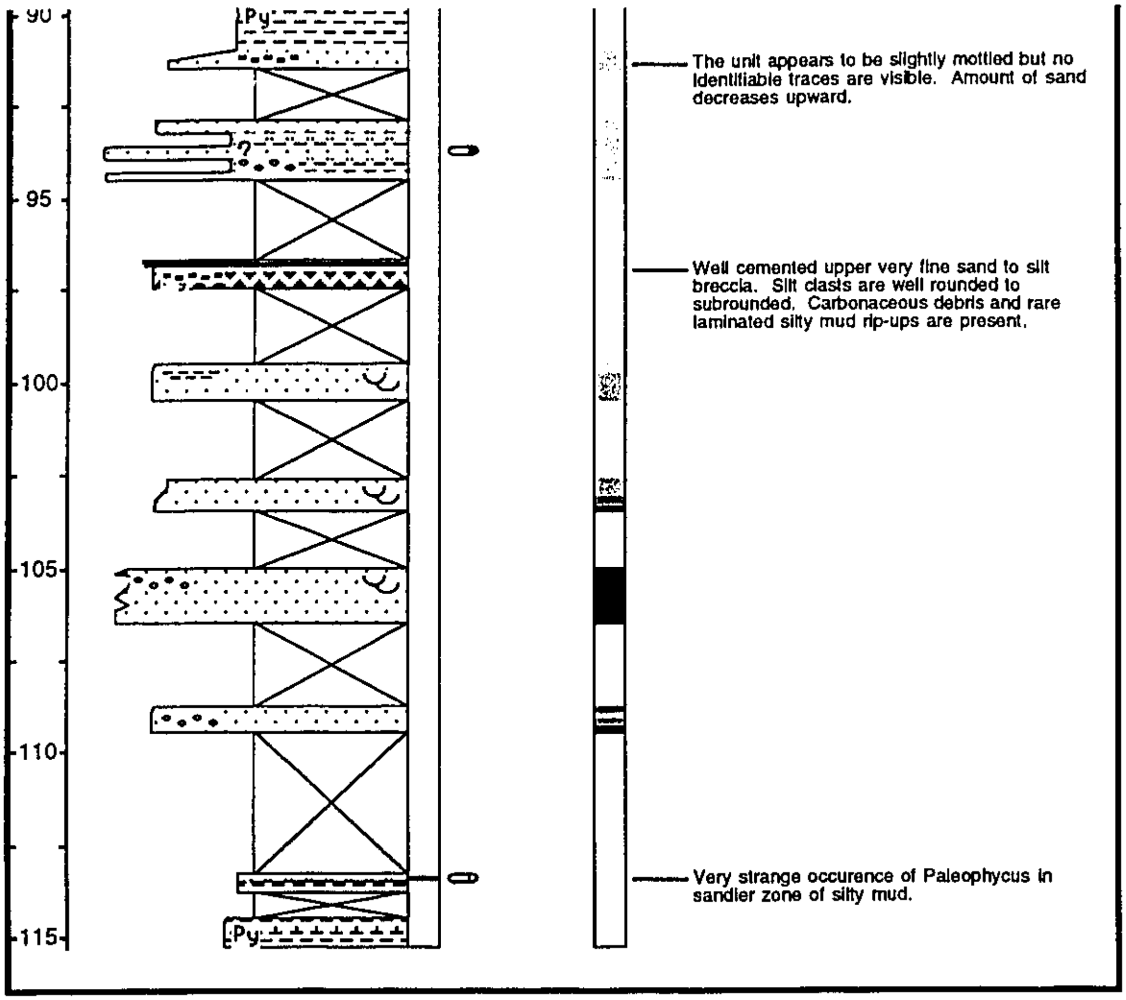
Very light colored silty mud, no calcite.

This mud unit becomes darker grey upward and less silty upward.

Very small Planolites and Palaeophycus.

Organic rich mud.

Silty mud with rootlets and finely brecciated appearance.



