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ICHNOLOGY AND SEDIMENTOLOGY OF THE LOWER CRETACEOUS BLUESKY FORMATION, SINCLAIR FIELD AREA, WEST CENTRAL ALBERTA

BY
HOWARD GORDON BREKKE ©

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

FALL, 1995

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Without a trace

standing in the sun
with a popsicle
everything is possible

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ABSTRACT

Facies, facies associations, and depositional environments of the Bluesky Formation in the Sinclair field area of west-central Alberta are determined by cored intervals from 23 wells and geophysical well logs from ~150 wells. Facies are resolved using lithological, process-sedimentological, and ichnological evidence, and grouped into five facies associations based on recurring (vertical) facies patterns.

Facies Association 1 (FA1) consists of a fining upward succession that was deposited in a lower shoreface to offshore setting during transgressions at the start and end of Bluesky time. Facies Association 2 (FA2) is a coarsening upward succession capped by bioturbated tempestites. The upper portion of these beds is typically bioturbated by trace fossils of a "*Macaronichnus* sp." assemblage generated in a storm-influenced, lower to middle shoreface setting. The Facies Association 3 (FA3) succession coarsens upward from shale to sandstone. These sandstones lack bioturbation and are tempestites produced in a storm-dominated lower to middle shoreface setting. Facies Association 4 (FA4) consists of fine- to medium-grained trough cross-bedded and swash laminated sandstone. The swash laminated sandstone is locally bioturbated by a *Macaronichnus* assemblage developed in a very high energy environment. The trough cross-bedded and swash laminated sandstone represent upper shoreface and foreshore deposition respectively. Facies Association 5 (FA5) is highly variable, and facies include coal, organic-rich shale, rooted sandstone, breccia, and rippled to distrupted sandstone; these are interpreted to have been deposited in various back barrier environments.

The Bluesky Formation is encased in a marine shale and was deposited in the transgressive Moosebar Seaway. It consists of a barrier island succession interpreted to have been deposited during relative stillstands in sea-level; during these stillstands the succession prograded northeast into the foreland basin. The Bluesky in the Sinclair area makes up one cycle of these series of backstepping barrier island complexes.

ACKNOWLEDGEMENTS

The masterpiece you now hold in your hands is the end result of too many years of graduate work at the University of Alberta. The following are some of the people that can in part be held responsible for this *objet d'art*...

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Last but not the least: Ole and Alice, Louis and Hazel, Lyle, Ruth, Graham, and Wade...thanks for everything. A very special thanks to Jen for the assistance on the final stages of this thesis, and for being my best friend.

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I INTRODUCTION

1.1 Introduction

This study represents an integrated sedimentological-ichnological examination of the Bluesky Formation in the Sinclair Field area of west-central Alberta (Figure 1). The primary objective of this study was to combine paleoecological information interpreted from ichnofossils (trace fossils) with process-sedimentologic data interpreted from sedimentary structures, in order to better constrain paleoenvironmental interpretations of the Bluesky Formation. The second objective of this study was to use paleoenvironmental interpretations, combined with subsurface mapping, to construct a sequence stratigraphic framework and depositional model for the Bluesky Formation in west-central Alberta.

This study achieved these objectives through three major stages. The first stage consisted of data acquisition through the logging of core. Environmental conditions present during Bluesky time were then interpreted from the logged facies and their associations. Finally, sequence stratigraphic relationships and a depositional model for the Bluesky Formation were resolved, aided by subsurface maps and cross-sections.

The results of this study may provide a powerful tool in hydrocarbon exploration. Reservoir continuity and sandbody geometries may be predicted through facies characteristics and relationships. This is applicable to the Bluesky Formation around the study area, and also holds true for Cretaceous sandstones deposited in similar environments.

1.2 The Bluesky Formation and Setting

Lithologic information was acquired through the examination of cored intervals, and inferred from wireline well logs. Wireline well logs provide abundant data for the Bluesky Formation throughout northeast British Columbia and west-central Alberta. In this study approximately 150 wells were examined. Over 780 wells penetrate the Bluesky Formation in the Sinclair area (Figure 2), and 23 have cored intervals which were studied (~290 m). This provides the basis for the ichnological and sedimentological interpretations.

The Bluesky Formation was deposited during Lower Albian time (~110-113 MA, Figure 3), and consists of numerous facies which are variably made up of shales, very fine to medium-grained sandstones, conglomerates, and coal. These facies comprise five facies associations (FA) determined on the basis of lithology, sedimentology, and ichnology. Facies Association 1 consists of a fining upward succession interpreted as a transgressive,

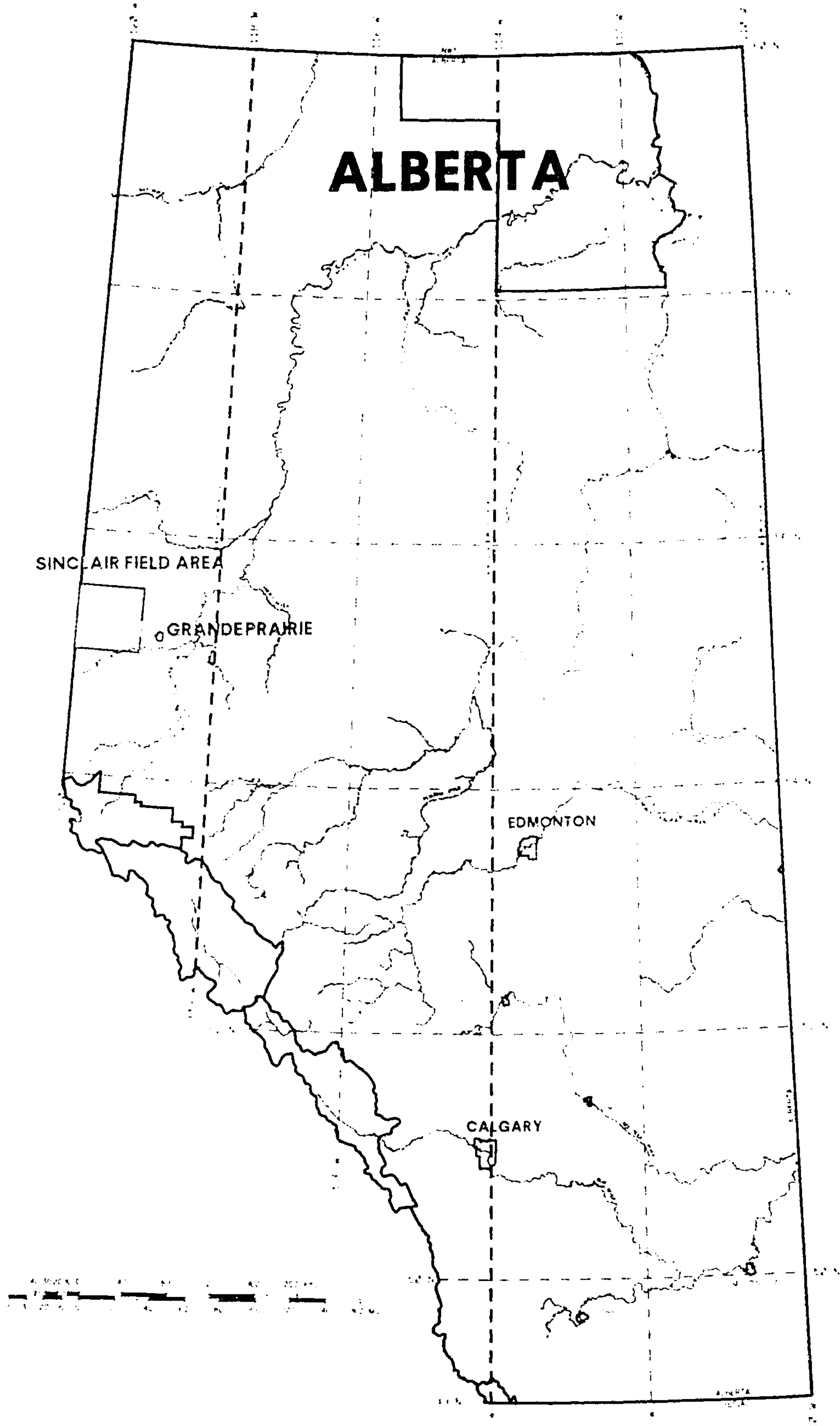


Figure 1. Location of the Sinclair field area.

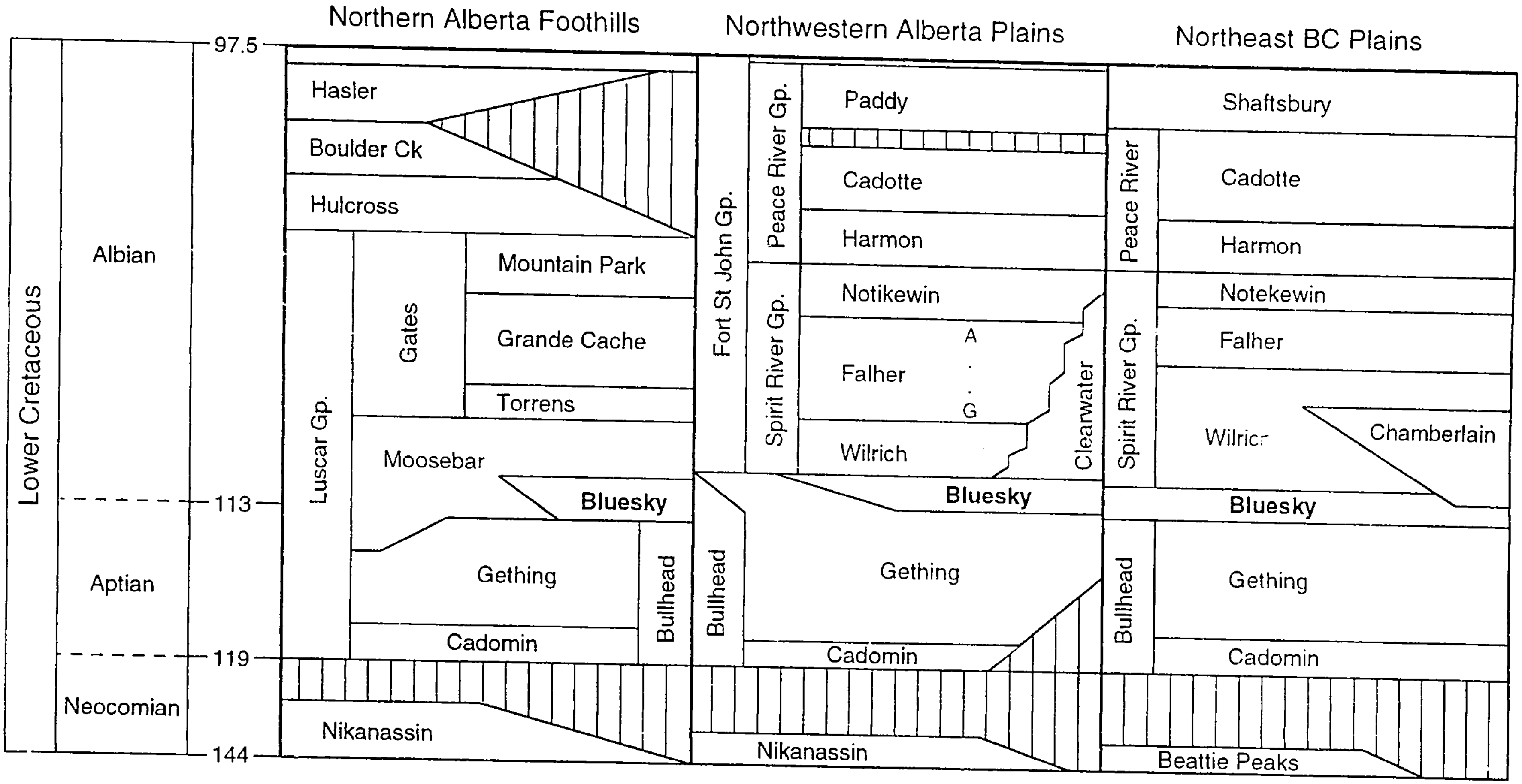


Figure 3. Table of stratigraphic terminology for the Sinclair field area including northwestern Alberta and northeastern British Columbia.

fully marine offshore deposit. Facies Association 2 consists of shale, coarsening upward to bioturbated and laminated sandstone, indicative of a storm-influenced, offshore to middle shoreface setting. Facies Association 3 is shale coarsening upward to well-laminated sandstone, likely deposited in a storm-dominated, lower to middle shoreface environment. Facies Association 4 is dominated by variably bioturbated, crossbedded sandstone reflecting upper shoreface deposition. Facies Association 5 includes a variety of facies, and includes crossbedded sandstone representative of tidal channel deposition. The tidal channel facies is a reservoir facies in at least two wells in the northwest portion of the study area. Three facies associations (FA2, FA3, and FA4) comprise the major portion of the Bluesky Formation throughout the study area.

Lower Albian sediments were deposited during the southward transgression of the Moosebar Sea. The stratigraphy of the Lower Albian is very complex owing to the large area these sediments cover, and the shallow depositional setting (Stelck *et al.*, 1956). Additionally, this transgression was highly episodic (O'Connell, 1988; Rosenthal, 1988), and deposited a diachronous layer of sediment from north-eastern British Columbia, throughout Alberta, and into most of Saskatchewan. Bluesky Formation sands were deposited between the Keg River Highlands and the Hoadley Barrier (Figure 4) in a wide range of environments, including shallow shelf, shoreline and prograding barrier, and deltaic and fluvial settings (Wood and Hopkins, 1989; Smith, 1994).

1.3 Economic Significance

Gas production from the Bluesky Formation in the Sinclair area is from fine to medium-grained sandstones of FA4 and FA5. The Bluesky Formation discovery well for the Sinclair Field (Figure 2), CHIEFCO TEXACO SINCLAIR [2-23-75-13w6], was drilled in 1982 and has yielded a cumulative gas production of 6.5 e^6m^3 (181.6 mmcf). Production from the Bluesky Formation in the Sinclair Field has yielded 460.8 e^6m^3 (16.5 bcf) from 6 wells, with some wells producing at rates over 28.9 e^3m^3/d (1 mmcf/d). Recent activity has resulted in new producing wells in the northeast portion of the study area at the LaGlace, Valhalla, and Wembley Fields. Three wells in the LaGlace Field have averaged over 28.3 e^6m^3 (1 bcf) each during the period 1991 to 1994. One well in the Valhalla Field has produced 18.5 e^6m^3 (654 mmcf) in the last 9 months of 1994. A second well in the Valhalla Field has produced 27.9 e^3m^3 (780 mmcf) and 19 m^3 condensate (120 bbls) in 9 months from the basal Bluesky and Gething formations. Bluesky Formation pools in the Sinclair Field are widely separated (Figure 2), and likely produce from discontinuous, stratigraphically defined pools.

Figure 4. Bluesky paleogeography for the Western Canada Sedimentary Basin with the Sinclair field area located in the red square. The diagram shows the main Bluesky Formation and equivalent sandbodies. Lower Albian sediments were deposited during the southward transgression of the Moosebar Sea. The sea transgressed southeastward between the Keg River Highlands and the Cordillera, depositing clastic sediments in a shallow foreland basin (modified after Smith, 1994).

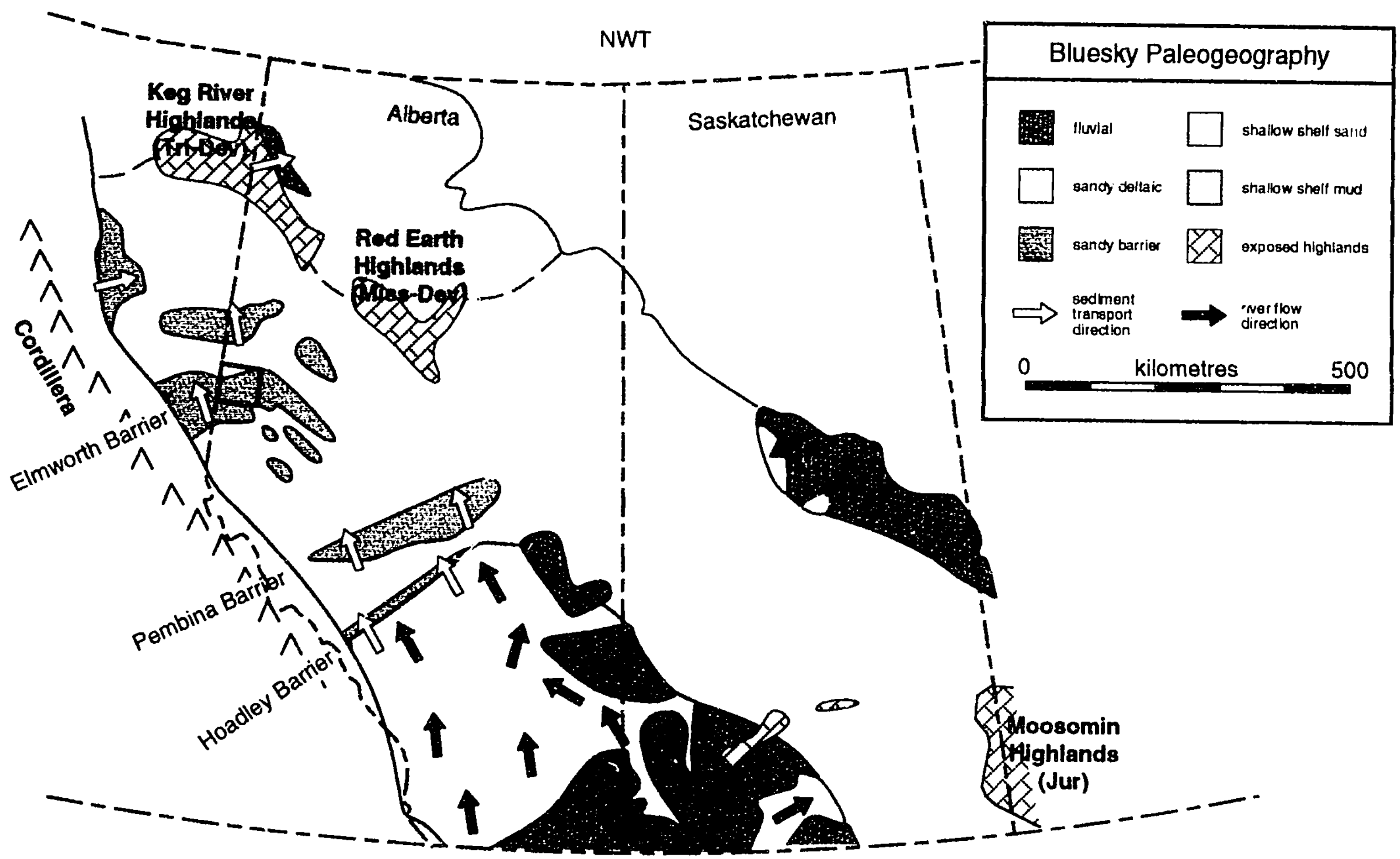


Figure 4. Bluesky paleogeography (modified after Smith, 1994).

1.4 Previous Work

Lower Cretaceous: Early Work

Early work on the Lower Cretaceous strata of Alberta was carried out by the Geological Survey of Canada in the late 1800's and early 1900's. The purpose of these studies was to survey and scientifically examine the geology and natural history of the Dominion of Canada. The first geologist to document the stratigraphy of the area was Selwyn, in 1877, who described shales and Cretaceous megafauna (ammonites) along cliffs of the Peace, Pine, and Smoky rivers. This was followed by the work of Dawson (1879), who described Cretaceous strata in the area from Edmonton to Port Simpson (B.C.), and compared these to the Cretaceous strata of England, Nebraska, and California. In his comparative table of Cretaceous rocks, Dawson (1879, p. 128-129B) subdivided the Cretaceous into;Lower Shales/Fort St. John group, Lower Sandstones/Dunvegan group, Upper Shales/Smoky River group, and Upper Sandstones/Wapiti River group. Dawson's work was followed by McConnell (1893) who surveyed the country between the Peace River and the Athabasca River north of Lesser Slave Lake (Figure 5). The Cretaceous was further subdivided by McConnell into the Laramie Sandstones and Shales, the Foxhill Sandstones, the La Biche Shales, the Pelican Sandstone, the Pelican Shale, the Grand Rapids Sandstone, the Clearwater Shale, and the Tar Sands. The Cretaceous section made up from outcrops along the Peace and Smoky Rivers includes; the Wapiti River Sandstone, the Foxhill Sandstone, the Smoky River Shales, the Dunvegan Sandstones, the Fort St. John Shales, the Peace River Sandstones, and the Loon River Shales. McLearn (1916) remeasured part of McConnell's Athabasca River section;the new Cretaceous section was notably bounded by unconformities above and below. Although McLearn did not further subdivide the Cretaceous, he did add more lithologic information and raised some sandstone and shale units to formation status. The Tar Sands were redefined based on depositional settings (*vs.* bitumen content), and were renamed the McMurray Formation. The "newly" defined Cretaceous succession along the Athabasca River now included; the La Biche Formation, the Pelican Sandstone, the Pelican Shale, the Grand Rapids Formation, the Clearwater Formation, and the McMurray Formation (Figure 5). McLearn also measured sections along the Peace River (1917) and Smoky River (1918) with the emphasis on stratigraphic relations and structure for oil exploration. Borings from the Peace River Oil Co. Well No. 2 were used to help determine broad structures, and oil samples from the No. 1 and No. 2 wells were analysed. The Smoky-Peace section includes;the Bull Head Mountain Formation, the Loon River Formation, the Peace River Formation, the St. John Formation, the Dunvegan Formation, the Smoky River Formation and Bad Heart Sandstone member, and the Wapiti Formation. McLearn is also credited by

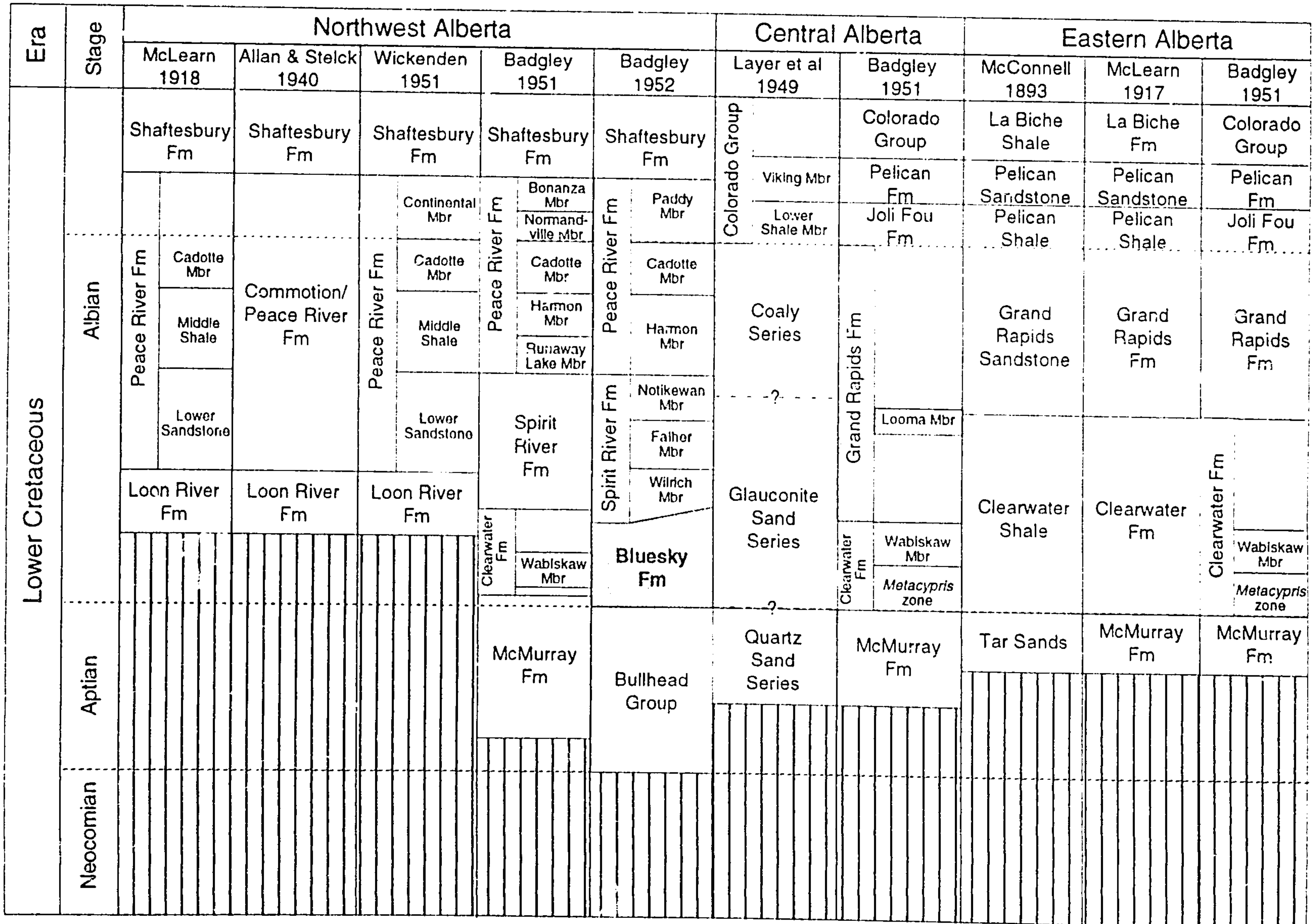


Figure 5. History of stratigraphic terminology for northwestern, central, and eastern Alberta.