The unit appears to be slightly mottled but no identifiable traces are visible. Amount of sand decreases upward.

Well cemented upper very fine sand to silt breccia. Silt clasts are well rounded to subrounded. Carbonaceous debris and rare laminated silty mud rip-ups are present.

Very strange occurence of Paleophycus in sandier zone of silty mud.

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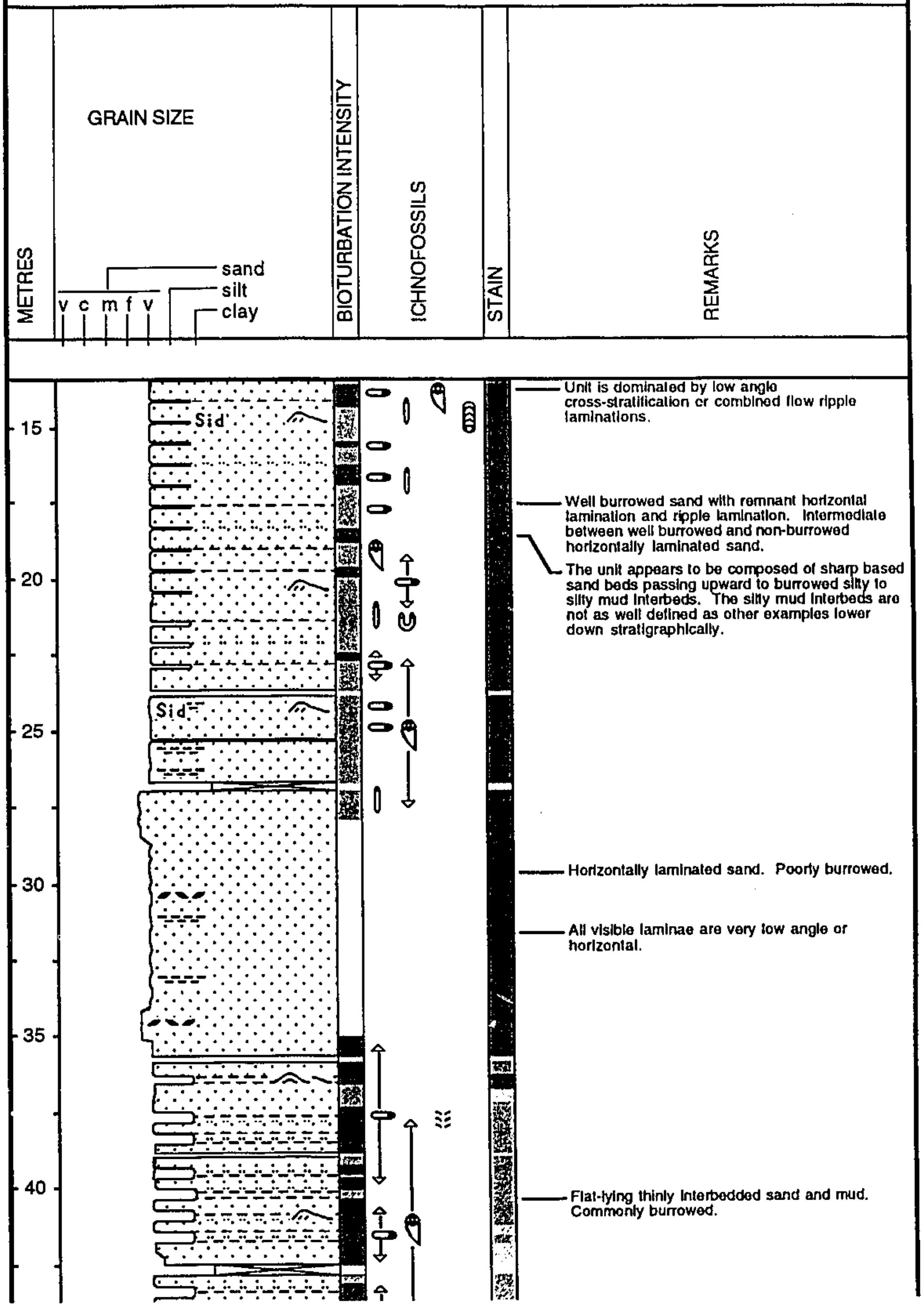


Unit is dominated by low angle cross-stratification or combined flow ripple laminations.

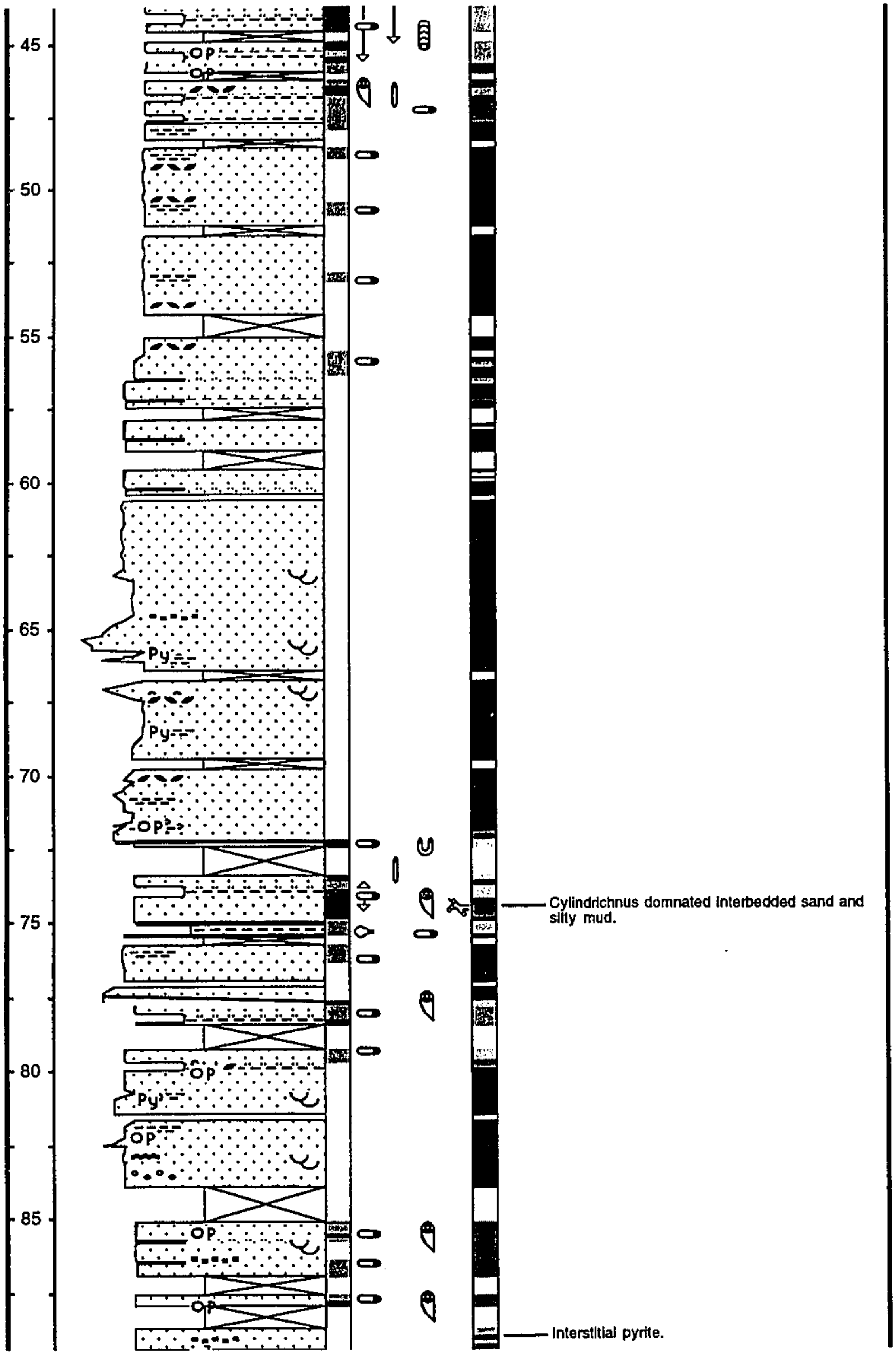
Well burrowed sand with remnant horizontal lamination and ripple lamination. Intermediate between well burrowed and non-burrowed horizontally laminated sand.