Badgley (1951) for naming the Cadotte member in 1918, and named the Gething member (1923) in a survey of coal-bearing formations of northeastern B.C.. McKay (1929) named the Cadomin conglomerate from railway cuttings at Cadomin in west-central Alberta.

Refinement of the Lower Cretaceous continued as Allan and Stelck (1940) described well cuttings from the Guardian Well No. 1 [7-7-80-12w6] in the Pouce Coupe River district. A complete Lower Cretaceous succession was described including; the Bullhead Mountain Formation, the Moosebar Shale, the Gates Sandstone, and the Fort St. John Formation. The Bullhead Mountain Formation, at this location, was interpreted to be transitional between westward continental deposits, and eastward marine deposits. McLearn (1940) continued to survey the geology and physical features, as well as the culture, of the Peace River Foothills. He described rocks from the Lower Cretaceous to the Triassic and considered the Bullhead Mountain Formation to be dominantly nonmarine. Wickenden and Shaw (1943) mapped the Mount Hulcross-Commotion Creek map area of British Columbia. They found that the Lower Cretaceous formations in B.C. were thicker and of different lithologies than those exposed in the plains and the Peace River area. Wickenden and Shaw raised the Fort St. John Formation and Bull Head Mountain Formation to group status (Figure 5). The renamed Bullhead Group contained many coal seams, and was interpreted to be dominantly nonmarine in this area. McLearn (1944, 1945) refined the stratigraphy and paleogeography of the Lower Cretaceous with an influx of fossils submitted to the Geological Survey from gover ment agencies and oil companies. A series of five paleogeographic maps (1944), and a new table correlating formations of the Lower Cretaceous (1945) were constructed. Wickenden (1951) described many detailed sections along the Peace River which were correlated by a preliminary study of foraminifera.

Bluesky Formation

Badgley (1952) described drill core, samples, and electric logs in a broad tract from the Athabasca area to the Peace River area resulting in the designation of; the Paddy Member, the Harmon Member, the Notikewin Member, the Falher Member, the Wilrich Member, the Spirit River Formation, and the Bluesky Formation (Figure 5). The Bluesky Formation was originally described as the sandstone directly underlying the Wilrich Member (Badgley, 1952). The lower contact with the Gething Formation was based on the change from "porous, glauconitic sandstones above to dominantly non-marine interbedded sandstones, shales, and coals". The Alberta Study Group (1954) later simplified this definition, designating the Bluesky Formation as the sandstone and shale overlying the Gething Formation. The Bluesky Formation type well, SHELL B.A. BLUESKY NO. 1 [4-29-81-1W6], was drilled in northwestern Alberta in 1950. Stelck *et al.* (1956) correlated middle Albian formations using ammonite and foraminifera datings. The upper portion of the McMurray Formation and the basal glauconitic sands of the Clearwater Formation, was found to correlate to the *Trochammina mcmurrayensis* foraminifera zone. At this time the *T. mcmurrayensis* zone was not recognized outside of the McMurray area, but locally indicated a brackish setting with deeper water to the west. The observed megafauna were consistent with the brackish interpretation, and were more areally extensive than foraminifera. They were also present in the underlying Mannville Formation. In northeastern British Columbia the Bluesky and Gething formations were examined in a subsurface study by Pugh (1960). Pugh proposed to use the Bluesky Formation in northeastern British Columbia to describe a thin series of beds overlying the Gething Formation that had lithologies and log characteristics similar to the Bluesky Formation in the Peace River area.

Bluesky Formation: Recent Work

Few regional syntheses have been written on the Bluesky Formation due to the formation's heterogeneity and diachronous nature (O'Connell, 1988; Rosenthal, 1988). Stott (1982) examined the stratigraphy of northeastern British Columbia and showed the paleogeography and depositional history from the Barremian to the Cenomanian. He showed that the Bluesky Formation is equivalent to the upper portion of the Gething Formation in the B.C. foothills, and is the uppermost portion of the first of four major regressive pulses in the Cretaceous. These regressions are related to tectonic movements along the Omineca Geanticline.

AAPG memoir 38, Elmworth-Case Study of a Deep Basin Gas Field, edited by Masters (1984) focused more attention on Lower Cretaceous sediments in the deep basin in Alberta. Papers from this volume by Chiang (1984), Jackson (1984), Smith (1984), and Smith *et al.* (1984) cover the Bluesky Formation and equivalent formations. Jackson (1984) outlined the paleogeography of western Canada for the Mannville Group with a series of maps and cross-sections. Jackson illustrated the important transgressive and regressive stages, and major sandstone trends of the Mannville Group. The paleogeography of the Mannville Group around the Deep Basin area was mapped by Smith *et al.* (1984). Gas reserves and production performance of the Deep Basin area were summarized by Smith (1984). Chiang (1984) mapped and correlated Glauconitic shoreface and channel deposits along the Hoadley Barrier.

More recent work focusing on the Bluesky Formation has begun to target specific areas and problems. Moslow and Pemberton (1988) compared the Bluesky Formation to the Cadotte Member in terms of shoreface *vs.* deltaic processes in west-central Alberta. The Bluesky Formation was interpreted to be made up of shoreface facies, which are typically associated with a barrier island or strand plain. Oppelt (1988) described the lithological, ichnological, and sedimentological features of the Bluesky Formation in northeastern British Columbia. Oppelt concluded that the Bluesky Formation comprised marginal marine, wave-dominated offshore sand bars seaward of the prograding Chamberlain Delta. The distribution of Bluesky Formation facies in northern Alberta, and the influence of the Peace River Arch were studied by O'Connell (1988). O'Connell found the Bluesky Formation to thicken locally over the Peace River Arch axial graben, and divided the Bluesky Formation sandstones into offshore and overlying inshore deposits. Wave-dominated shorelines and incised channels of the Glauconite Formation were examined by Rosenthal (1988) in west-central Alberta. Rosenthal found the Glauconite Formation to show three transgressive-regressive successions, each incised by deep, narrow channels. A statistical analysis on ichnofossil associations in northwestern Alberta was conducted by Ranger and Pemberton (1991). Ichnological data indicate that the Bluesky Formation in this area was deposited as a nearshore- to marginal-marine, regressive sequence following the transgression over the Gething Formation. For the Karr area of west-central Alberta, Male (1992) discussed the sedimentology and ichnology of the Bluesky Formation. Male found the Bluesky Formation to be deposited during an overall transgressive phase, with upper and lower Bluesky sediments deposited during transgression. One relatively thin progradational cycle produced a "middle Bluesky strand plain" with sediments supplied from the west. Leckie and Smith (1992) examined the Bluesky Formation, in addition to other Cretaceous strata, in a paper on foreland basins. Brekke and Pemberton (1994a,b) used ichnological and sedimentological information to interpret paleoenvironmental conditions of the Bluesky Formation in the Sinclair area. Brekke and Pemberton found the Bluesky Formation to be a wave-influenced to wave-dominated shoreface succession. Smith (1994) reviewed the Bluesky Formation in an overview of the development of the Western Canada Foreland Basin. The Bluesky Formation is also illustrated by Hayes *et al.* (1994) in a study of the Mannville Group. The Bluesky Formation at Aitken Creek in northeastern British Columbia was studied by Alway (1995). Alway interpreted the Bluesky Formation at the Aitken Creek Field to be made up of fluvial and estuarine valley-fill deposits.

1.5 Geologic Framework

The development of the Western Canada Sedimentary Basin (WCSB) occurred in two stages, separated by the collision of exotic superterranes with the North American craton. These two stages comprise the passive margin/cratonic platform which ranges in age from the late Precambrian to Triassic, and the Western Canada Foreland Basin which ranges in age from the middle Jurassic to early Eocene.

The passive margin/cratonic platform of North America can be subdivided into four sequences bounded by interregional unconformities. These sequences were documented by Sloss (1963) and comprise; the Sauk sequence (upper Precambrian to early Ordovician), the Tippecanoe sequence (middle Ordovician to early Devonian), the Kaskaskia sequence (late early Devonian to latest Mississippian), and the Absaroka sequence (latest Mississippian to early Jurassic). Carbonate sedimentation occurred throughout these sequences on the passive margin edge and within intracratonic basins.

The accretion of the Intermontane Superterrane occurred in the late Jurassic, and the Insular Superterrane accreted in the mid-Cretaceous. The most widely accepted model for terrane accretion involves the collision of these two allochthonous terranes to the western margin of the North American craton (Fermor and Moffat, 1992; Stockmal *et al.* 1992). Terrane accretion was initiated in the Triassic with the breakup of Pangea. The collision of the Intermontane Superterrane loaded the craton and forced the margin downward resulting in the Foreland Basin which was an elongated depression with an asymmetric trough shape. The development of the Foreland Basin started in the Jurassic with the Columbian orogeny, and sedimentation styles switched from carbonate- to clastic-dominated. Two sequences (Sloss, 1963) are present in the foreland basin: the Zuni sequence (Middle Jurassic to middle Paleocene) and the Tejas sequence (late Paleocene to present).

1.6 Stratigraphic History of the Cretaceous Period

Leckie and Smith (1992) subdivided the Zuni sequence into five cycles that record two major transgressive phases separated by a regression at the end of the late Neocomian. This regression created an unconformity known as the "pre-Cretaceous" or sub-Cretaceous unconformity.

The first transgressive phase of the Zuni sequence started in the mid-Jurassic and ended in the early Cretaceous. In the mid-Jurassic, sedimentation occurred over a wide, stable continental shelf of the passive margin which was transformed into a narrow, subsiding, foredeep trough due to the accretion of two superterranes. Deposition in the foredeep rapidly filled the trough with westerly-derived sediments, while shorefaces in southern Saskatchewan and Alberta formed from sediments derived from the craton (Stott, 1984; Smith, 1994). Sea level dropped at the end of the Neocomian, permitting the development of the sub-Cretaceous unconformity.

The second transgressive phase lasted from Aptian to the middle Paleocene and resulted in the filling of the foreland basin. Loading of the craton continued due to terrane accretion, and alluvial and fluvial deposition occurred along the eastern edge of the rising

Cordillera. During the Aptian, the Spirit River Valley formed between the rising Cordillera and the Fox Creek Escarpment (Smith, 1994). This provided a major basin drainage system for the Cordillera, which flowed north to the boreal sea. A series of northwest to southeast trending highlands provided local sediments and served to confine the seaway. As sea level continued to rise, the alluvial and fluvial environments were transgressed from the north by the Moosebar Sea. This transgression is thought to have been episodic (Wood and Hopkins, 1985; O'Connell, 1988; Rosenthal, 1988; Hayes *et al.*, 1994). The rising Moosebar Sea resulted in the deposition of brackish bay deposits initially, followed by shoreline sands, and finally shelfal shales.

Continued transgression of the Moosebar Sea ultimately drowned most highlands (Hayes *et al.*, 1994), and created a shallow shelf setting from the Arctic extending south to the Hoadley Barrier near Edmonton, and to the U.S.A. border with Saskatchewan (Figure 4). The Moosebar Sea was bounded to the west by the emergent Cordillera, and to the east by the Moosomin Highlands (Figure 4). The rising Cordillera provided a major influx of sediment to the foreland basin, as provenance switched from the craton in the middle Albian (Stott, 1984; Smith, 1994). The maximum Moosebar transgression was reached in the middle Albian, after which the basin rapidly filled from the west.

1.7 Stratigraphic Nomenclature and Relationships

The Lower Albian Bluesky Formation type well is the SHELL B.A. BLUESKY NO. 1 well [4-29-81-1W6] in northwestern Alberta (Stelck, 1990). It was originally described from core and electric logs by Badgley in 1952. The Alberta Study Group (1954) designated the Bluesky Formation as the sandstone and shale overlying the Gething Formation. Sediments of the Bluesky Formation consist of shoreline and prograding barrier sandstones and shales deposited between the Keg River Highlands near Fort Nelson, and the Hoadley Barrier near Edmonton (Wood and Hopkins, 1989; Smith, 1994).

The Bluesky Formation is stratigraphically equivalent to the Glauconitic Member of the Clearwater Formation in the central plains of Alberta, and the Wabiskaw and Lloydminster formations in eastern Alberta. In the northern mountains and foothills of Alberta, the Bluesky Formation is equivalent to the upper Gladstone Formation (Stott, 1982), and the upper Gething Formation (Stott, 1982; Stelck, 1984) in the foothills and Peace River area of B.C. (Figure 5).

Stratigraphic relationships for the Bluesky Formation are difficult to determine due to the heterogeneous and diachronous nature of the deposits (Stott, 1982; Stelck, 1984; O'Connell, 1988; Rosenthal, 1988). The greatest complication involves the relationship of the Bluesky and the Gething formations. The Bluesky Formation conformably overlies the Gething Formation throughout Alberta (Stott, 1982; Stelck, 1990), whereas in the foothills of British Columbia the Bluesky Formation is equivalent to the upper Gething Formation (Figure 6) (Stott, 1982; Stelck, 1984). For this study, the Bluesky Formation is considered to be the shale and sandstone succession that overlies the Gething Formation. The Gething Formation is considered to be the succession comprising 'related' coals, sandstones, marine siltstones, and marine mudstones (Stott, 1990).

Figure 6. Schematic cross-section of the Bullhead Group shows the Bluesky Formation to consist of shallow marine sandstones and shales. Although they conformably overlie the Gething Formation throughout Alberta, they are equivalent to the upper portion of the Gething Formation in the foothills of British Columbia.

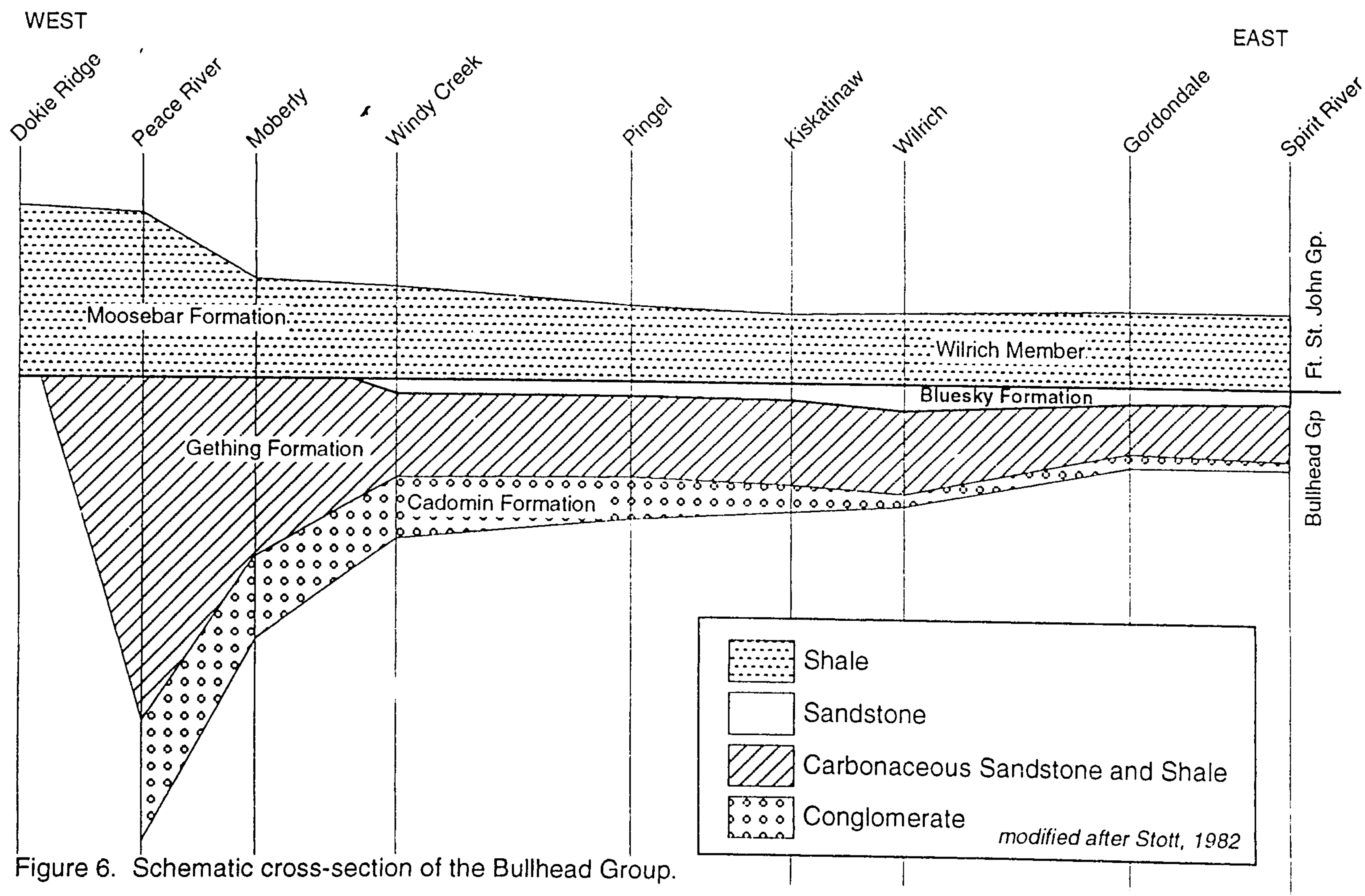


Figure 6. Schematic cross-section of the Bullhead Group.

II CONCEPTUAL FRAMEWORK OF ICHNOLOGY

2.1 Introduction

The interpretation of depositional environments in ancient rocks has typically drawn together all the information available. Sedimentary structures and lithology have long been used as the primary indicators of environmental parameters such as wave energy and bathymetry. Body fossils have also been used in many studies to determine environmental conditions, but were not observed in this study. Ichnology (the study of sediment-organism interactions) provides another line of evidence for the interpretation of depositional environments.

Ichnofossils are useful in investigating paleoenvironments; the concept of functional morphology, a basic premise employed by ecologists and paleoecologists in environmental reconstruction, is equally applicable to ichnology. Ichnofossils are unique in that they represent not only the morphology of the trace-making organism, but also its behaviour. Pemberton *et al.* (1992a,b) suggest that substrate coherence and stability, energy levels, oxygenation, water salinity, temperature, bathymetry, food resources (nutrients), and periodic erosion all have a profound effect on the resultant ichnofossil morphologies, and therefore may be used in determination of paleoenvironmental conditions.

Ichnology is especially useful in paleoenvironmental interpretations for several additional reasons. Ichnofossils are not generally regarded as being useful in stratigraphy since they have a long temporal range which makes ichnofossils an excellent tool in comparing rocks of vastly different ages, *e.g.* many ichnofossils, like *Teichichnus*, persist throughout the Phanerozoic. These interpretations are possible because some ichnofossils have a narrow facies range, although there are a few ichnofossils that cross ichnofacies boundaries. Ichnofossils are created by trace-making organisms in response to environmental parameters. As such, many different organisms may create one type of ichnofossil, *e.g.* fugichnia may be created by annelids, scaphopods, anemones, *etc.*.

Trace fossils represent normal 'fairweather' conditions *vs.* ephemeral depositional events responsible for sedimentation in many environments. Biogenic activity therefore represents the typical environmental conditions present and unburrowed zones record the transient high energy events.