The unit appears to be composed of sharp based sand beds passing upward to burrowed silty to silty mud interbeds. The silty mud interbeds are not as well defined as other examples lower down stratigraphically.

Horizontally laminated sand. Poorly burrowed.

All visible laminae are very low angle or horizontal.

Flat-lying thinly interbedded sand and mud. Commonly burrowed.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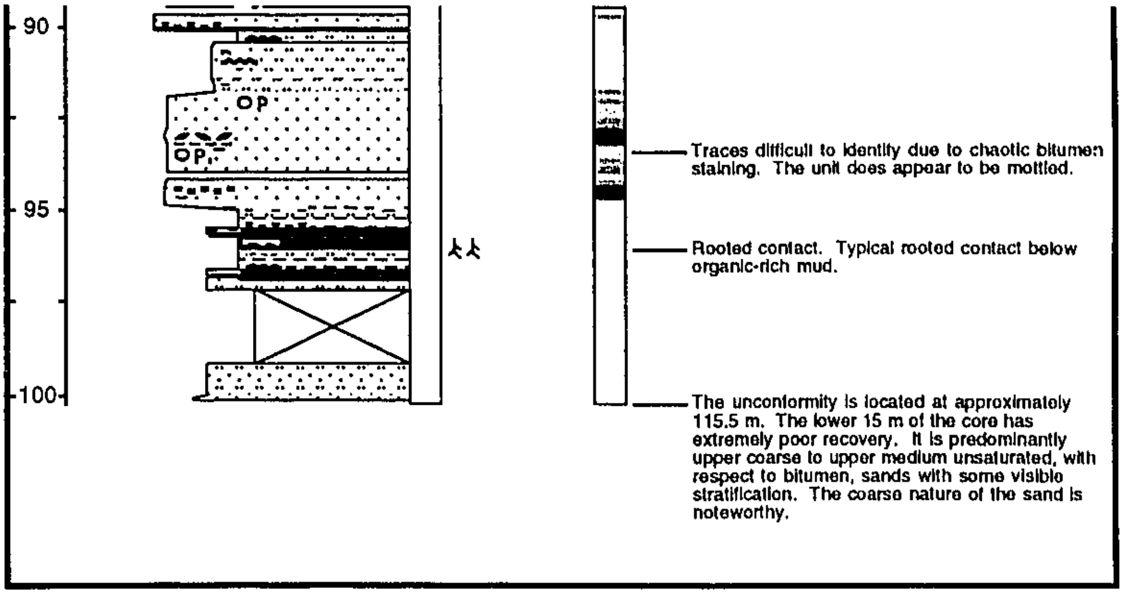
Cylindrichnus domnated interbedded sand and silty mud.
Interstitial pyrite.



Traces difficult to identity due to chaotic bitumen staining. The unit does appear to be mottled.

Rooted contact. Typical rooted contact below organic-rich mud.

The unconformity is located at approximately 115.5 m. The lower 15 m of the core has extremely poor recovery. It is predominantly upper coarse to upper medium unsaturated, with respect to bitumen, sands with some visible stratification. The coarse nature of the sand is noteworthy.