Another aspect of ichnofossils that makes them excellent in paleoenvironmental use is that they are usually found *in situ*. Whereas body fossils are subject to reworking and 'leaking', ichnofossils are 'in place', and are directly related to the paleoenvironmental parameters in which they were formed. Some robust trace fossils, like *Rosselia* in this study, may be eroded and re deposited. Most trace fossils, though, would be broken up or dispersed by erosion of the substrate.

Another reason ichnofossils are useful in environmental reconstructions is that they are usually the only evidence of soft-bodied organisms. The body fossils of these organisms are the exception in many environments, and soft-bodied biota frequently comprise the greatest biomass (*e.g.* in the Burgess shale). Additionally, body fossils that are buried and subjected to diagenetic processes may be removed. For some ichnofossils, these same diagenetic processes may enhance their appearance aiding identification. Trace fossils are the only biogenic evidence in 'unfossiliferous rocks'.

2.2 Environmental Parameters on Ichnologic Structures

Ichnofossils represent ethological patterns that are determined by the organism's response to environmental parameters (*e.g.* bathymetry, wave energy, sedimentation rates, and substrate consistency). A single organism may create a number of ichnogenera in response to variations in environmental conditions. Therefore, ichnofossils are generally better indicators of slight fluctuations in sedimentary dynamics and other environmental parameters than are physical sedimentary structures.

2.2.1 Bathymetry

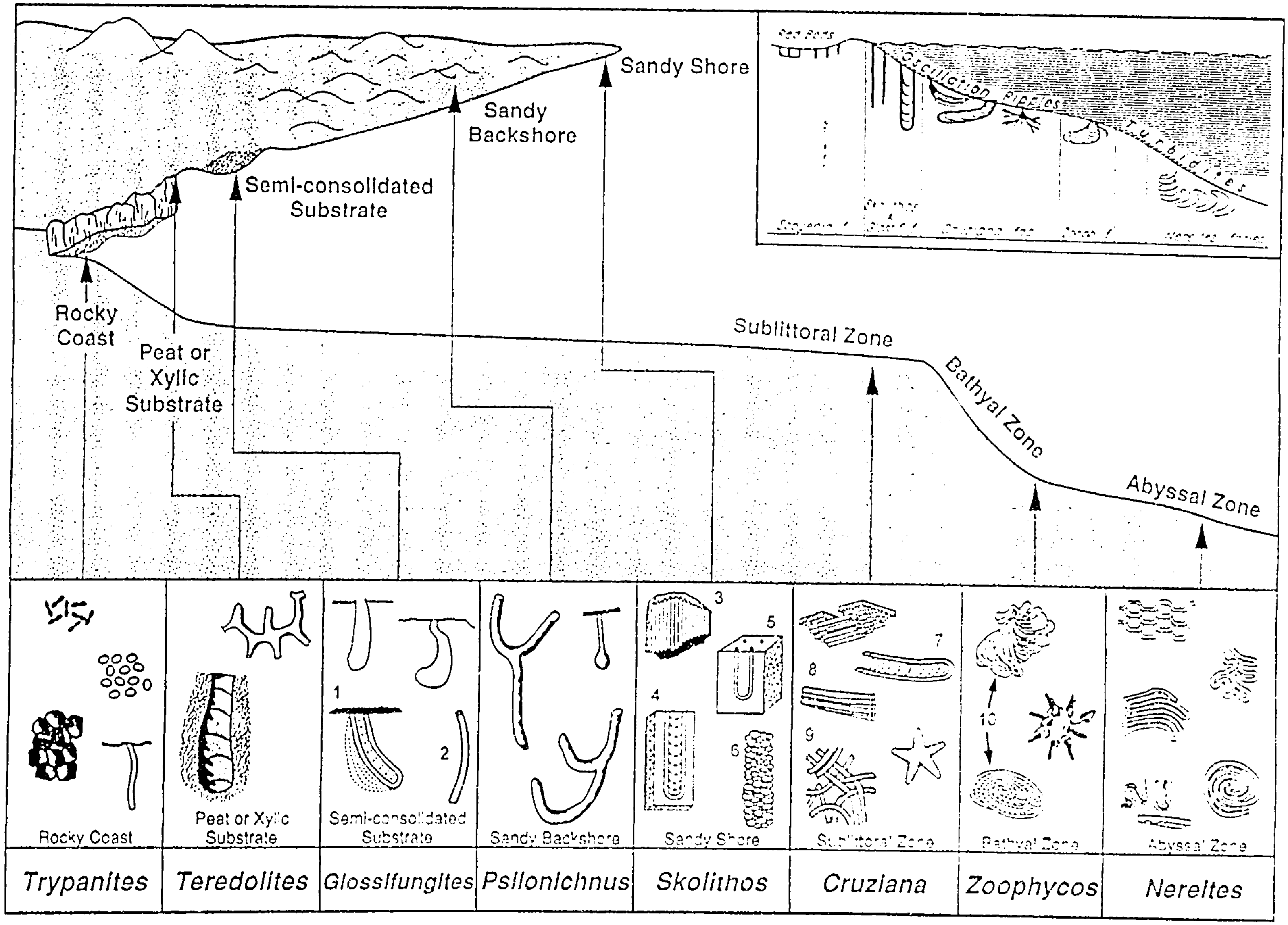
Seilacher's (1967) original ichnofacies designations are often regarded by geologists as indicators of purely bathymetric information (Figure 7, inset). Although there is a relationship between ichnofacies and water depth, ichnofacies should be used in a relative sense to denote the relationship of ethology and wave base (*e.g.* storm wave base and fair weather wave base). Bathymetry may also be considered to be roughly analogous to the distance from the shoreline within shallow, epeiric seaways. Ethological patterns typically vary from the dwelling traces of suspension-feeding organisms (shallow marine environments, *e.g.* foreshore to lower shoreface) to the grazing traces of deposit-feeding organisms (deep marine environments, *e.g.* offshore).

2.2.2 Wave Energy

Wave energy is closely associated with bathymetry in marine environments, and includes both fair weather and storm events. The fair weather wave base extends approximately down to the base of the lower shoreface, which is dominated by burrowed to laminated, clean to slightly muddy sand. Trace-making organisms in this setting must deal with shifting, noncohesive substrates. As such, dwelling structures of suspension- and deposit-feeding organisms exist in this setting.

Storm wave base (SWB) marks the water depth to which storm energy contacts the substrate, and demarcates the offshore-shoreface transition. Interbedded and bioturbated sandstone and shale comprise the sediments of this zone. Tempestites (rapid sand

Figure 7. The nine ichnofacies in a schematic shoreline section indicating environmental gradients. The inset shows Seilacher's (1967) original zonation which was used to interpret bathymetry. Ichnofacies are ultimately controlled by many factors which are interrelated. Trace fossils found in the Bluesky Formation include 1) *Diplocraterion*, 2) *Skolithos*, 3) *Skolithos*, 4) *Diplocraterion*, 5) *Arenicolites*, 6) *Ophiomorpha*, 7) *Rhizocorallium*, 8) *Teichichnus*, 9) *Planolites*, 10) *Zoophycos*.



modified after Seilacher, 1967; and Pemberton et al., 1992 accumulation due to storms) interrupt the resident background sedimentation (typically slow mud accumulation), and are commonly preceded by erosion. The net result of tempestite deposition is an uncharacteristic, high energy substrate deposited in a low energy environment. These substrates are typically colonized by opportunistic suspension-feeding organisms if they are present (MacEachern *et al.*, 1992b).

In a specialized case, *e.g.* very high wave energy of the upper shoreface to foreshore, migrating megaripples make the substrate uninhabitable for most organisms. The migrating megaripples would destroy any dwelling structures and epibenthic organisms would quickly be buried or removed. This leaves a niché for endobenthic deposit-feeding organisms that may inhabit sandy substrates.

2.2.3 Sedimentation Rate

Sedimentation rates are dependent on sediment supply, accommodation space (bathymetry), and transport velocity (wave energy). In shallow environments, *i.e.* foreshore to shoreface, sedimentation is typically rapid due to high sediment supply and rapidly decreasing transport energy. Farther from the shoreface, *i.e.* offshore, sedimentation rates are relatively slow, with sediment comprising mud. Rapid sedimentation results in well preserved, discrete trace fossils while slow sedimentation allows trace-making organisms to thoroughly rework the substrate generating a bioturbate texture. In this respect, ichnofossil assemblages and abundance may provide information on sedimentation rates, which is important in recognizing the degree of storm intensity and frequency.

2.2.4 Substrate Consistency

Substrate consistency is important in determining which types of organisms can inhabit the substrate, and what types of behaviour are exhibited (Figures 7, 8). Soft, soupy, mud substrates normally accumulate slowly from suspension. These types of substrates prevent unlined dwelling structures from remaining open, and shallow, feeding and grazing structures such as *Helminthopsis*, *Teichichnus*, *Zoophycos*, and *Chondrites* dominate. Since these sediments accumulate slowly , this allows the upper part of the substrate to be reworked into a bioturbate texture.

Shifting (non-cohesive), sandy substrates are typically deposited in higher energy environments. Within these environments trace-making organisms typically create dwelling- and suspension-feeding structures so they may take advantage of the high degree of suspended foodstuff available in the water column. Suspension-feeding organisms are adapted to the turbulent, high energy environments. They either build heavily lined dwelling structures, *e.g. Ophiomorpha*, or aggrade with sedimentation, *e.g. Conichnus.*

Firm substrates (firmgrounds) may be present under many different environmental parameters, and are generally considered to be associated with a depositional hiatus. Trace fossils generated in firmgrounds are typically robust and unlined, cross-cutting physical sedimentary structures and trace fossils in the underlying facies. Trace fossil assemblages associated with these substrates are typical of the *Glossifungites* ichnofacies, which may mark important sequence stratigraphic surfaces (MacEachern *et al.*, 1992b). A similar trace fossil association has been observed by Bromley (1975), and consists of a palimpsest assemblage (genetically related to erosion without a depositional hiatus) cross-cutting the original softground trace fossil suite (genetically related to deposition). Since this palimpsest assemblage may appear similar to a *Glossifungites* ichnofacies it is important to positively identify any *Glossifungites* ichnofacies observed.

2.3 Ethologic Classification

Basic ethologic patterns are genetically controlled, *i.e.* trace-making organisms will create ichnofossils typical of their behaviour, but specific ichnofossils (ichnogenera) are not restricted to a single trace-making species. And although trace-making organisms have evolved throughout the Phanerozoic, ethologic patterns have persisted. The ichnofossils identified in this study fall into seven behavioural categories: resting, dwelling, grazing, feeding, predation, and escape. Individual trace fossils may reflect multiple behavioural strategies, *e.g. Rosselia* is both a dwelling structure and a (deposit) feeding structure.

2.3.1 Resting

Resting traces (cubichnia) are created by mobile epibenthic (or endobenthic) organisms that have interrupted movement and have briefly come to rest on the substrate. As such, these traces are intergradational with locomotion traces and shallow ephemeral dwelling traces, and may also be associated with escape traces. Resting traces typically comprise passively filled, shallow, trough-like depressions due to the displacement of fine-grained sediment (mud) or excavation of coarser material (sand). Since the trace-making organism came to rest on the substrate, cubichnia may record ventral morphology, and are generally observed at bedding planes. Resting traces in this study include: *Bergaueria* and *Lockeia*

2.3.2 Dwelling

Dwelling traces (domichnia) are dominantly vertical, permanent to semi-permanent domiciles created by endobenthic suspension feeders. Dwelling traces are passively filled, and may be cone-shaped, U-shaped, tubes, shafts, or shaft and tunnel systems. In unconsolidated substrates, to keep the burrow open, the trace-making organism must line the burrow with mucus or agglutinated sediment. The burrow opening is typically the size and shape of the trace-making organism, and is approximately an external mold of the organism's morphology. The burrow lining (wall) of dwelling traces precludes deposit-feeding, distinguishing the two ethological categories. Domichnia in this study include: *Arenicolites, Bergaueria, Conichnus, Cylindrichnus, Diplocraterion, Ophiomorpha*, and *Skolithos*.

2.3.3 Grazing

Grazing traces (pascichnia) are shallow deposit-feeding traces generated by mobile epibenthic or endobenthic organisms. Grazing traces are intergradational between locomotion and feeding traces. Grazing traces may be discontinuous and consist of compact, approximately planar, shallow to surficial coiled or looped meanders. Pascichnia may have spreiten, indicative of a laterally shifting burrow; or a fecal core, indicative of an organism feeding while moving on, or through, the substrate. Pascichnia in this study include: *Anconichnus, Helminthopsis*, and *Zoophycos*.

2.3.4 Feeding

Feeding traces (fodinichnia) are dominantly made by endobenthic organisms exhibiting deposit-feeding and dwelling behaviour. Feeding traces may have no wall, a mud-packed wall (which is the deposit that is mined), or a distinct mantle (created by selective sorting and feeding). As such, feeding traces are temporary structures that provide shelter for the trace-making organism while it 'mines' the substrate. Burrows range from simple tubes to complex three dimensional structures. Feeding traces may have a passive back-fill; or where trace-making organisms pass fine sediment back, an active meniscate back-fill. Fodinichnia in this study include; *Asterosoma, Chondrites, Macaronichnus, Planolites, Rhizocorallium, Rosselia, Teichichnus, Terebellina*, and *Thalassinoides*.

2.3.5 Predation

Predation traces (preadichnia) are created by mobile endobenthic organisms transitional between locomotion and dwelling behaviour. Predation traces are typically horizontal, passively filled, mucus lined tubes. The mucus lining is necessary to keep the tube open while the predatory organism waits for some prey organism. Within this study, the only ichnogenera exhibiting predatory behaviour is *Palaeophycus*.

2.3.6 Escape

Escape structures (fugichnia) are created by endobenthic organisms. Fugichnia are created in response to an organism's need to keep in contact with the sediment-water interface, or to maintain a consistent substrate position. Escape traces are generated in response to burial of an organism by an abrupt sedimentological event. Escape traces are usually vertically nested, funnel-shaped laminae. These laminae are disrupted by upward moving organisms, and collapse into the underlying cavity recently evacuated by the trace-making organism. Fugichnia within this study are not divided into ichnogenera.

2.4 Bluesky Formation Ichnogenera

In this study the Bluesky Formation contains a well preserved and diverse (22 ichnogenera) ichnofossil assemblage including; *Anconichnus*, *Arenicolites*, *Asterosoma*, *Bergaueria*, *Chondrites*, *Conichnus*, *Cylindrichnus*, *Diplocraterion*, fugichnia, *Helminthopsis*, *Lockeia*, *Macaronichnus*, *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Rhizocorallium*, *Rosselia*, *Siphonichnus*, *Skolithos*, *Teichichnus*, *Terebellina*, *Thalassinoides*, and *Zoophycos*. In addition, many beds are characterized by a bioturbate texture in which individual forms are difficult to discern. Root traces (rhizoliths) are also locally present in the Bluesky Formation. Ichnofossil abundances were recorded as rare (r), moderate (m), common (c), to abundant (a). Appendix A contains a description of ichnogenera observed in the Bluesky Formation.

2.5 Ichnofacies Concept

The trace fossil assemblages identified in this study correspond to the *Cruziana* ichnofacies, *Skolithos* ichnofacies, *Glossifungites* ichnofacies (Figures 7, 8), and two distinct *Macaronichnus* assemblages. Trace fossil ichnofacies (and assemblages) are divided into softground ichnofacies, and substrate-controlled ichnofacies. Softground substrates are developed in non-cohesive sandy substrates or uncompacted muddy substrates and are interpreted to develop contemporaneously with sedimentation. Substrate-controlled ichnofacies are interpreted to be noncontemporaneous with deposition. This includes firmground substrates which are semi-lithified or compacted.

The *Cruziana* ichnofacies is developed in a low energy environment with slow, but episodic sedimentation. It is dominated by grazing and feeding structures developed within a soupy or softground substrate. This ichnofacies is generated in the offshore to lower shoreface transition (Pemberton *et al.*, 1992a,b). The *Skolithos* ichnofacies is characteristic of a higher energy environment, usually developed in a shifting substrate (Figure 8) (Pemberton *et al.*, 1992a,b). Dwelling- and suspension-feeding structures are dominant, although escape and grazing structures may be present. The *Skolithos* ichnofacies is also a softground ichnofacies, that may occur in the lower to upper shoreface (Figure 7) (Pemberton *et al.*, 1992a,b). Elements of the *Skolithos* ichnofacies may occur with trace fossils from the *Cruziana* ichnofacies in roughly equal abundance to produce a mixed *Skolithos-Cruziana* assemblage. The *Skolithos-Cruziana* assemblage may occur in the transitional setting between the offshore and lower shoreface (Figure 7). This is also found in association with storm deposits (Pemberton *et al.*, 1992a,b). Trace-making

"non-contemporaneous" with deposition			"contemporaneous" with deposition	
Woodground	Hardground	Firmground	Softground	SUBSTRATE
xylic	lithified	semi-lithified to compacted	non-cohesive to non-compacted	CONSISTENCY / ENVIRONMENT
			Scoyenia *Psilonichnus*	Freshwater
Teredolites	*Trypanites*	*Glossifungites*	*Skolithos* *Cruziana* *Zoophycos* *Nereites*	High energy — Low energy: Marine

modified after Pemberton et al., *1992b*

Figure 8. Substrate consistency relationships with the nine ichnofacies, the shaded areas represent the ichnofacies observed in this study. The timing of deposition and bioturbation has been approximated by the consistency of the substrate. Softground ichnofacies are generally interpreted to be approximately contemporaneous with deposition and are controlled by numerous factors. The *Teredolites*, *Trypanites*, and *Glossifungites* ichnofacies are dominated by dwelling structures which are controlled by the consistency of the substrate.

organisms from the *Skolithos* ichnofacies are moved into a lower energy setting by storm events where they inhabit the newly deposited substrate. After some time the organisms indigenous to the environment will recolonize the area producing the mixed assemblage.

Conversely, the *Glossifungites* ichnofacies is a substrate controlled ichnofacies that develops in exhumed firmgrounds. Substrate coherence controls the ichnofossil generated, and therefore highlights breaks in the rock record (MacEachern *et al.*, 1992b). *Glossifungites* ichnofacies may demarcate important sequence stratigraphic surfaces that may otherwise be overlooked in the rock record. A complete review of the ichnofacies described can be found in Pemberton *et al.*, (1992a,b).

2.6 Recurring Ichnofacies and Paleoenvironmental Indications

2.6.1 *Skolithos* ichnofacies

The *Skolithos* ichnofacies is associated within the lower to upper shoreface (Pemberton *et al.*, 1992a,b). The substrate is unconsolidated, and is generally well sorted with fine to medium-grained sand and subordinate mud. It is generated above fairweather wave base (FWWB) which dictates a high energy subtidal environment and a shifting substrate.

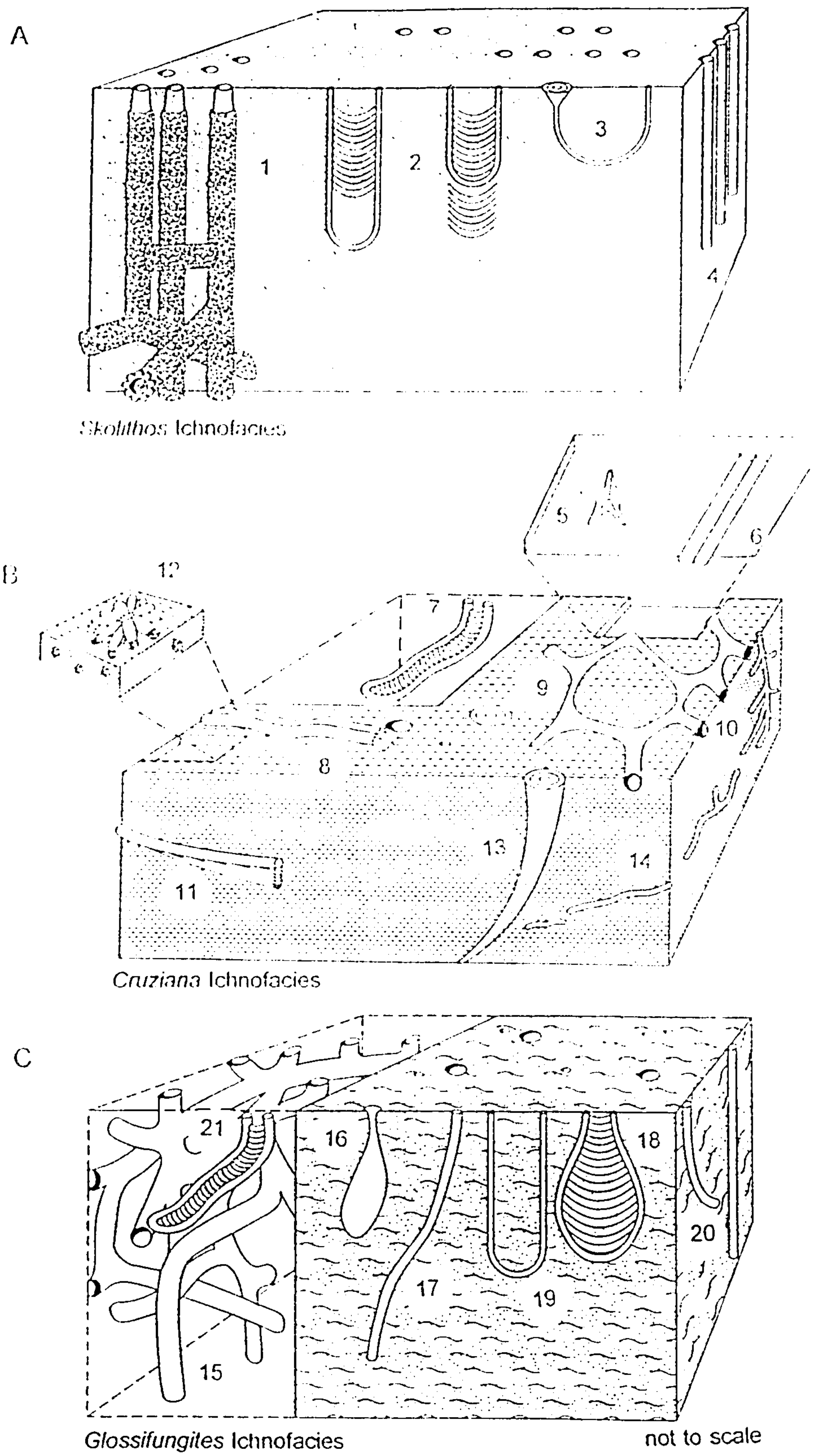
Due to the shifting substrate and high energy, structures are generally deep vertical, cylindrical, or U-shaped domiciles (Figure 9a). The deep vertical structures are necessary for the trace-making organism to anchor within the substrate. These are normally made by suspension-feeding organisms, but filter-feeding organisms may also be represented. Structures are generally dwelling burrows (domichnia) made by relatively few mobile organisms; diversity is usually low while burrow abundance may locally be high. Trace fossils of the *Skolithos* ichnofacies in this study are: *Conichnus*, fugichnia, *Ophiomorpha*, and *Skolithos*.