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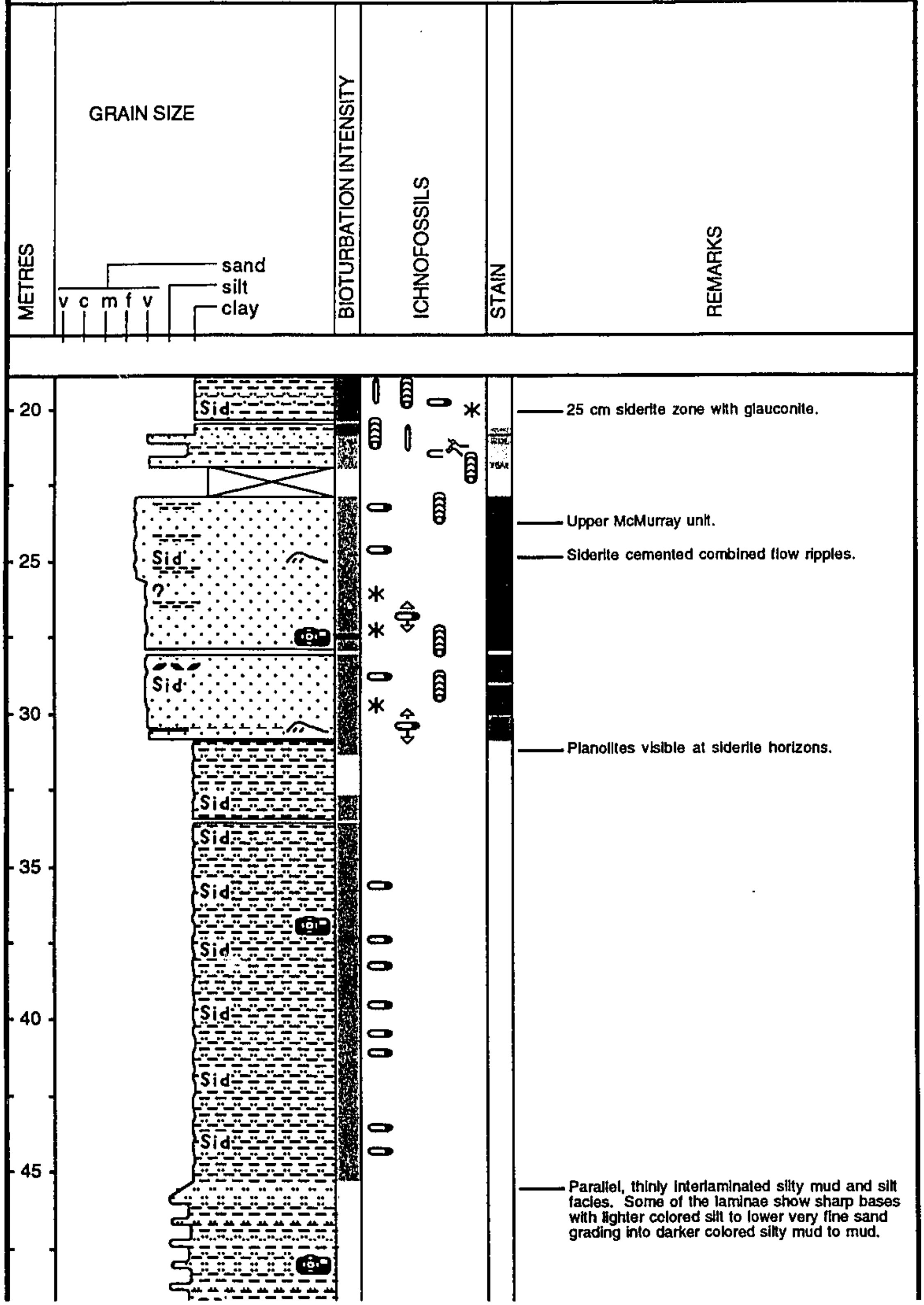
1-27-95-8w4