2.6.2 *Cruziana* ichnofacies

Of the assemblages present within the study area, the *Cruziana* ichnofacies is representative of the deepest, lowest energy environment in the Bluesky Formation. The *Cruziana* ichnofacies is generated in a subtidal environment (Pemberton *et al.*, 1992a,b) and occurs from the lower shoreface to offshore. The substrate is made up of variable amounts of sand and mud, but is unconsolidated and may be poorly sorted. The *Cruziana* ichnofacies is the dominant ichnofacies below FWWB, and is developed in a moderate to low energy environment. Sedimentation rates are variable and range from negligible to appreciable, but are not rapid.

Trace-making organisms in the *Cruziana* ichnofacies create dominantly horizontal burrows (Figure 9b). Food ingested in this environment is suspended and deposit-type, so

Figure 9. Trace fossils associated with the *Skolithos*, *Cruziana*, and *Glossifungites* ichnofacies. The *Skolithos* ichnofacies (A) is typififed by deeply penetrating vertical domiciles and includes 1) *Ophiomorpha*, 2) *Diplocraterion*, 3) *Arenicolites*, 4) *Skolithos*. The *Cruziana* ichnofacies (B) is typically developed in a softgound by deposit-feeding and grazing organisms. Trace fossils commonly include 5) *Asteriacites*, 6) *Cruziana*, 7) *Rhizocorallium*, 8) *Aulichnites*, 9) *Thalassinoides*, 10) *Chondrites*, 11) *Teichichnus*, 12) *Asterosoma*, 13) *Rosselia*, 14) *Planolites*. The *Glossifungites* ichnofacies is a substrate controlled ichnofacies developed in a firm, unlithified substrate. Trace fossils excavated into this substrate include 15) *Thalassinoides*, 16) *Gastrochaenolites*, 17) *Skolithos*, 18) *Diplocraterion*, 19) *Arenicolites*, 20) *Skolithos*, 21) *Rhizocorallium*.



modified after MacEachern et al., *1992b; Pemberton* et al., *1992b* feeding (fodichnia) and grazing (agrichnia) structures are present. This yields an ichnofacies with mixed horizontal, vertical, and inclined structures. Trace fossil diversity and abundance are high in the *Cruziana* ichnofacies. These trace fossils are made by mobile organisms that forage though the substrate while feeding.

Within this study the trace fossils that comprise the *Cruziana* ichnofacies are; *Anconichnus*, *Asterosoma*, *Chondrites*, *Cylindrichnus*, *Helminthopsis*, *Planolites*, *Rhizocorallium*, *Rosselia*, *Teichichnus*, and *Terebellina*.

2.6.3 *Cruziana-Skolithos* assemblage

The *Cruziana-Skolithos* assemblage is a mixed assemblage with elements from both ichnofacies. This assemblage is generated in an unconsolidated substrate and is normally well sorted medium to fine-grained sand with minor mud. In this study it is considered to represent deposition on the lower to middle shoreface, which is an environment of moderate fairweather energy punctuated by frequent storm activity. The result is a deposit dominated by high energy events.

Trace fossils in this assemblage have similar characteristics to the two ichnofacies. Throughout the assemblage diversity may be high, but locally diversity and abundance may be low. Storm variability, intensity and frequency, determine relative abundances of trace fossils present.

Traces present in the *Cruziana-Skolithos* assemblage generally are; *Arenicolites*, *Asterosoma*, *Bergaueria*, *Chondrites*, *Conichnus*, *Cylindrichnus*, *Diplocraterion*, *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Rhizocorallium*, *Rosselia*, *Skolithos*, *Teichichnus*, and *Terebellina*.

The *Macaronichnus* sp. assemblage is a specific *Cruziana-Skolithos* assemblage occurs in the Bluesky Formation, and is dominated by large numbers of *Macaronichnus* sp. (robust) with subordinate numbers of *Rosselia*. This recurring assemblage is typical of the laminated to bioturbated sandstone facies encountered in this study. This assemblage is indicative of a moderate-energy marine environment.

2.6.4 *Macaronichnus* assemblage

Macaronichnus was originally described by Clifton and Thompson (1978). The *Macaronichnus* assemblage has previously been described as a monogeneric association of *M. segregatis* or *M. spiralis* in the Cretaceous Bearpaw-Horseshoe Canyon Formation transition by Saunders and Pemberton (1986) and Saunders (1989), and in the Cretaceous Cadotte Member by Saunders *et al.* (1994). This assemblage occurs in a noncohesive, shifting sandy substrate interpreted to reflect swash stratification, and indicative of the foreshore zone. The foreshore is considered to be one of the most physically severe of modern marine environments.

M. segregatis and *M. spiralis* are limited to a zone within the swash-stratified facies, or the nearshore-beach facies of Saunders *et al.* (1994). Although bioturbation in the swash-stratified facies is limited to *Macaronichnus*, the burrowed zone is typically completely bioturbated. *Macaronichnus* comprises a mafic rich mantle and a mafic deficient fill, and burrow diameter is typically 2-3 mm. The *Macaronichnus*-making organism is thought to be a opheliid or an opheliid-like polychaete that inhabits the substrate of a highly reflective shoreface-foreshore. The trace-making organism thrives in what Saunders *et al.* (1994) have called an "oxygen window" wherein the organism feeds on epigranular bacteria and organic material suspended in the pore waters of the substrate (*cf.* Saunders *et al.*, 1994). These types of organisms are interpreted to be highly mobile infaunal deposit feeders (Saunders and Pemberton, 1986; Saunders, 1989; and Saunders *et al.*, 1994).

In this study the *Macaronichnus* assemblage is a monogeneric assemblage observed exclusively in the bioturbated and low-angle planar laminated sandstone facies. It develops, below the sediment-water interface, in very high energy shoreface environments. The trace-making organisms in this ichnofossil assemblage exhibit deposit-feeding behaviour due to very adverse conditions (high wave energy and non-cohesive substrates) and is found in high energy foreshore deposits.

III FACIES DESCRIPTIONS AND INTERPRETATIONS

3.1 Introduction

Due to the emphasis of this study on the facies relationships of the Bluesky Formation, the project was core intensive involving detailed descriptions of lithology, sedimentology, and ichnology. These aspects of the rocks were grouped in order to define 'facies' which were subsequently grouped into facies associations based on recurring patterns. Individual facies were described within each facies association, and the facies associations were then interpreted to yield depositional environments. Facies associations were traced laterally with core and wireline well logs.

3.2 The Facies Concept

In this study, the term 'facies' will be used to refer to the aspect, appearance, and outward characteristics of a rock including: lithology, sedimentary structures, and ichnofossils. The facies observed in this study are grouped together into facies associations based on the recurring nature of facies successions. The facies within a facies association are genetically related, and were generated in similar or adjacent depositional environments. For this reason, paleoenvironmental interpretations for this study were based on the interpretation of facies associations since individual facies are not always indicative of a depositional environment.

Walther (1894) stressed the relationship of depositional environments and the resulting stratigraphic successions. Walther's Law states "...that only those facies and facies areas can be superimposed primarily which can be observed beside each other in time" (in Middleton, 1973). Middleton succinctly discussed the implications and the misinterpretations of Walther's Law by other authors from the late 1930's through the mid 1950's, and illustrated the importance of the law. It contends that only those facies generated in depositional environments immediately adjacent to one another may directly overlie one another in a conformable facies succession. Walther's Law therefore applies to facies within a facies association, but not necessarily to facies between facies associations.

Walther also stated that erosional processes and depositional processes are equally important in many environments (in Middleton, 1973). Walther also noted the intrinsic relationship between biological and sedimentological processes, in allowing for both lithofacies and biofacies.

3.3 Sedimentary Structures

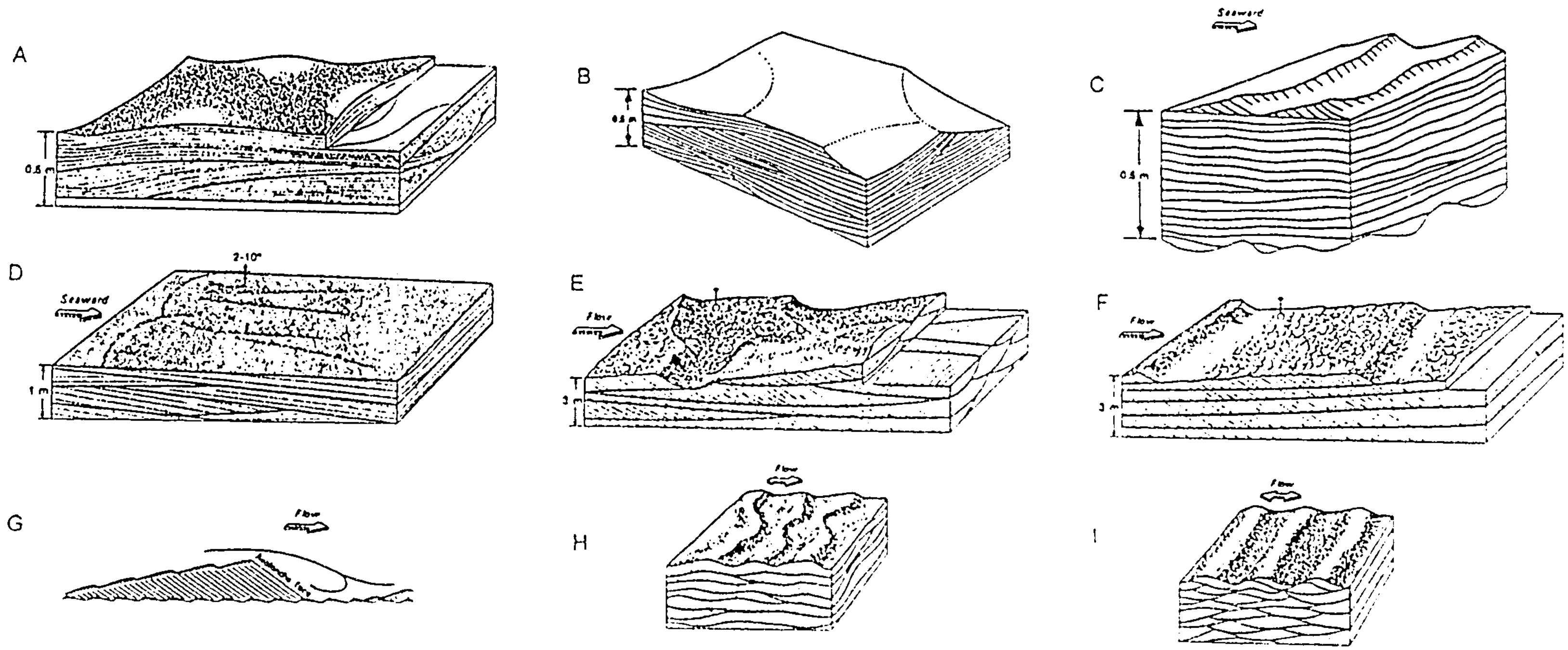
Observed sedimentary structures were subdivided into two classes, those of primary origin and those of secondary origin. Primary sedimentary structures are syngenetic depositional structures, and secondary sedimentary structures post-date initial deposition, but are penecontemporaneous with deposition. Secondary sedimentary structures include synaeresis cracks, dewatering structures, and trace fossils.

In this study, primary sedimentary structures were subdivided into three groups: low-angle curvilinear (wavy) cross-stratification, low-angle planar cross-stratification, and high-angle cross-stratification. Low-angle curvilinear (wavy) laminations include hummocky cross-stratification (HCS, Figure 10a), swaley cross-stratification (SCS, Figure 10b) (*cf.* Leckie and Walker, 1982), and quasi-planar lamination (QPL, Figure 10c) (*cf.* Arnott, 1993). Strictly speaking, QPL is not a type of cross-stratification, but is included in this group because at the scale of observation (*i.e.* less than 9 cm across) it is typically indistinguishable from SCS and HCS. Low-angle planar cross-stratification is interpreted to be swash cross-stratification (Figure 10d). The high-angle cross-stratification bedforms present are interpreted to be trough cross-stratification (TXB, Figure 10e) and planar tabular cross-stratification (Figure 10f). Three types of ripples were observed in the Bluesky Formation and include waning-flow (current) ripples, oscillation ripples, and combined flow ripples (Figure 10g,h,i).

3.4 Reference Logs

Representative wireline logs are matched to cores of the Bluesky Formation for DOME TOTAL KNOPCIK 6-32 (Figure 11), and DOME TOTAL SINCLAIR 11-18 (Figure 12). Figure 11 shows a single, 21.5 m thick coarsening upward cycle from shale to medium-grained sandstone. The basal portion of the Bluesky Formation is a conglomerate overlying an amalgamated flooding surface/sequence boundary (FS/SB), which is overlain by a single coarsening upward cycle. The basal 3.5 m thick shale represents deposition in an offshore setting. The sandstone portion of the Bluesky Formation is 14. 5 m thick and represents a lower to upper shoreface succession. The second wireline log (Figure 12) shows three coarsening upward cycles over a 27 m interval. The cored interval represents two stacked lower to middle shoreface cycles and a lower to upper shoreface succession. Although these two wells are only 11.6 km (7.2 miles) apart, they illustrate the marked differences in the preserved record of shoreface deposition within the Bluesky Formation.

Figure 10. Sedimentary structures observed in the Bluesky Formation include A) hummocky cross-stratification, B) swaly cross-stratification, C) quasi-planar lamination, D) swash stratification, E) trough cross-bedding, F) tabular cross-bedding, G) current ripples, H) combined flow ripples, I) oscillation ripples. Hummocky cross-stratification, swaly cross-stratification, and quasi-planar lamination are large bedforms, up to several metres across and decimetres thick. At the scale of observation in this study these three structures are indistinguishable.



modified after Friedman and Sanders, 1978; Leckie and Walker, 1982; McCubbin, 1982; and Arnott, 1993

Dome Total Knopcik
6-32-74-12w6

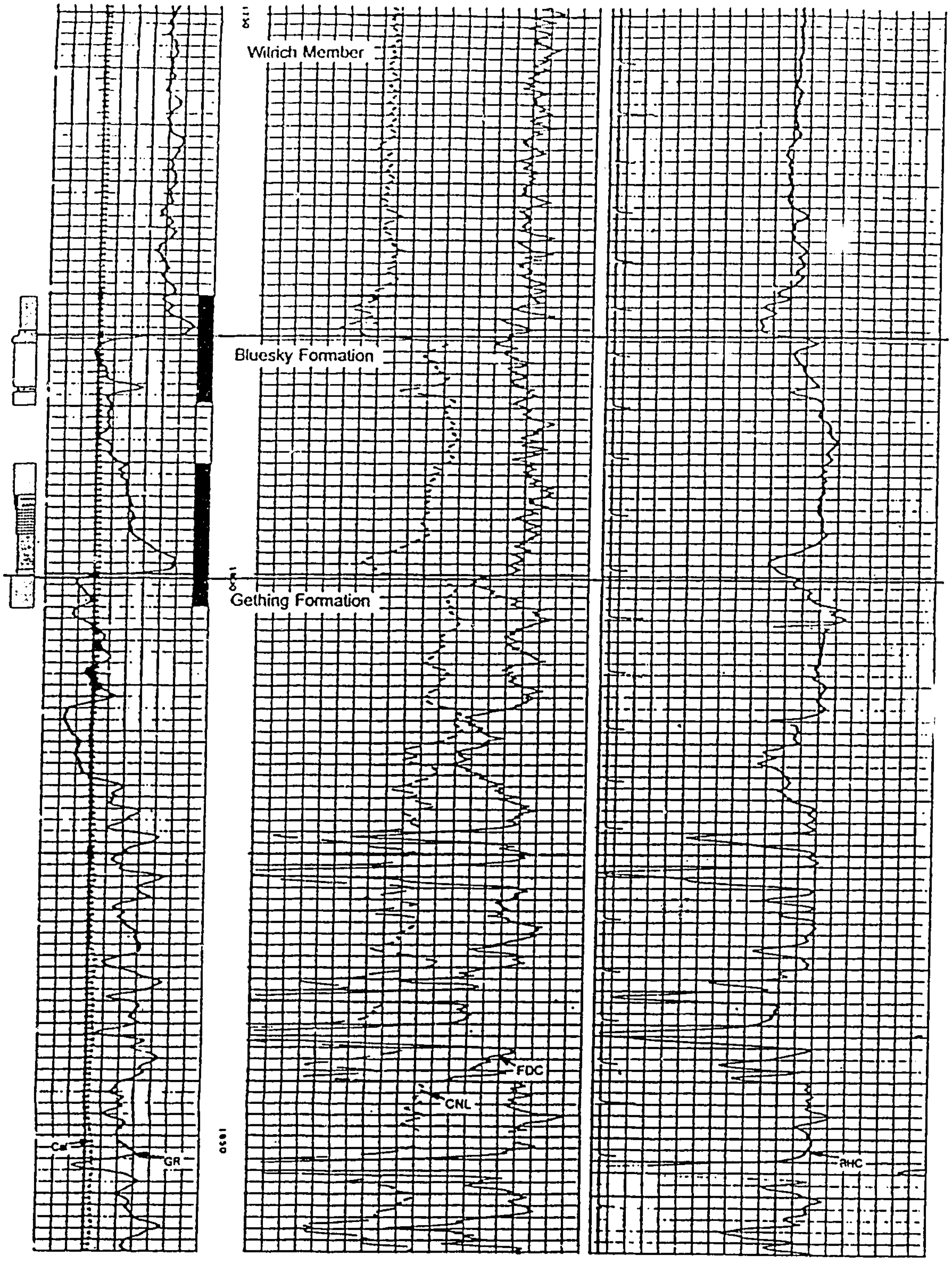


Figure 11. Wireline log (GR, CNL, FDC, BHC) and core (lithology) showing the Wilrich Member, the Bluesky Formation, and the Gething Formation. The Bluesky Formation shown here consists of one coarsening upward cycle from offshore to lower-middle shoreface, and transgressive deposits.

Dome Total Sinclair
11-18-74-13w6

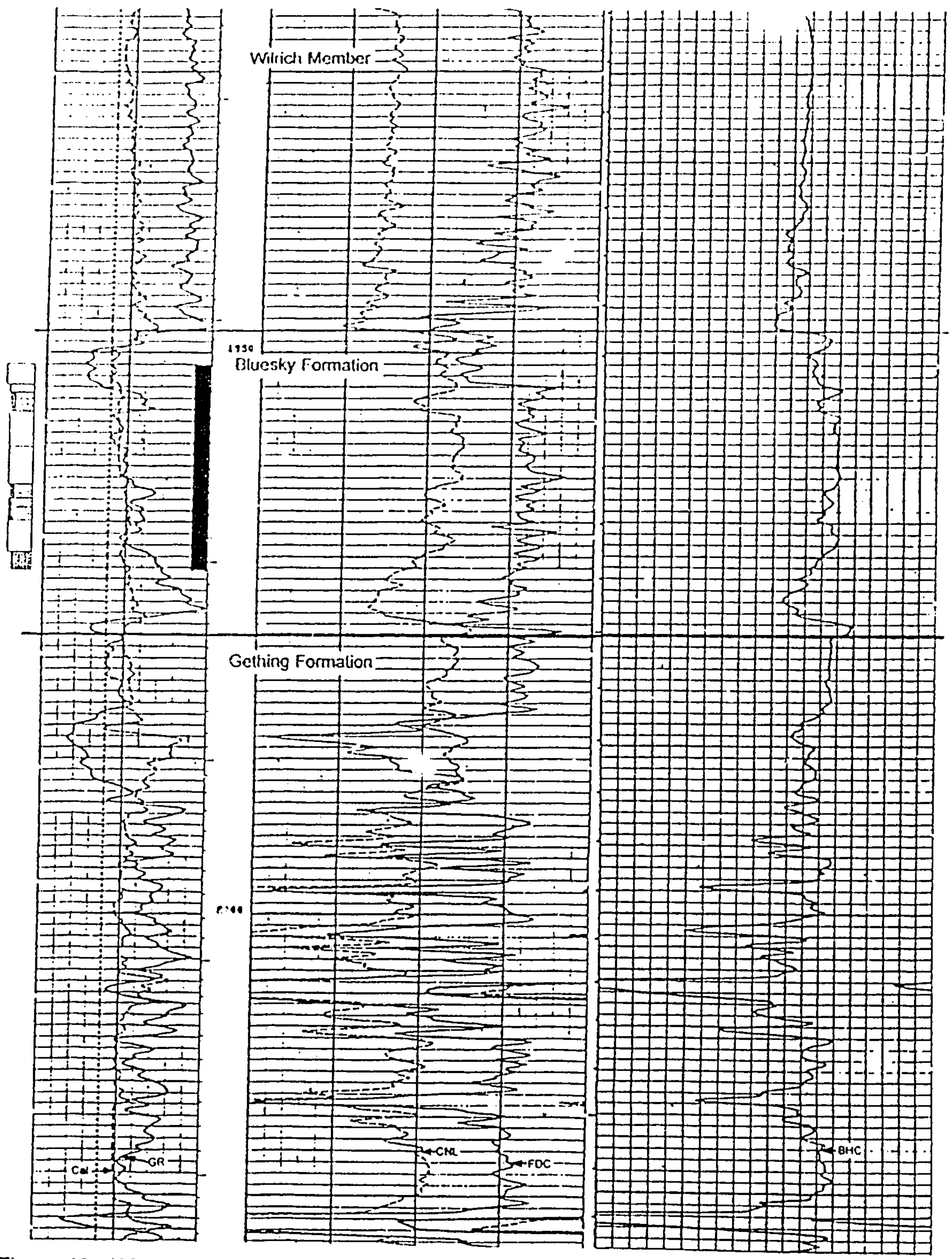


Figure 12. Wireline log (GR, CNL, FDC, BHC) and core (lithology) showing the Wilrich Member, the Bluesky Formation, and the Gething Formation. The Bluesky Formation shown here consists of three coarsening upward cycles fluctuating between offshore and upper shoreface.