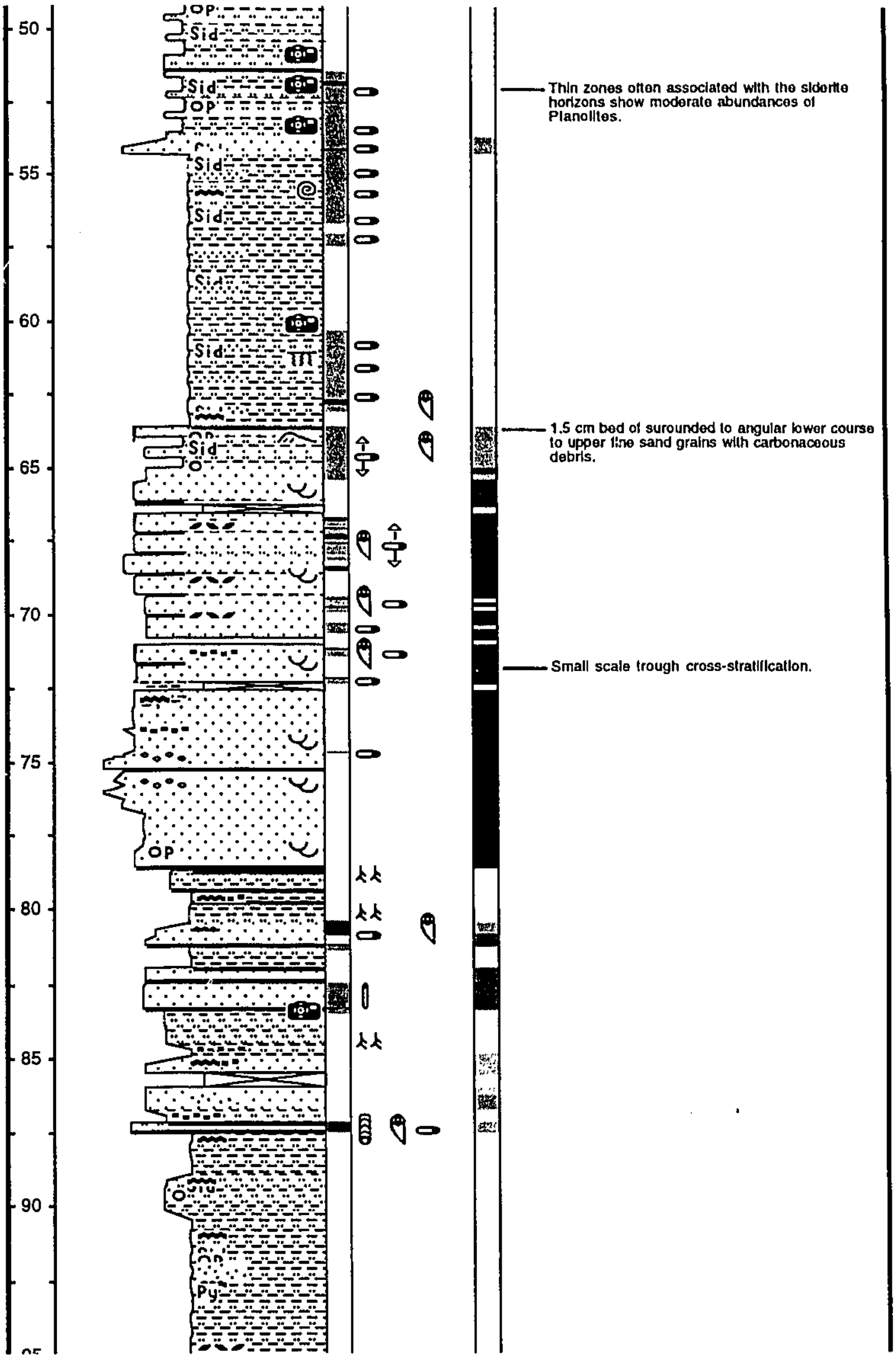
25 cm siderite zone with glauconite.

Upper McMurray unit.

Siderite cemented combined flow ripples.

Planolites visible at siderite horizons.