3.5 Facies Descriptions

In this study, twenty four facies were observed (Table 1), and were divided into five facies associations based on recurring facies successions. The facies observed can be broadly split into shale-dominated, sandstone-dominated, interbedded sandstone and shale, coarse deposits, and coal. The shale facies (Table 1) consist of four discrete facies based on lithological accessories. The dark shale, bioturbated silty shale, and the bioturbated sandy shale typically lack physical sedimentary structures, are mottled by trace fossils, and contain variable amounts of dispersed silt and fine sand. The organic-rich shale facies is the fourth shale facies, and is thin and has root traces and dispersed silt.

The sandstone-dominated units of the Bluesky Formation can be separated into thirteen distinct facies. These are defined by a variety of lithologic accessories and biogenic and physical sedimentary structures (Table 1). The pebbly sandstone facies is sharp-based and occurs at the base and top of the Bluesky Formation. Muddy sandstones occur at the base of the main Bluesky sandbody, and are fine-grained and well bioturbated. The low angle parallel laminated sandstone facies are fine- to very fine-grained, and have variable amounts of bioturbation (Table 1). A cross-bedded sandstone facies was observed, and together with the laminated sandstone facies comprises the bulk of the main Bluesky sandbody. The bioturbated and low-angle planar laminated sandstone facies is also common. It is typically thin and overlies the trough cross-bedded sandstone facies. A glauconite-rich, erosively based, sandstone facies occurs and overlies sandstones of the Gething and Bluesky formations. Some sandstone facies are rare, but occur near the top of the Bluesky Formation (Table 1). These include the rippled sandstone facies, disrupted sandstone facies, salt and pepper sandstone facies, the coaly trough cross-bedded sandstone facies, the pebbly, coaly sandstone facies, and the structureless coaly sandstone facies.

Four interbedded sandstone and shale facies were distinguished by the degree of bioturbation (reworking), and physical sedimentary structures. In one location, at the base of the Bluesky Formation, a sandstone-dominated, interbedded sandstone and shale facies is present, and is dominated by low angle wavy parallel laminations. A bioturbated, interbedded sandstone and shale facies is common in the lower portion of the Bluesky Formation, and contains remnant low-angle wavy parallel laminations in the unburrowed sandstone portion of the facies. The sharp-based, interbedded sandstone and shale facies is made up of low-angle wavy parallel and ripple laminations, and lacks bioturbation. The pinstripe laminated shale and sandstone is shale-dominated and occurs near the top of the Bluesky Formation, and contains current ripple stratification and a reduced (stressed) trace fossil assemblage.

Table 1. Facies Observed in the Bluesky Formation, Sinclair Area

Facies	Sed Structures	Contacts	Ichnofacies/Assemblage	Depositional Process	Depositional Environment
Pebbly Sandstone		erosional		winnowed	transgressive lag
Bioturbated Shaly Sandstone	mottled	sharp, bioturbated	Skolithos-Cruziana	suspension & tempestite	offshore transition
Bioturbated Sandy Shale	mottled	gradational	diverse Cruziana	suspension	upper offshore
Bioturbated Silty Shale	mottled	gradational	distal Cruziana	suspension	offshore
Glauconitic Sandstone	mottled	bioturbated		suspension & tempestite	lower-middle shorface
Interbedded Sandstone and Shale	SCS	sharp	Cruziana	suspension & tempestite	backstepped shoreface
Dark Shale		gradational	not visible	suspension	lower offshore
Bioturbated, Interbedded Sandstone and Shale	SCS, ripple	gradational	Cruziana	suspension & tempestite	offshore-shoreface transition
Laminated to Bioturbated Sandstone	SCS	erosional	Cruziana-distal Skolithos	tempestite	storm influenced L-M shoreface
Laminated Sandstone	SCS	erosional		tempestite	storm dominated L-M shoreface
Sharp-based Interbedded Sandstone and Shale	SCS, ripple	sharp		suspension & tempestite	lower-middle shorface
Conglomerate		erosional		winnowed	shoreface lag
Trough Cross-bedded Sandstone	TXB	erosional, gradational		migrating megaripples	upper shoreface
Bioturbated and Low-angle Planar Laminated Sandstone	swash	gradational? sharp	Macaronichnus	swash	foreshore
Mudstone Rip-up Breccia		erosional		unidirectional flow	channel lag
Coaly Trough Cross-bedded Sandstone	current ripples	erosional		unidirectional flow	tidal channel
Pebbly, Coaly Sandstone		erosional		unidirectional flow	tidal channel
Organic-rich Shale			rhizoliths	suspension	marsh
Pinstripe Laminated Shale and Sandstone	current ripples		stressed assemblage	suspension	lagoon
Coal		sharp		suspension	marsh
Structureless Coaly Sandstone			rhizoliths	storm deposit	washover fan
Rippled Sandstone	ripples		Macaronichnus sp.	current	flood tidal delta
Disrupted Sandstone	dewatering	sharp, gradational		rapidly deposited	flood tidal delta
Salt and Pepper Sandstone	TXB	erosional		transgressive	upper shoreface

The coarse facies of the Bluesky Formation include a single occurrence of a mudstone rip-up breccia, and the rare conglomerate facies. The mudstone rip-up breccia consists of large rip-up clasts in a sandstone matrix, and erosively overlies the laminated sandstone facies. The conglomerate facies is made up of chert and other lithic pebbles in a sandstone matrix, and is erosively based and thin. The final facies is a coal, which occurs in one core near the top of the Bluesky Formation. It is sharp-based, thin, and overlies the bioturbated and low-angle planar laminated sandstone facies and is overlain by the disrupted sandstone facies.

The facies of the Bluesky Formation were observed to occur in a number of facies successions, or facies associations. Some facies occurred in several successions, and are components of more than one facies association. shows the five facies associations and the facies relationships observed. Facies Association 1 (FA1) is a fining upward succession made of six different facies. This association commonly occurs at the base and top of the Bluesky Formation, but also occurs within the Bluesky Formation. Facies Association 2 (FA2) is a coarsening upward succession that consists of six discrete facies, and typically overlies FA1. This facies association fines upward from the dark shale facies to the laminated to bioturbated sandstone facies. Facies Association 3 (FA3) also overlies FA1 and is made up of five distinct facies from silty shale facies to the laminated sandstone facies. The shale-dominated facies occur in FA1, FA2, and FA3 and were grouped into their respective facies associations based on the nature of the succession, *e.g.* a fining upward *vs.* coarsening upward succession, and the overlying sandstone of FA2 or FA3. Facies Association 4 is a coarsening upward facies association dominated by sandstone facies, and typically overlies FA3 or FA2. Facies Association 5 is uncommon and consists of ten facies. Facies Association 5 overlies FA2, FA3, and FA4 and is overlain by FA1.

3.5 Facies Associations of the Bluesky Formation

3.5.1 Fining Upward Succession

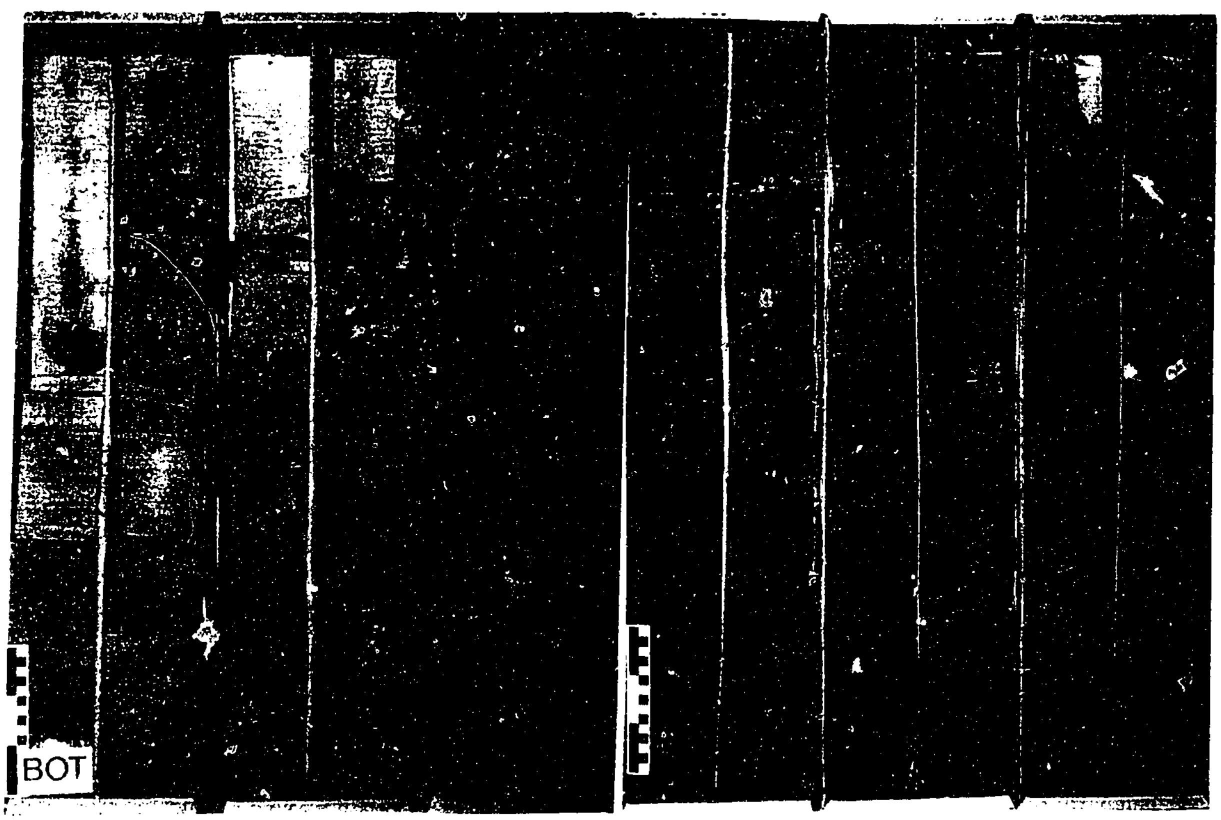
Facies Association One (FA1): Pebbly Sandstones, Bioturbated Sandstones, and Sandy Shales

Sedimentology and Ichnology

Facies Association 1 is a fining upward facies association located throughout the study area. It has been recovered dominantly in the northern portion of the study area, with only two cored locations in the south (Figure 13). It variably consists of six facies which form a fining upward succession, and are dominated by pebbly sandstone, bioturbated sandstone, bioturbated sandy shale, and bioturbated silty shale (Figure 14). Secondary facies include a glauconitic sandstone facies, and an interbedded sandstone and shale

Figure 14. Box photographs of the 6-32-74-12w6 core; bottom (BOT) is at lower left and top (TOP) is at upper right. This core displays a single fining upward cycle within the Bluesky Formation (compare with Figure 11). Lower contact at the red arrow is sharp with a pebbly sandstone of FA1 overlying sandstone of the Gething Formation. Facies Association 1 continues upward into the shale-dominated facies. Scale in photograph is 15 cm.


TOP


BOT

facies.

FA1 displays a characteristic succession that typically fines upward from pebbly sandstone into bioturbated sandstone, and into bioturbated sandy shale. The pebbly sandstone and the bioturbated sandstone facies are commonly present at the base of FA1. The bioturbated sandy shale facies is present throughout FA1, and sharply overlies sandstone deposits of the Bluesky Formation, and coal or sandstone deposits of the Gething Formation, and fines upward into deposits of FA2 and FA3. The bioturbated silty shale facies is rare in this facies association, but where present, occurs at the top of FA1, grading into the basal shale facies of FA2. The glauconitic sandstone facies is locally present in the northeastern part of the study area at the base of FA1, and ultimately grades upward into the bioturbated sandy shale facies. The interbedded sandstone and shale facies is a single occurrence, and is discussed later. Facies Association 1 is separated from underlying facies associations at the top of the Bluesky Formation by a stratigraphic disconformity. A similar stratigraphic disconformity separates the underlying Gething Formation from FA1 at the base of the Bluesky Formation. The single cored interval from the southeast portion of the study area displays the anomalous FA1 succession consisting entirely of the interbedded sandstone and shale facies.

The upper contact with FA2 and FA3 is gradational which makes it difficult to measure the thickness of this facies association. The facies association ranges from 5 to 150 cm thick. The facies association with the anomalous interbedded sandstone and shale facies is 4.35 metres thick. The wireline log response of FA1 in the 6-32-74-12w6 well is illustrated in Figure 12.

The pebbly sandstone facies occurs at the base of seven cored Bluesky-Gething contacts. It consists of pebbly sandstone with chert pebbles, lithic mudstone rip-up clasts, and rare shale beds and pyrite (Figure 15a). The grain size of the sandstone matrix ranging from vfU-vcU, but is typically very coarse. The chert pebbles and lithic mudstone rip-up clasts are well rounded, and range from 0.5 to 2.5 cm, averaging 1 cm in diameter. In some cores, the lower contact of the pebbly sandstone facies was destroyed for permeability tests, but where preserved, the contact with the Gething Formation is sharp and erosive. The thickness of the facies ranges from 5 to 55 cm. No physical sedimentary structures were observed from this facies. Rare trace fossils were observed in one core (10-8-74) represented by *Palaeophycus* in a mottled bed.

The bioturbated muddy sandstone facies overlies Gething Formation sandstones and the pebbly sandstone facies of FA1. The lower contact with the pebbly sandstone facies of FA1 is bioturbated (Figure 15a), whereas the contact with the Gething Formation

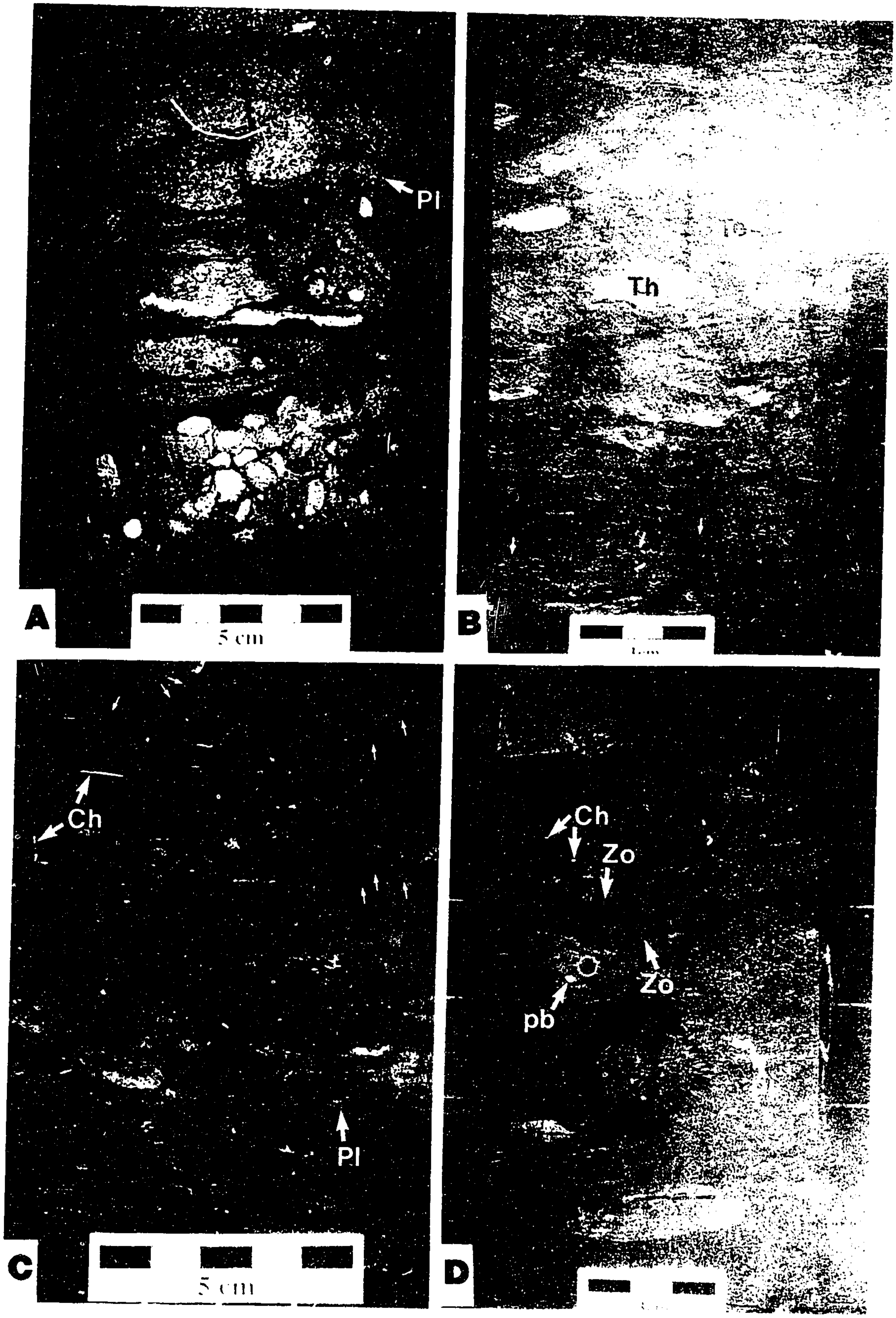
Figure 15. Facies photographs for FA1.

A) The pebbly sandstone facies and the bioturbated muddy sandstone facies in the 6-6-75-7w6 well (1581.2 m). The lower contact with the Gething Formation is sharp and erosive. The pebbly sandstone is thin and consists of rounded lithic pebbles in a sandstone matrix. The overlying bioturbated muddy sandstone facies contains *Planolites* (Pl) and *Teichichnus* (Te) as well as dispersed pebbles.

B) The sandy shale facies in the 2-23-74-13w6 well (1771.1 m) consists of biogenically dispersed sand and shale. Biogenic activity has reworked the mud and sand into a bioturbate texture. Present are *Anconichnus* (small white arrows), *Planolites* (Pl), *Palaeophycus* (Pa), and *Thalassinoides* (Th). Rare remnant laminations are preserved; sand laminae in upper centre of photo.

C) Well bioturbated sandy shale facies in the 7-3-75-13w6 well (1775.3 m) with mottled, bioturbate texture. Discrete trace fossils are *Anconichnus* (small white arrows), *Chondrites* (Ch), and *Planolites* (Pl).

D) Sandy shale facies with a rare pebble (pb) in the 3-9-74-12w6 well (1859.9 m). *Planolites* (Pl), *Chondrites* (Ch), and *Zoophycos* (Zo) are the discrete trace fossils present.


Pl
A
5 cm
Th
B
Ch
Pl
C
5 cm
Ch
Zo
Zo
pb
D

is sharp. This sandstone is moderately to thoroughly bioturbated and contains dispersed shale and rare pebbles, with local occurrences of glauconite, pyrite, and coaly detritus (Figure 15a). Sand size ranges from fL-fU, and pebble diameter ranges from 0.2 to 0.5 cm. Pebbles are predominantly chert, are subrounded to rounded, and are equant to spherical. Although rare, pebbles are dispersed throughout the facies and are most common near the base of the facies. Individual beds and physical sedimentary structures are not discernible in this facies, although some indistinct laminae are locally visible.

The bioturbated muddy sandstone facies is thin, and ranges from 15 to 95 cm in thickness, averaging 25 to 40 cm thick. Bioturbation is typically abundant to moderate in intensity, but locally may be absent. Individual trace fossils include *Planolites* (a-c), *Teichichnus* (m-r), robust *Diplocraterion* (m), *Palaeophycus* (r), *Macaronichnus* (r), and *Thalassinoides* (r). The trace fossils represent a softground ichnofossil assemblage. *Planolites* is the dominant trace fossil with subordinate numbers of *Teichichnus*, *Macaronichnus*, and *Thalassinoides*. These trace fossils exhibit a feeding and dwelling behaviour characteristic of the *Cruziana* ichnofacies. *Diplocraterion* and *Palaeophycus* are dwelling structures created as permanent to semi-permanent domiciles of suspension feeders and passive carnivores respectively, and are indicative of the *Skolithos* ichnofacies. The overall assemblage displays a low diversity and corresponds to a mixed *Skolithos-Cruziana* ichnofacies, or a proximal *Cruziana* suite.

A bioturbated sandy shale facies typically overlies the pebbly sandstone or bioturbated sandstone facies of FA1. This facies is extensive and occurs throughout the study area in ten cored wells. Some cores are thoroughly fractured, preventing a complete description of the facies. This facies consists of biogenically dispersed, fine-grained sandy shale with pyrite and rare dispersed chert pebbles (Figure 15b,c,d). Secondary accessories include local occurrences of glauconite, organic shale, and allochthonous coaly detritus. The bioturbated sandy shale facies ranges in thickness from 20 to 140 cm, but is generally between 20 to 40 cm thick. Pebbles are typically less than 0.5 cm long, except at the base of the facies, where it is in contact with the Gething Formation. Pebbles in such intervals range up to 3.0 cm in diameter, and are similar in size to those found in FA1 pebbly sandstones.

Primary physical sedimentary structures are absent due to the high intensity of biogenic reworking. The pervasive biogenic activity throughout this facies has resulted in a bioturbate texture. Discrete ichnogenera include *Anconichnus* (c-r), *Helminthopsis* (c-r), *Teichichnus* (c-m), *Chondrites* (c-r), *Rosselia* (c-r), *Diplocraterion* (m), *Planolites* (m), Cosmorhaphe (m-r), *Terebellina* (m-r), *Rhizocorallium* (m-r), *Zoophycos* (r), *Ophiomorpha* (r), *Asterosoma* (r), *Thalassinoides* (r), *Cylindrichnus* (r), *Skolithos* (r), and

Palaeophycus (r). This assemblage is dominated by grazing structures, with subordinate amounts of deposit-feeding structures. A large number of grazing structures may be generated by a small number of grazing organisms (Seilacher, 1978), but deposit-feeding structures have a closer correspondence to the numbers of trace-making organisms. Therefore, the deposit-feeding structures in this assemblage represent the majority of the trace-making organisms although grazing structures such as *Anconichnus* and *Helminthopsis* may be more abundant. The behaviours are characteristic of a diverse *Cruziana* ichnofacies, developed in a low energy environment with a soft, muddy substrate containing abundant nutrients. It is consistent with slow continuous sedimentation, although this may be punctuated by episodic, high energy (storm) events.

Locally, the bioturbated sandy shale facies directly overlies the Gething Formation or the basal sandstones of the Bluesky Formation. Basal contacts are sharp where the bioturbated sandy shale facies directly overlies the Gething Formation or the pebbly sandstone facies of FA1. The lower contacts locally may be sharp or gradational over the bioturbated sandstone facies of FA1. The bioturbated sandy shale facies typically grades upward into the shale facies of FA2 and FA3, and near the top of the Bluesky Formation, into the shales of the Wilrich Member.

The bioturbated silty shale facies is rare in FA1, and was observed in one cored well. It gradationally overlies the bioturbated sandy shale facies of FA1 and fines upward into the overlying dark shale facies of FA2. It consists of biogenically dispersed silty shale with pyrite. No physical sedimentary structures were present. Visible bioturbation in this facies appears moderate to rare with discrete trace fossils including *Planolites* (r) and *Chondrites* (r), although a lack of lithologic contrast and abundant biogenic reworking may mask a more complete trace fossil assemblage. The traces observed represent a diverse *Cruziana* ichnofacies.

The glauconitic sandstone facies in FA1 occurs in three wells. It sharply overlies sandstones FA3, FA4, and FA5 and is in turn overlain by the bioturbated muddy sandstone facies of FA1. The glauconitic sandstone facies typically consists of glauconitic, shaly, fU to mL grained sandstone, and ranges in thickness from 15 to 60 cm (Figure 16). Accessories include local dispersed pebbles, tabular, sideritized mudstone clasts and wood/coal detritus. This facies is thoroughly bioturbated, lacking primary physical sedimentary structures in two wells, and is moderately bioturbated in one well. Trace fossils present in this facies locally include *Skolithos* (a-r), *Planolites* (m-r), and *Palaeophycus* (m).

The lower contact with other sandstones is sharp and locally bioturbated, with firmground *Diplocraterion* and *Conichnus* deeply subtending into the underlying facies.

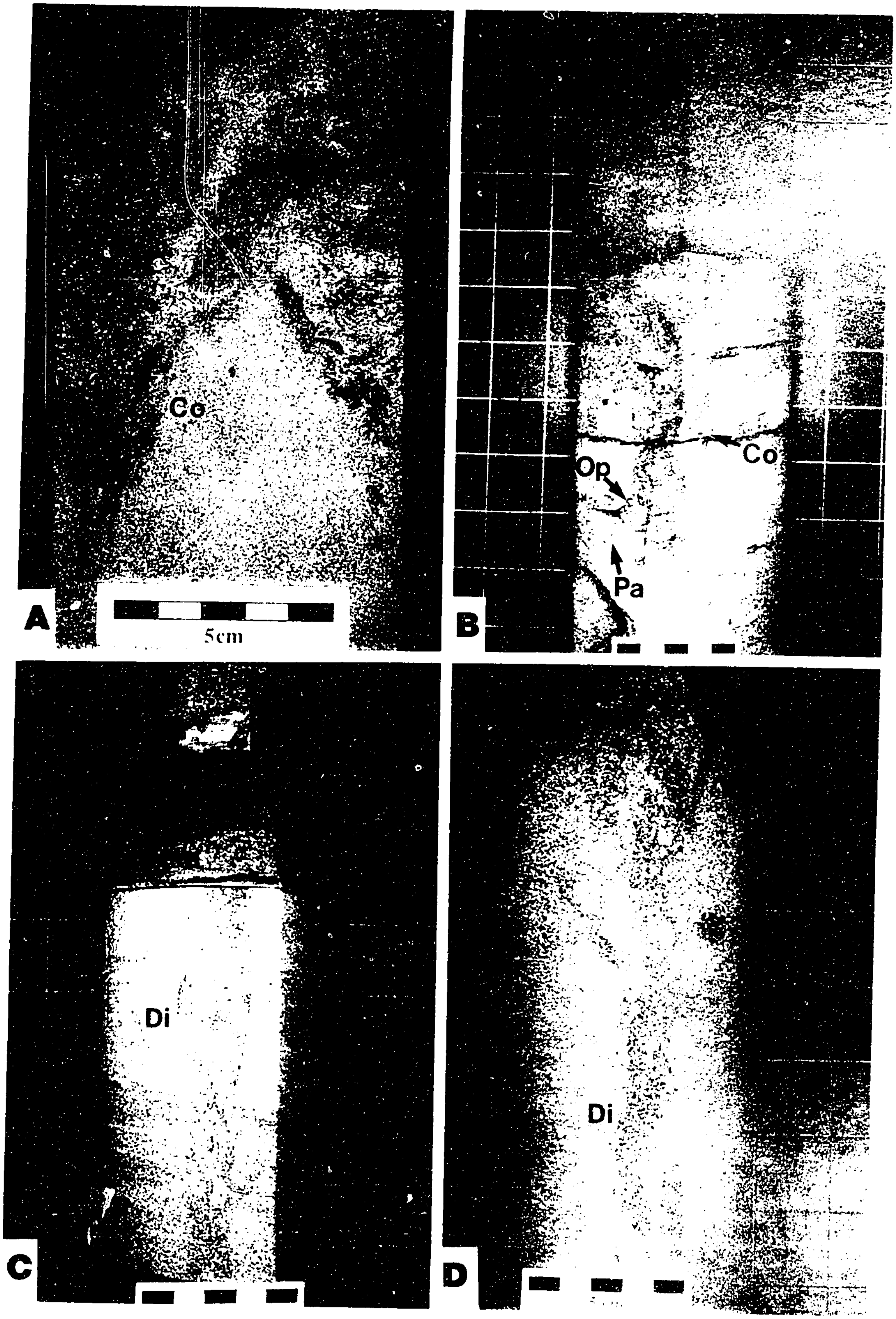
Figure 16. Facies photographs for the glauconitic sandstone facies in FA1.

A) Deeply penetrating *Conichnus* (Co) cuts across structures in the laminated sandstone facies of FA3 in the 6-32-74-12w6 well (1779.2 m). The fill of the *Conichnus* includes pebbles and contrasts sharply with the underlying 'clean' laminated sandstone.

B) *Conichnus* (Co) and *Ophiomorpha* (Op) cut across the resident trace fossil suite of *Paleophycos* (Pa) in the 2-23-75-13w6 well (1762.8 m). Although the *Ophiomorpha* is lined, the *Conichnus* is unlined and penetrates into the underlying 'clean' sandstone.

C) *Diplocraterion* (Di) subtends across a sharp contact and is filled with sand from the overlying glauconitic sandstone facies, 6-10-75-8w6 (1567.9 m).

D) *Diplocraterion* (Di) cuts across the laminated sandstone facies of FA3 in the 6-10-75-8w6 well (1558.8 m).


A
Co
5cm
B
Op
Pa
Co
C
Di
D
Di

These burrows have a glauconitic, pebbly sand fill, contrasting prominently with the underlying 'clean' sandstone and cross-cut the resident softground trace fossil suites and physical stratification of the underlying sandstones. This is genetically related to erosion of the substrate followed by colonization and may represent a *Glossifungites* surface or a palimpsest assemblage.

The interbedded sandstone and shale facies is an anomalous unit in FA1 and sharply overlies the pebbly sandstone facies of FA1 in one well. This well records the only cored FA1 interval in the southeast. It is very coarse-grained at the base of the unit, fines upward to very fine-grained, and is interbedded with shale over a thickness of 4.3 m. Rounded chert pebbles up to 1 cm diameter occur at the base of this facies. Other accessories include wood/coal detritus, pyrite, glauconite, and mudstone rip-up clasts. Low-angle, parallel laminated sandstone beds with internal truncation surfaces are interpreted as swaley cross-stratification. Amalgamated beds of SCS range from 5 to 20 cm thick, but are generally 10 to 15 cm. Interbedded shale intervals are 5-30 cm thick and contain biogenically dispersed fine-grained sand. Thin, 1-2 cm thick, sharp-based, fine-grained sandstone beds occur within thicker shale beds near the top, and fine upward to siltstone.

Bioturbation in the SCS beds is uncommon, and is almost exclusively restricted to shaly intervals, where it ranges from common to rare in intensity. Thick SCS amalgamated sandstone beds contain only rare numbers of fugichnia. Trace fossils in the thin shaly intervals include; *Helminthopsis* (c), *Planolites* (c-m), *Thalassinoides* (m), *Diplocraterion* (m), and *Chondrites* (m-r). A thin, 10 cm thick, shale dominated section is interpreted to represent fairweather deposition and contains: *Teichichnus* (c), *Planolites* (m), *Chondrites* (m), *Palaeophycus* (r), and *Skolithos/Ophiomorpha* (r). Most of the trace fossils exhibit deposit-feeding and grazing strategies (*e.g. Teichichnus, Helminthopsis, Planolites, Thalassinoides*, and *Palaeophycus*), with highly subordinate suspension-feeding/dwelling behaviours indicated (e.g. *Skolithos/Ophiomorpha, Diplocraterion*). These assemblages represent the softground *Cruziana* ichnofacies.

Environmental Implications of FA1

The vertical succession of facies observed in FA1 is; locally a basal pebbly sandstone facies overlain by a bioturbated sandstone facies, which is overlain by bioturbated sandy shale facies. The basal pebbly sandstone and bioturbated sandstone facies sharply overlie the Gething Formation or Bluesky Formation sandtones, and are interpreted to be erosional. Locally, the glauconitic sandstone facies is present at the base of FA1, and is gradational with the bioturbated sandy shale facies.

The pebbly sandstone facies is interpreted to represent an erosional lag deposit.

Granules and pebbles at the base of the sandstone and the bioturbated sandy shale facies may also reflect minor lag accumulation. The chert pebbles and rip-up clasts are locally derived from coarse-grained Gething and Bluesky deposits. The pebbly sandstone facies is interpreted to be a transgressive lag overlying an erosional surface [TSE] created by wave scour across underlying sediments of the Gething and Bluesky formations as sea level rose. This erosive event would likely have created a gently undulating erosional surface (ravinement surface). These surfaces are alternately called transgressive surfaces of erosion (TSE) or high energy flooding surfaces (HEFS). Ravinement surfaces are typified by low relief and limited areal extent, and pass basinward into low energy, non-erosive flooding surfaces (LEFS).

The glauconitic sandstone facies overlies a ravinement surface created by wave scour across underlying sediments of the Gething and Bluesky formations during sea level rise and shoreface retreat. This erosionally exhumed surface locally provided a firmground substrate which was colonized by trace makers of the *Glossifungites* ichnofacies. The *Glossifungites* ichnofacies demarcates a surface which indicates three stages including initial erosion of the surface, colonization, and subsequent deposition of the overlying sediments (Figure 17). The *Glossifungites* trace makers were suspension-feeding organisms, and generated the unlined dominichnia which subtend across the contact. The trace fossils are not related to the initial high energy event, but indicate subsequent reduced energy levels which allowed the substrate to be colonized prior to deposition of the glauconitic sandstone. During colonization of the substrate the environmental conditions would be relatively low energy accompanied by little or no deposition. A second high-energy event is interpreted from the deposition of the pebbly, glauconitic sandstone that fills the trace fossils of the *Glossifungites* ichnofacies. These *Glossifungites* surfaces represent an erosional discontinuity, but further biostratigraphic work is required to determine the extent of the time break.

The bioturbated muddy sandstone facies, bioturbated sandy shale facies, and bioturbated silty shale facies form a continuous spectrum of deposits that fine upward as energy in the depositional environment decreased. These facies are interpreted to be a transgressive succession. The lithology of these facies is indicative of a quiet, low energy environment dominated by deposition of very fine-grained material from suspension. Accessory materials include glauconite which is indicative of low detrital sedimentary rates and is normally deposited in waters deeper than 10 m (Johnson and Baldwin, 1989). Other secondary components are wood/coal/organic detritus, which are hydraulically light components and may be transported far into low energy environments before settling out. Pyrite in this facies is secondary after silty trace fossils or bioturbated mud streaks. The

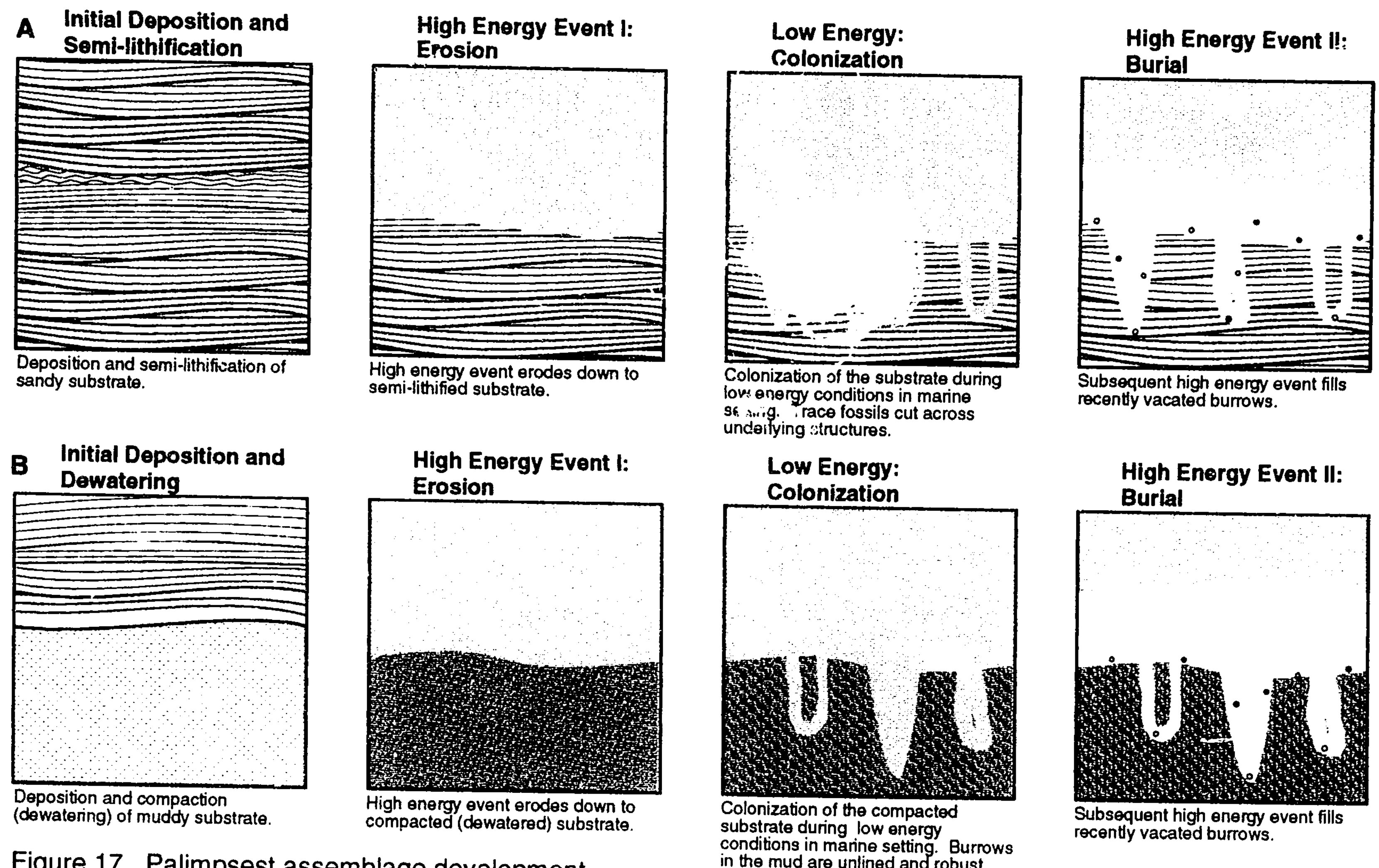


Figure 17. Palimpsest assemblage development.

sand laminae and pebble stringers are indicative of ephemeral, high energy events. These physical structures are interpreted as the distal portions of tempestites; sandstone laminae fine upward into shale indicating the waning of the high energy event before returning to the quiet conditions. Pebble stringers were likely winnowed out from previous, coarser deposits.

The discrete trace fossil suite present is a distal *Cruziana* assemblage. This assemblage is dominated by grazing structures, with subordinant deposit-feeding structures. These behaviours are characteristic of the *Cruziana* ichnofacies which is developed in low energy environments consisting of soupy, muddy substrates containing abundant nutrients. The high intensity of burrowing is consistent with slow continuous sedimentation. Discrete ichnofossils are not readily visible due to a lack of lithologic contrast, and result in a thoroughly bioturbated texture. The high intensity of burrowing and the high diversity of the ichnogenera within the *Cruziana* ichnofacies are characteristic of the offshore to offshore-shoreface transition (MacEachern and Pemberton, 1992). The bioturbated muddy sandstone and bioturbated sandy shale facies are interpreted to have been deposited in a proximal lower shoreface setting. The burrowed, sandy to silty shales of FA1 were deposited in an upper offshore to offshore setting. The overall fining upward succession corresponds to rising sea level and the concomitant decrease in energy.

The interbedded sandstone and shale facies consists of SCS sandstones interbedded with fairweather shales. Bioturbation in the SCS beds is uncommon, and is almost exclusively restricted to shaly intervals, where it ranges from common to rare in intensity. Trace fossils dominantly exhibit deposit-feeding and grazing strategies, with highly subordinate suspension-feeding/dwelling behaviours. These assemblages represent the softground *Cruziana* ichnofacies. The anomalous interbedded sandstone and shale facies in the southeast is interpreted to be a storm-dominated, transgressively reworked, deposit. These deposits were likely deposited in a lower shoreface setting as sea level rose.

FA1 Summary

The typical succession, locally a basal pebbly sandstone facies overlain by a bioturbated sandstone facies, which is overlain by bioturbated sandy shale facies, is representative of deposition during a transgressive event. The lithology, sedimentary structures, and ichnofossils present in a typical FA1 succession are consistent with deposition in a tempestite influenced offshore setting. This setting is dominated by shale deposition, with distal tempestites deposited during infrequent storm events. The glauconitic sandstone facies may be associated with a *Glossifungites* demarcated surface that would indicate a stratigraphic discontinuity developed in a marine setting.

3.5.2 Coarsening Upward Successions

Facies Association Two (FA2): Burrowed Silty Shale, Interbedded Sandstone and Shale, and Laminated to Burrowed Sandstone

Sedimentology and Ichnology

Six facies comprise Facies Association 2, and are from bottom to top; dark shale, bioturbated silty shale, bioturbated sandy shale, bioturbated interbedded sandstone and shale, bioturbated muddy sandstone, and laminated to bioturbated sandstone. The bioturbated silty and sandy shales are common throughout the facies association. The dark shale facies, and the bioturbated muddy sandstone facies are uncommon, and the bioturbated interbedded sandstone and shale facies occurs in only one location. The shale facies form a gradational, coarsening upward spectrum from shale to sandy shale that is difficult to accurately subdivide. Typically, FA2 gradationally overlies FA1, but may locally overlie sediments of FA3, and FA4 across a sharp contact. The succession is dominated by biogenic reworking near the base, and shows a progressive decrease in burrow intensity as it coarsens upward and increases in sand content (Figure 18). Facies Association 2 deposits are relatively thick compared to other facies associations, and combined with FA3, make up the bulk of the Bluesky Formation. Deposits of FA2 were recovered from 14 wells; 12 in the northwestern portion, and 2 in the southwestern portion of the study area (Figure 19). Facies Association 2 deposits may be up to 11.1 m thick, but typically range from 5 to 7 m. The wireline log response of FA2 in the 6-32-74-12w6 well is illustrated in Figure 11.

The dark shale facies occurs at the base of the FA2 succession in three wells. This facies gradationally overlies the bioturbated silty shale facies of FA1 and consists of dark grey to black shale with secondary pyrite and rare silt (Figure 20a). The dark colour and fracturing make description of the facies difficult in some wells. This facies ranges from 0.7 to 1.65 m thick, and is typically difficult to measure due to the gradational contact with overlying and underlying facies. There is a conspicuous lack of burrowing throughout the facies: the only trace fossils observed were rare *Chondrites*. This apparently unburrowed facies may have been completely burrowed, but has no visible trace fossils. This may be due to a lack of lithological contrast rendering trace fossils invisible. Also, trace fossils may have been developed in a soupground (*vs.* softground) and were not preserved (*cf.* MacEachern *et al.*, 1992).

The bioturbated silty shale facies of FA2 is present in eight wells in the northwest portion of the study area. Bioturbated silty shale with subordinate amounts of dispersed glauconite, pyrite, sand laminae, coaly detritus, and rare pebbles comprises this facies (Figure 20b,c). Biogenic activity has dispersed most of the components of this facies.

Figure 18. Box photographs of the 2-23-75-13w6 core; bottom (BOT) is at lower left and top (TOP) is at upper right. This core displays FA2 deposits erosively overlain by the mudstone rip-up breccia of FA5. Scale in photograph is 15 cm.