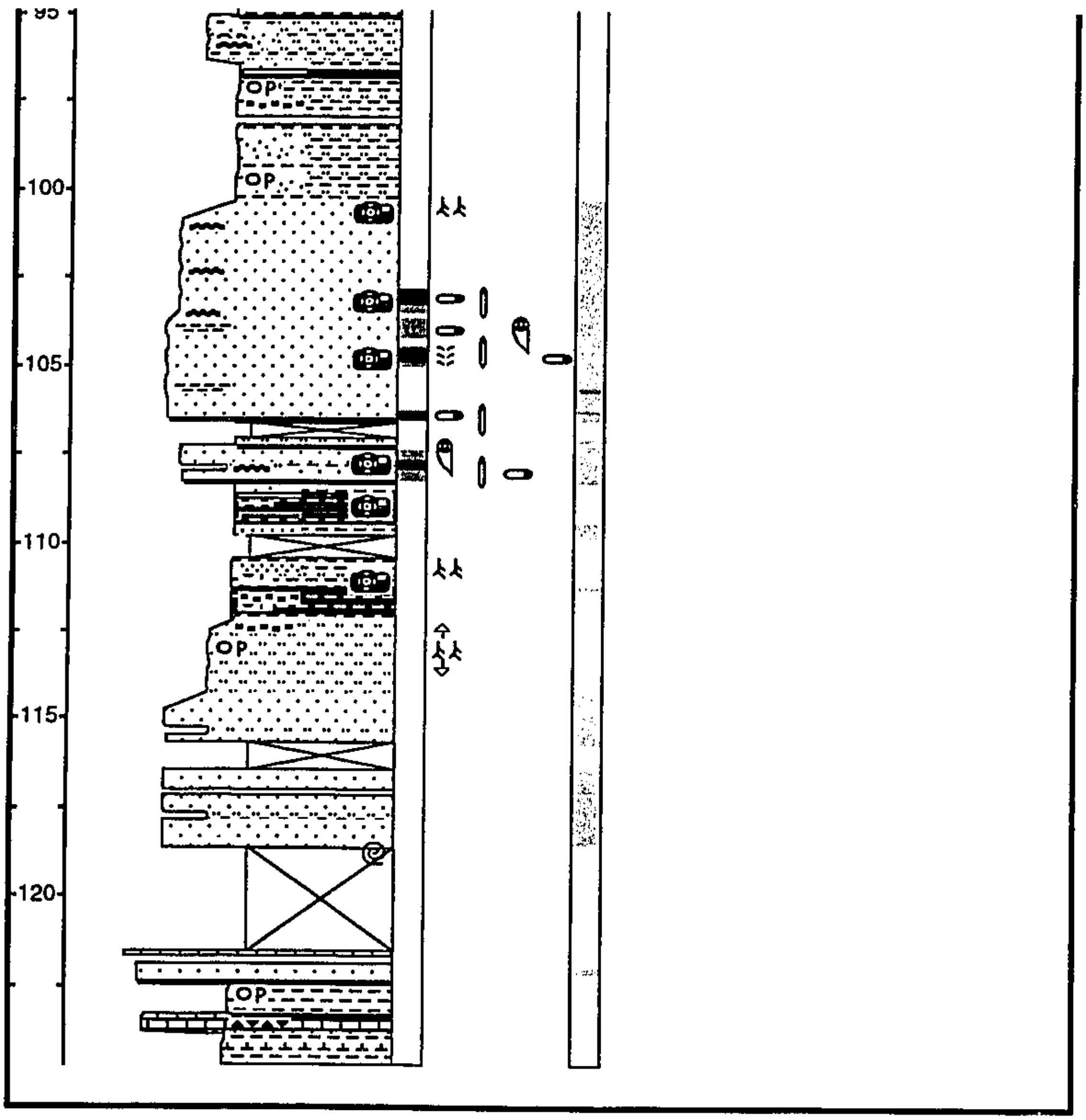
Parallel, thinly interlaminated silty mud and silt facies. Some of the laminae show sharp bases with lighter colored silt to lower very fine sand grading into darker colored silty mud to mud.



Thin zones often associated with the siderite horizons show moderate abundances of Planolites.

1.5 cm bed of surounded to angular lower course to upper fine sand grains with carbonaceous debris.

Small scale trough cross-stratification.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