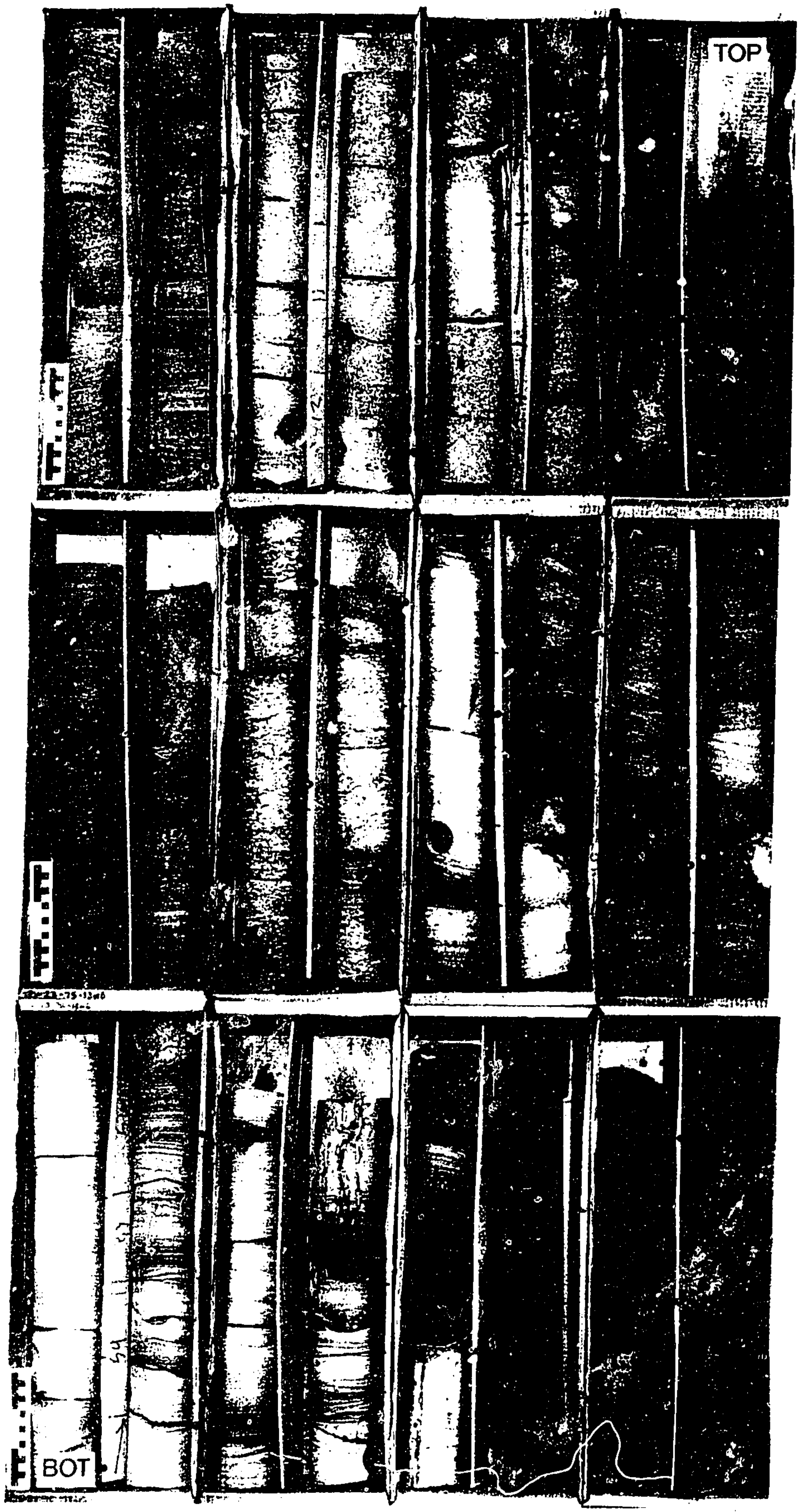

TOP
BOT

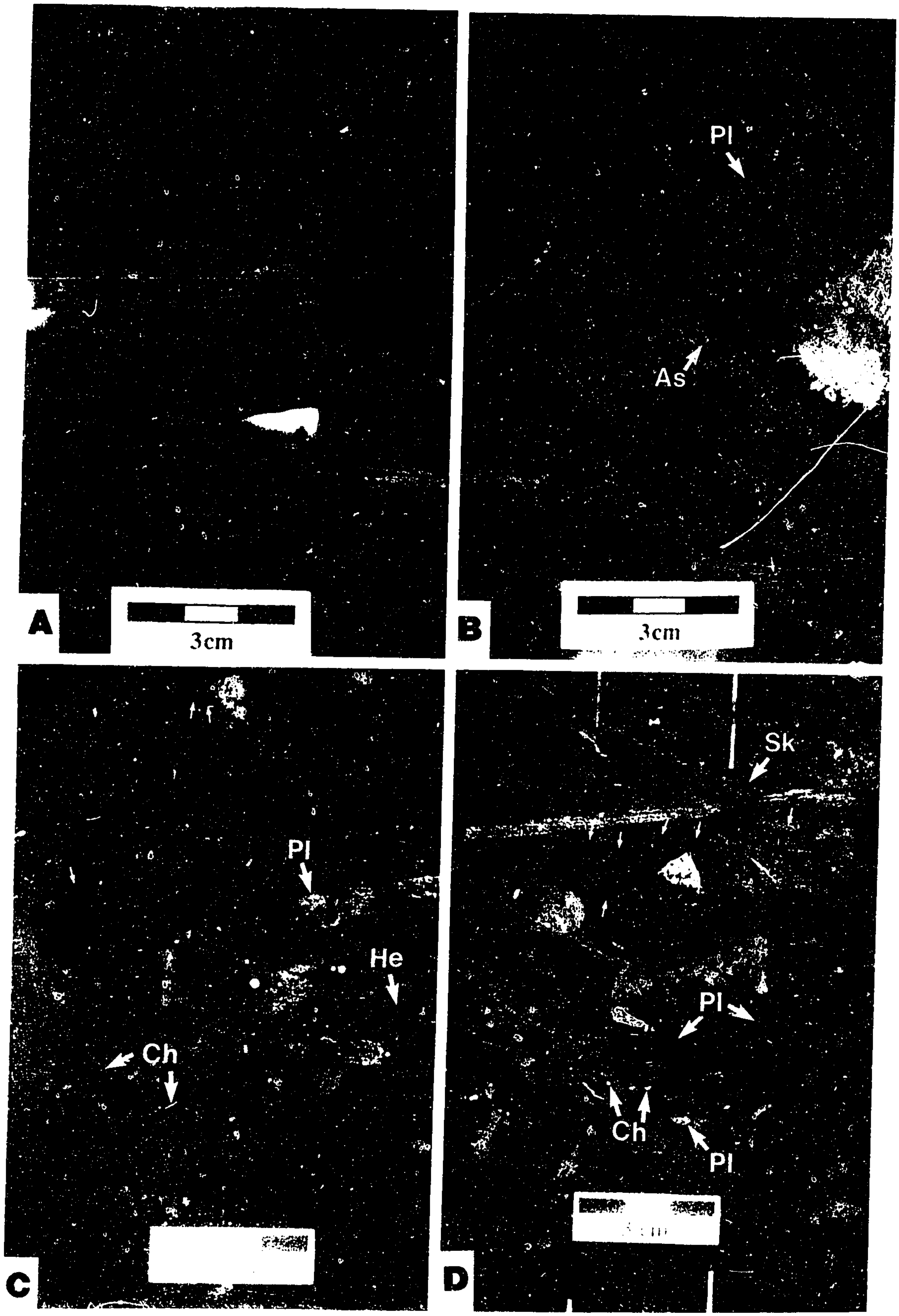
Figure 20. Facies photographs for FA2.

A) The dark shale facies appears to lack trace fossils, and is interpreted to have been deposited in a distal offshore setting. The deficiency of discrete trace fossils is due to insufficient lithological contrast and intense biogenic reworking. This photograph is from the 6-32-74-12w6 well (1798.5 m).

B) *Asterosoma* (As), *Planolites* (Pl), and *Anconichnus* (small white arrows) are deposit-feeding structures generated in a bioturbated sandy shale 6-32-74-12w6 (~1797 m). This facies represents deposition in a proximal offshore setting.

C) The sandy shale facies in the 6-5-74-13w6 well (~1984.4 m) is well bioturbated and has a discrete trace fossil assemblage of *Planolites* (Pl), *Helminthopsis* (He), *Anconichnus* (small white arrows), and *Chondrites* (Ch).

D) The sandy shale facies in the 6-5-74-13w6 well (1984.8 m) is well bioturbated, but has remnant, unburrowed sand laminae. The discrete trace fossil assemblage consists of *Planolites* (Pl), *Anconichnus* (small white arrows), *Chondrites* (Ch), *Skolithos* (Sk), and *Thalassinoides* (Th).


A
3cm
B
Pl
As
3cm
C
Pl
He
Ch
D
Sk
Pl
Ch
Pl

Thin, unburrowed sandstone beds are infrequent, and on the order of 1 cm thick. Rare remnant physical sedimentary structures include oscillation ripples and climbing ripples in sharp-based very-fine grained sandstone and siltstone laminae. This facies ranges from 1.2 to 3.85 m thick.

Bioturbation is moderate to abundant throughout this facies, and trace fossils include *Anconichnus* (c-r), *Helminthopsis* (c-r), *Chondrites* (c-r), *Planolites* (m-r), *Terebellina* (m-r), *Teichichnus* (m-r), *Palaeophycus* (r), *Zoophycos* (r), *Asterosoma* (r), *Rosselia* (r), *Thalassinoides* (r), and *Skolithos* (r). The dominant trace fossil assemblage includes *Anconichnus*, *Helminthopsis*, *Chondrites*, *Planolites*, *Terebellina*, and *Teichichnus*. This assemblage is dominated by the surficial grazing and shallow deposit-feeding behaviours characteristic of a distal *Cruziana* assemblage developed in a softground. A secondary assemblage comprising *Skolithos* and *Thalassinoides* represents the dominichnia of suspension-feeding organisms, probably due to the colonization of the sandstone laminae by opportunistic organisms.

The bioturbated sandy shale facies occurs in three wells in the northwestern portion of the study area. This facies overlies, and is gradational with, the bioturbated silty shale facies of FA2. It ranges in thickness from 0.9 to >3.9 m. The bioturbated sandy shale facies consists of dispersed very fine to fine grained sand and shale (Figure 20d). Accessories include rare pyrite, glauconite, and allochthonous coaly detritus. Discrete, sharp-based siltstone and sandstone beds are locally present, fine upward into the shale, and are undisturbed by biogenic processes. Thick sandstone and siltstone beds show remnant horizontal and ripple lamination. They range in thickness from 1 to 5 cm, but are typically 1 to 2 cm thick.

The bulk of the facies is normally moderately to completely reworked by biogenic activity, resulting in the thorough dispersion of sand and silt throughout the shale, producing a bioturbate texture. Discrete trace fossils include *Anconichnus* (m-c), *Helminthopsis* (c-m), *Chondrites* (m-r), *Rosselia* (c-r), *Planolites* (m-r), *Palaeophycus* (c), *Terebellina* (r), *Diplocraterion* (m), *Asterosoma* (r), *Rhizocorallium* (r), *Thalassinoides* (r), *Skolithos* (r), *Ophiomorpha* (?). The principal assemblage consists of *Anconichnus*, *Helminthopsis*, *Chondrites*, and *Planolites* in the sandy shale portion of the facies. *Diplocraterion*, *Rosselia*, and *Skolithos* are typically associated with the sandstone laminae. The principal assemblage represents surficial grazing and shallow deposit-feeding behaviours. This facies is dominated by pascichnia and subordinate fodinichnia, and characterizes a diverse *Cruziana* assemblage. The secondary assemblage is dominated by dominichnia of suspension-feeding organisms, probably due to the colonization of the sandstone laminae by opportunistic organisms.

The bioturbated, interbedded sandstone and shale facies occurs in a single well, and is made up of two distinctly bedded units. The lower unit is thickly bedded and sandstone dominated, whereas the upper unit is shale dominated with thin sandstone beds. This facies is interstratified with laminated to bioturbated sandstone facies. The lower contact is gradational with the sandstone facies, and the upper contact is sharp. This facies is 3.7 m thick, and is made up of interbedded vfU to vfL sandstone and shale beds with rare pyrite and coaly detritus. Sandstone beds are sharp based and range from 1-5 cm thick and include coaly detritus. They are typically low angle parallel laminated near the base of the facies, progressively accompanied by oscillation and climbing ripple laminations towards the top. Shale beds range from 0.5 to 15.0 cm thick, but are typically 1 cm. They contain biogenically dispersed sand, are moderately to thoroughly burrowed with pyrite replacing the *Chondrites* fill. Shale beds may sharply to gradationally overlie the sandstone beds.

Bioturbation in the shale-dominated portion of the facies is of moderate to common intensity, and may diffuse the lower contacts with sandstone beds. Trace fossils associated with shale beds are; *Anconichnus* (c-m), *Chondrites* (c-m), *Planolites* (m-r), *Helminthopsis* (r), *Palaeophycus* (r), and *Macaronichnus* sp. (r). *Macaronichnus* sp. is a deposit-feeding structure distinct from other species of *Macaronichnus*. The primary shaly assemblage comprises *Anconichnus*, *Chondrites*, and *Planolites*. The trace fossils are fodinichnia and are characteristic of feeding and dwelling behaviour. This assemblage is characteristic of the *Cruziana* ichnofacies. Sandstone beds are typically devoid of trace fossils, but locally display moderate degrees of bioturbation characterized by *Macaronichnus* sp. (c), *Rosselia* (m-r), *Planolites* (m-r), *Teichichnus* (m), and *Asterosoma* (?). Highly bioturbated beds are dominated by *Macaronichnus* sp., *Rosselia*, and *Planolites*. The primary sandstone assemblage comprises deposit-feeding structures characteristic of the *Cruziana* ichnofacies.

The bioturbated muddy sandstone facies of FA2 occurs in two wells. Biogenically mottled vfL to vfU sandstone and shale comprises this facies (Figure 21a,b). The bioturbated muddy sandstone facies locally contains accessory pyrite, glauconite, and coaly detritus. In one well the lower contact with the underlying bioturbated sandy shale facies of FA2 is sharp. The bioturbated muddy sandstone facies is 1.0 m thick, and is sharply overlain by the laminated to bioturbated facies of FA2. In the second well, the lower contact with an underlying laminated to bioturbated facies of FA2 is also sharp. The bioturbated muddy sandstone facies is 2.1 m thick, and grades upward into the laminated to bioturbated facies of FA2. The bioturbated muddy sandstone facies is thoroughly bioturbated, with few remnant primary physical sedimentary structures. Discrete trace fossils include *Anconichnus* (a-c), *Planolites* (c-m), *Terebellina* (m-r), *Rosselia* (m-r), *Asterosoma* (m-r), *Chondrites* (m-r), *Thalassinoides* (r), and *Diplocraterion* (r). The trace

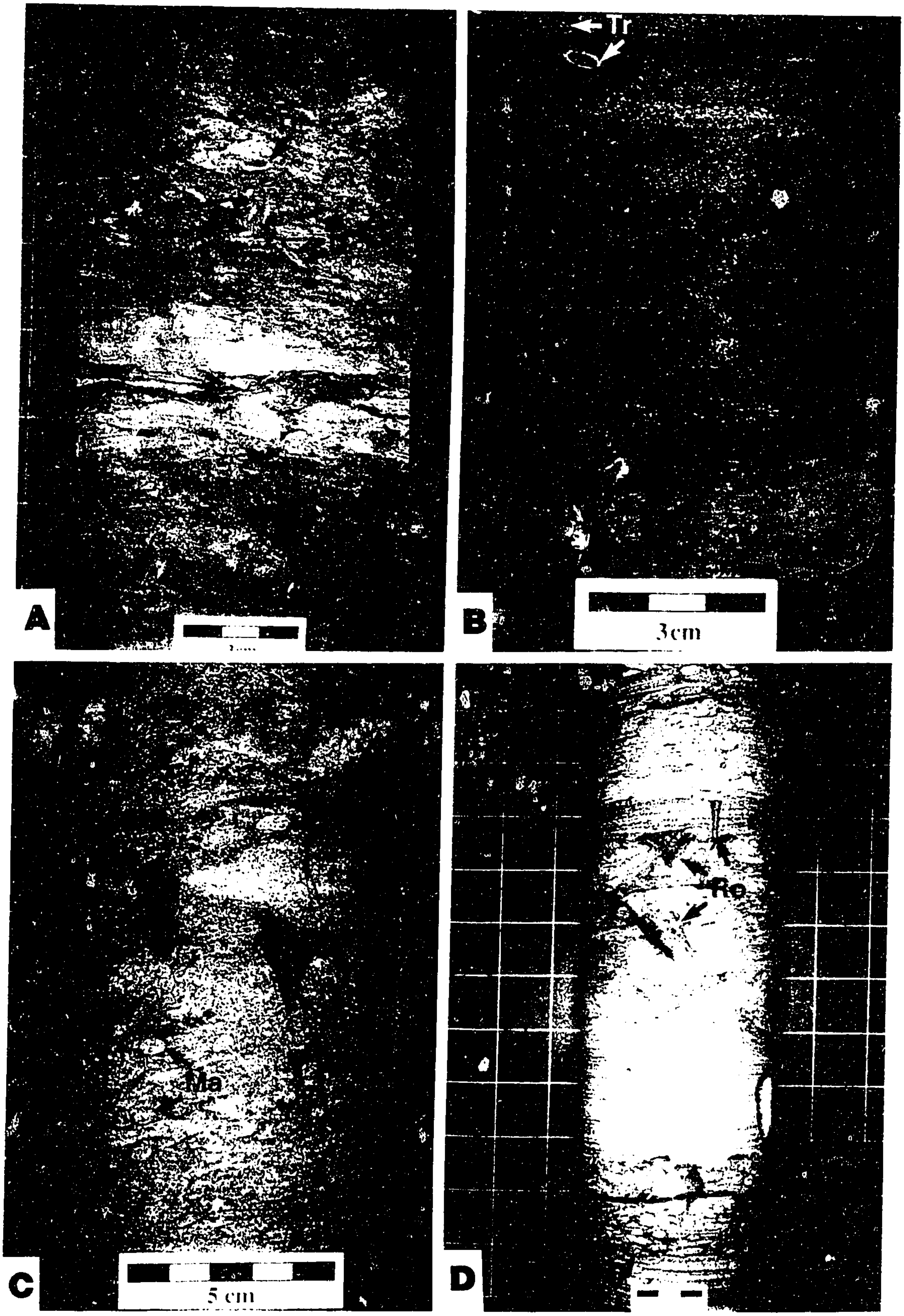
Figure 21. Facies photographs for FA2.

A) The muddy sandstone facies well bioturbated, but contains remnant sandstone laminae. Discrete trace fossils include *Terebellina* (Tr), *Rosselia* (Ro), *Palaeophycos* (Pa), and *Helminthopsis* (He) from 2-23-75-13w6 well (1770.7 m).

B) The bioturbated muddy sandstone facies with trace fossils from the mixed *Skolithos-Cruziana* assemblage in the 11-18-74-13w6 well (1958.7 m). Discrete trace fossils include *Rosselia* (Ro), *Palaeophycos* (Pa), *Asterosoma* (As), and *Terebellina* (Tr).

C) Thick burrowed portion of the laminated to bioturbated sandstone facies in the 2-23-75-13w6 well (1768.8 m). Trace fossils consist of *Macaronichnus* sp. (Ma) and *Rosselia* (Ro) are representative of the *Macaronichnus* sp. assemblage.

D) The laminated to bioturbated sandstone facies with abundant *Macaronichnus* (Ma) at the tops of bedsets, photograph from the 2-23-75-13w6 well (1769.5 m).


A
Tr
B
3cm
C
Ma
5 cm
D
Ro

fossil assemblage comprises *Anconichnus*, *Planolites*, *Chondrites*, *Terebellina*, *Rosselia*, and *Asterosoma*. This assemblage is dominated by pascichnia and fodinichnia and represents a *Cruziana* to distal *Skolithos* ichnofacies.

The laminated to bioturbated sandstone facies caps FA2, and occurs in nine of the cored wells. The laminated to bioturbated sandstone facies consists of cycles of sharp-based, laminated, vfU-mL sandstone grading upward to burrowed sandstone (Figure 21 c,d, Figure 22). Accessories include pyrite, shale laminae, dispersed pebbles, mudstone rip-up clasts, glauconite, and allochthonous coal detritus. This facies ranges from 1.0 to 11.1 m in thickness, and typically sharply overlies the various bioturbated shale facies of FA2, or FA3 and FA4 sandstones.

Burrowed layers of this facies range from 5 to 280 cm thick, and are generally from 10 to 40 cm thick. Burrowing intensity ranges from rare to abundant, but is typically moderate to abundant. Trace fossils observed include *Macaronichnus* sp. (a-r), *Rosselia* (a-r), *Chondrites* (a-r), *Anconichnus* (a-m), *Planolites* (c-r), *Teichichnus* (c-r), *Diplocraterion* (c-r), *Helminthopsis* (c-r), *Palaeophycus* (m-r), *Terebellina* (m-r), *Asterosoma* (m-r), *Skolithos* (m-r), *Conichnus* (r), fugichnia (r), *Thalassinoides* (r), *Ophiomorpha* (r). Two distinct trace fossil assemblages are represented in this facies. The dominant trace fossil assemblage, the "*Macaronichnus* sp. assemblage" (Figure 21 c,d, Figure 22 a,b,c), comprises *Macaronichnus* sp. (a-m) and *Rosselia* (c-m), with subordinate numbers of *Teichichnus*, *Conichnus*, and fugichnia. This assemblage is dominated by fodinichnia, and represent feeding and dwelling behaviours. The *Macaronichnus* sp. assemblage has a low diversity which was likely due to an environmental stress. A secondary trace fossil assemblage including *Anconichnus* (a-m), *Planolites* (a-m), *Chondrites* (a-m), *Terebellina* (m-r), and *Rosselia* (m-r) is made up of pascichnia and fodinichnia and forms a *Cruziana* to distal *Skolithos* ichnofacies.

Amalgamated sandstone beds range from 5 to 30 cm thick, but are generally from 10 to 15 cm thick. These beds are parallel laminated at a shallow angle, typically <15° (Figure 21d, Figure 22 c,d). Individual laminae sets are typically on the order of 3 to 5 cm thick, and are erosionally based. At the scale of observation (< 9 cm diameter) these physical sedimentary structures are interpreted to be SCS or HCS, and may be broadly classified as low angle cross-stratification. Burrowing within the amalgamated sandstone beds is limited to rare fugichnia.

Environmental Implications of FA2

FA2 represents a vertical succession of facies passing from a dark shale facies through burrowed shale facies, locally overlain by a bioturbated muddy sandstone or a bioturbated, interbedded sandstone and shale facies, and capped by laminated to

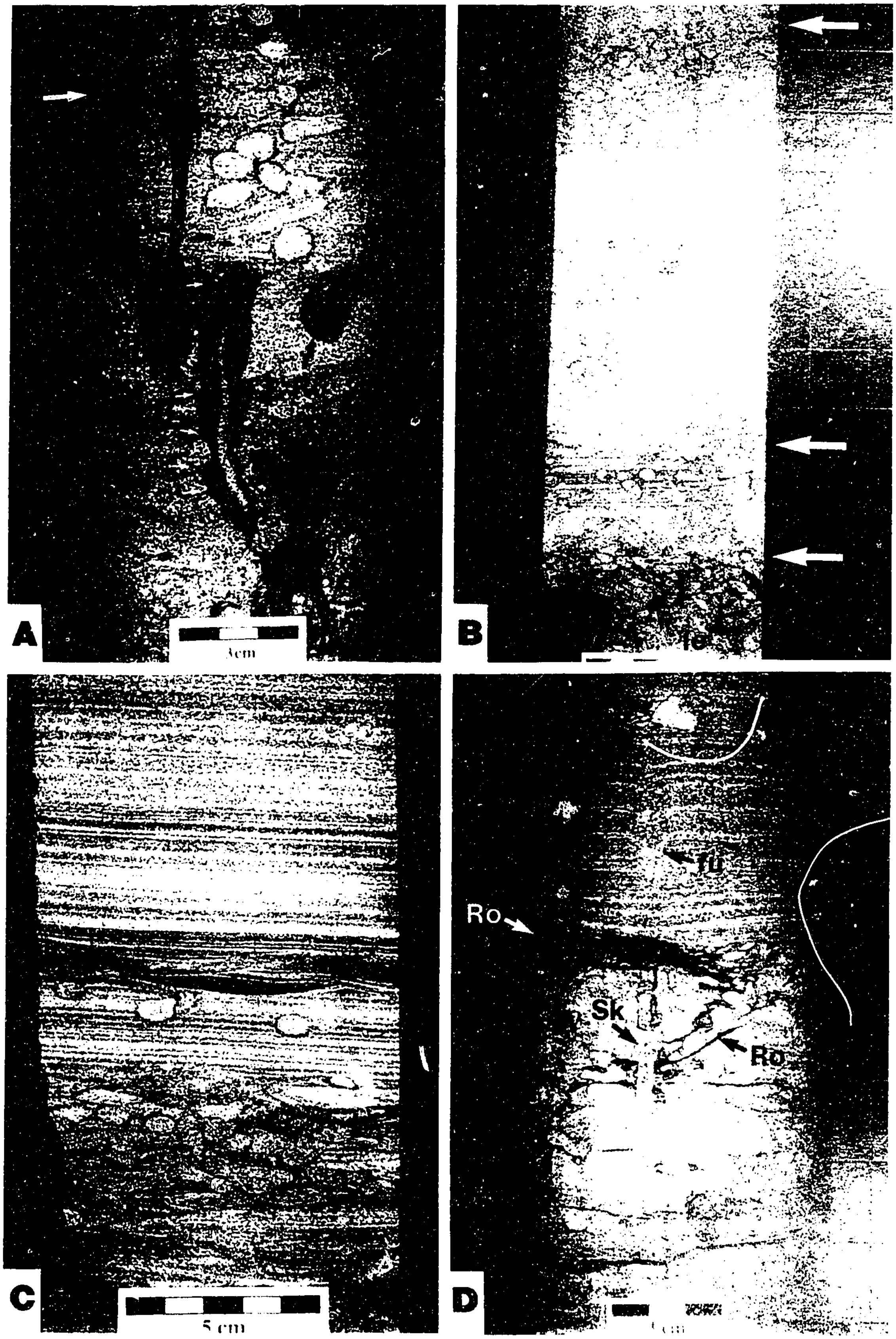
Figure 22. Facies photographs for FA2.

A) Amalgamated laminated to bioturbated sandstone beds with truncated *Rosselia* (Ro) and *Macaronichnus* (Ma) in the 7-27-72-13w6 well (2144.6 m). *Rosselia* show several stages of erosion and equilibrium (small white arrows), and the upper two *Rosselia* show the early stages of development with a sand filled tube outside the established 'mud-ball'.

B) Laminated to bioturbated sandstone beds, bedsets are marked by white arrows at the right. Physical structures are interpreted as swaly cross-stratification, and bioturbation is dominated by *Macaronichnus* sp. at the tops of bedsets. Rare *Teichichnus* (Te) is also present, in the 6-10-75-8w6 well (1577.6 m).

C) Laminated to bioturbated sandstone facies in the 6-10-75-8w6 well (1579.7 m). The underlying bioturbated bed contains abundant *Macaronichnus* sp., and is erosively overlain by a tempestite. Stratification in the tempestite includes oscillation ripples and low angle wavy laminations.

D) Laminated to bioturbated sandstone facies in the 3-28-74-11w6 well (1793.1 m). The mixed *Skolithos-Cruziana* assemblage is more diverse and includes abundant *Macaronichnus* sp. (Ma), *Rosselia* (Ro), *Skolithos* (Sk), and fugichnia (fu). The fugichnia is associated with the *Skolithos* and was produced when the organism was buried and subsequently escaped up to the new sediment-water interface.

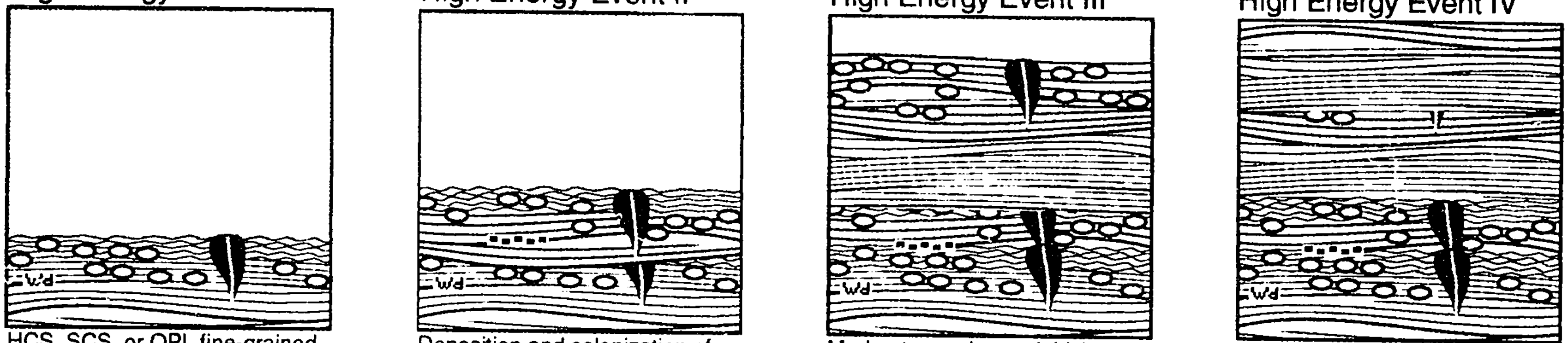

A
B
C
5 cm
D
fu
Ro
Sk
Ro

bioturbated sandstone. The succession is dominated by biogenic reworking near the base, and shows a progressive decrease in burrow intensity as it coarsens upward and sand content increases.

The dark shale facies is interpreted to have been deposited under very low energy, shelfal to lower offshore setting. Rare silts correspond to infrequent, distal storm deposits or tempestites. The dark shale facies is representative of offshore deposition under low energy accompanied by slow sedimentation rates. The overlying bioturbated silty shale facies represents similar environmental conditions. The higher silt content of the facies is interpreted to be due to the regular emplacement of distal storm deposits. Rare, thin silt and fine-grained sand beds contain oscillation ripples and climbing ripples and are indicative of waning energy conditions. Typically, the silt is thoroughly dispersed through the facies by biogenic activity represented by a distal *Cruziana* ichnofacies. The bioturbated silty shale facies represents deposition in a storm influenced offshore environment. The bioturbated sandy shale facies consists of a vf-f sandstone with biogenically dispersed sand, and discrete sandstone beds. The sandstone beds increase in frequency and thickness upward in the facies indicating a gradual increase in storm influence. This facies contains a diverse *Cruziana* ichnofacies, indicating a marine origin, and is interpreted to be deposited in an upper offshore setting.

The bioturbated muddy sandstone facies is made up of biogenically mottled vfL to vfU sandstone and shale. A higher degree of storm influence is evidenced by an increase in sand content *vs.* the bioturbated sandy shale facies. This facies has a *Cruziana* to distal *Skolithos* ichnofacies representing a transitional setting between the shoreface and offshore. This environment is similar to the bioturbated sandy shale facies, but is either more proximal to the shoreface, or is due to increased storm influence.

The laminated to bioturbated sandstone facies is characteristic of deposition in a storm-influenced lower to middle shoreface setting. The sedimentary structures consist of low angle curvilinear bedforms interpreted to be QPL, SCS, and HCS with rarer combined flow ripples. The tops of these beds are typically burrowed and disrupt primary physical sedimentary structures creating the laminated to bioturbated appearance (Figure 23). The resident trace fossil suite is dominated by a "*Macaronichnus* sp." assemblage which is indicative of feeding and dwelling behaviours developed in a moderate energy setting. The laminated to bioturbated facies is similar to the "burrowed zone" in the Cadotte Member (Saunders *et al.*, 1994). This "burrowed zone" has been interpreted by Saunders *et al.* (1994) to reflect the effects of summer storms (HCS or SCS) overprinting fairweather type conditions (bioturbation). Trace fossil assemblages in the Cadotte "burrowed zone" and the laminated to bioturbated facies of FA2 are nearly identical. Truncated and



Rapid Deposition: High Energy Event I

HCS, SCS, or QPL fine-grained sand, possibly with capping wave ripples. The substrate is colonized by deposit feeding organisms.

Rapid Deposition: High Energy Event II

Deposition and colonization of thin tempestite, erosion removes a portion of the bioturbated bed.

Rapid Deposition: High Energy Event III

Moderate erosion and thick deposition due to tempestite. The upper layer is colonized by the same equlibrium suite of organisms.

Rapid Deposition: High Energy Event IV

Subsequent erosion removes most evidence of biogenic activity in the upper layer.

Figure 23. Facies Association 2 development.

re-equlibriated *Rosselia* in the Bluesky Formation indicate 15 cm of net deposition during the lifetime of the trace-making organism. The burrowed to laminated facies of FA2 is interpreted to have been rapidly emplaced. The stress responsible for the *Macaronichnus* assemblage is interpreted as the regular emplacement of storm-derived sands.

The single occurrence of the bioturbated interbedded sandstone and shale facies grades out of the laminated to bioturbated sandstone facies, and is interpreted to have been deposited in an offshore-shoreface transition. The upward decrease of sandy material corresponds to an decrease of energy, probably associated with rise in sea level from the lower shoreface to the upper offshore transition.

FA2 Summary

An overall coarsening upward succession from a dark shale facies through burrowed shale facies, locally overlain by a bioturbated muddy sandstone or an bioturbated, interbedded sandstone and shale facies, and capped by laminated to bioturbated sandstone. This corresponds to a shift in ichnofacies from distal *Cruziana* to mixed *Cruziana-Skolithos*, and to the "*Macaronichnus* sp." assemblage in FA2. The vertical facies relationship is interpreted to represent the progradation of storm influenced, lower to middle shoreface sands over shelfal and offshore sediments. This is interpreted to reflect a relative drop in sea level, likely caused by an increase in sediment input.

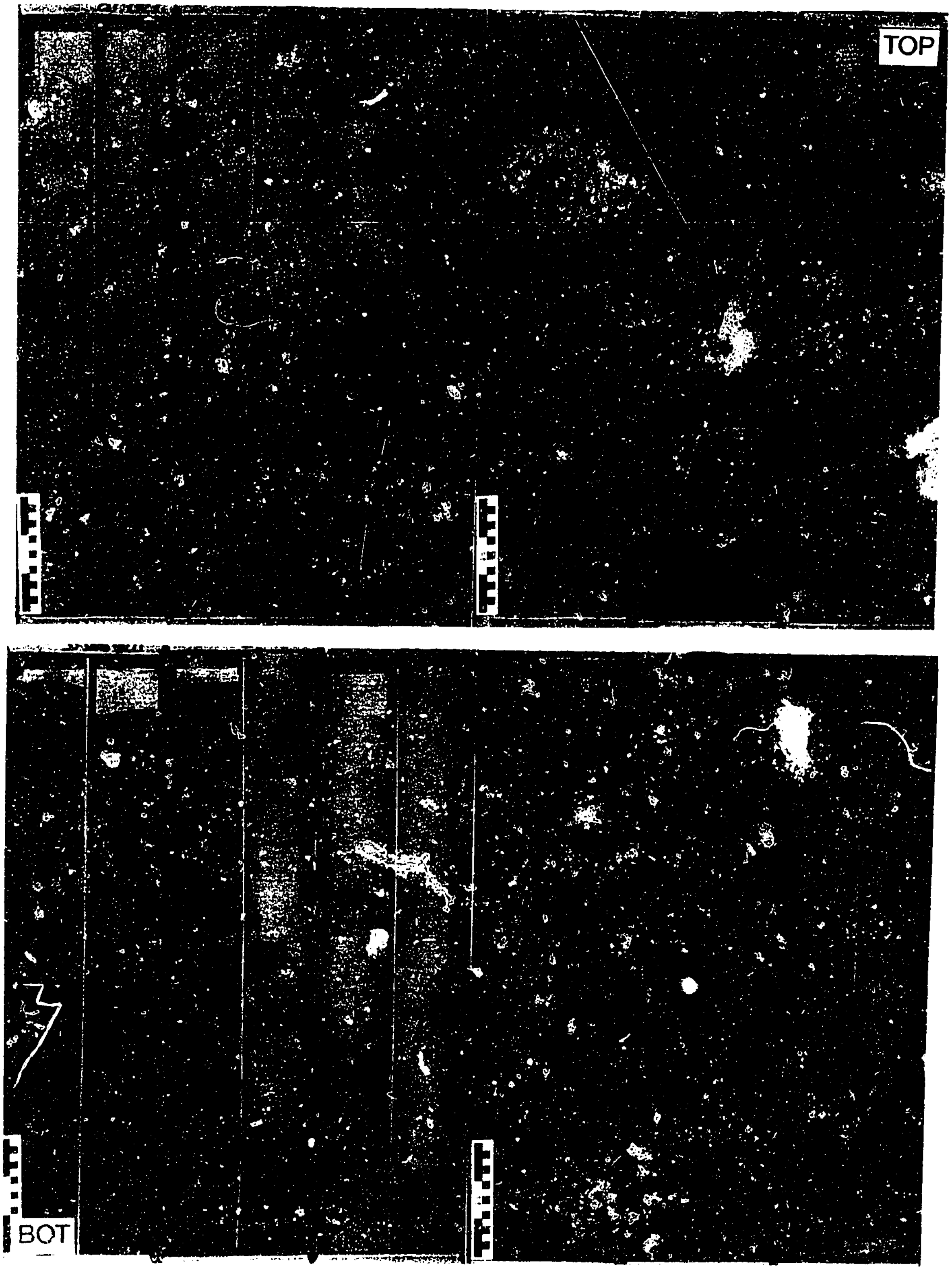
Facies Association Three (FA3): Burrowed Silty Shale, Interbedded Sandstone and Shale, Interbedded Shale and Sandstone, and Laminated Sandstone

Sedimentology and Ichnology

Five facies comprise FA3 and include from bottom to top; bioturbated silty shale, bioturbated sandy shale, bioturbated interbedded sandstone and shale, laminated sandstone, and sharp-based interbedded sandstone and shale. This facies association generally overlies FA1, although it locally overlies both FA2 and FA4. The lower facies are shale-dominated and are thoroughly bioturbated, similar to FA2. In contrast to FA2, however, the laminated sandstone facies has very little biogenic influence (Figure 24). Deposits of FA3 were recovered from 11 wells throughout the study area (Figure 25). This facies association is relatively thick compared to most other facies associations and combined with FA2 makes up the bulk of the Bluesky Formation. Measured thicknesses range from 2.5 to over 14.3 m thick, with typical thicknesses ranging from 6 to 10 m. The wireline log response of FA3 in the 14-15-73-9w6 well is illustrated in Figure 26.

The bioturbated silty shale facies of FA3 occurs in three wells in the northern portion of the study area. It ranges in thickness from 1.4 to 2.9 m, and averages 1.5 to 2 m, and is the similar to the bioturbated silty shale facies of FA2. Cored intervals that recovered the bioturbated silty shale facies were assigned to FA2 if wireline log responses

Figure 24. Box photographs of the 14-15-73-9w6 core; bottom (BOT) is at lower left and top (TOP) is at upper right. This core displays a single fining upward cycle from FA3 to FA4, lower contact at the red arrow. Scale in photograph is 15 cm.


TOP
BOT

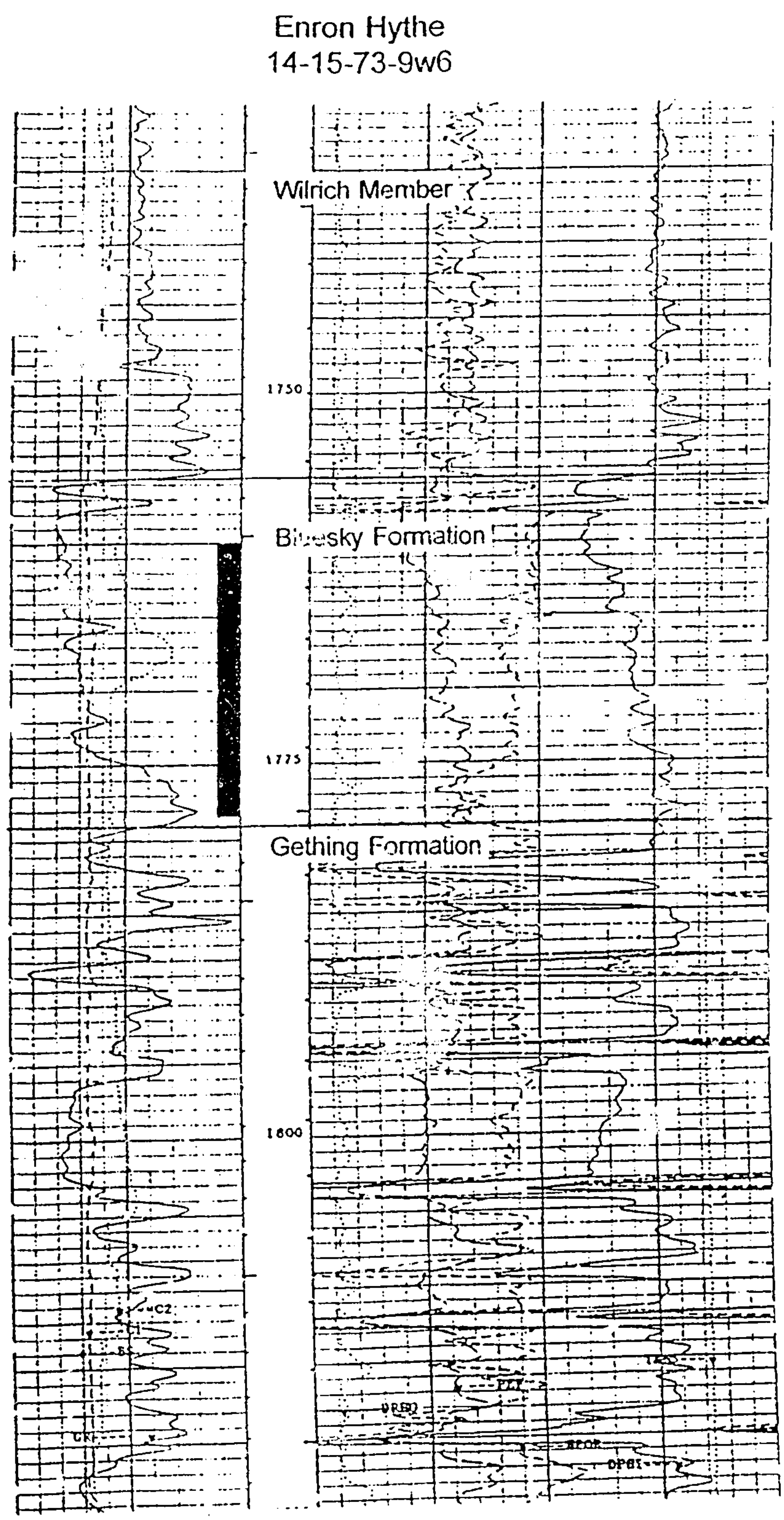


Figure 26. Wireline log (GR, CNL, FDC) showing the Wilrich Member, the ˈuesky Formation, and the Gething Formation. The Bluesky Formation shown here consists o: .ne coarsening upward cycle from offshore to foreshore.

were not sufficient to differentiate between FA2 and FA3.

The bioturbated sandy shale facies of FA3 occurs in three wells in the northern portion of the study area. It ranges in thickness from 0.5 to 2.7 m, and averages 1 m, and is the similar to the bioturbated sandy shale facies of FA2. Cored intervals that recovered the bioturbated sandy shale facies were assigned to FA2 if wireline log responses were not sufficient to differentiate between FA2 and FA3.

The bioturbated interbedded sandstone and shale facies occurs in four wells in the southern portion of the study area. This facies is up to 4.8 m thick, and comprises interstratified vfU to vfL sandstone and shale beds with pyrite and a localized pebble lag (Figure 27a). This facies gradationally overlies the sandstone-dominated interbedded sandstone and shale facies of FA1. The sandstone beds of the bioturbated interbedded sandstone and shale facies are unburrowed and sharp based. They range from 1 to 30 cm thick, but are typically 1-3 cm thick. The sandstone beds are low angle parallel laminated with rare preserved ripple laminated tops with the thicker amalgamated sandstone beds occurring in upper portion of the facies. Shale beds contain biogenically dispersed sand, are moderately to thoroughly burrowed, and may sharply to gradationally overlie the sandstone beds. Shale beds range from 0.5 to 3.0 cm thick, but are typically 1 cm thick.

Bioturbation in the shale beds is of common to moderate intensity typically churning the lower contacts with the thinner sandstone beds. Discrete trace fossils include *Anconichnus* (c-m), *Chondrites* (c-m), *Planolites* (c-r), *Teichichnus* (m-r), *Asterosoma* (m-r), *Thalassinoides* (m-r), *Palaeophycus* (r), *Rosselia* (r), *Ophiomorpha* (r), *Skolithos* (r), *Terebellina* (r), *Arenicolites* (r), and *Macaronichnus* (r). The shaly trace fossil assemblage comprises *Anconichnus*, *Chondrites*, *Planolites*, *Asterosoma*, and *Teichichnus*, with subordinate *Thalassinoides*. The trace fossils are primarily fodinichnia, and are characteristic of feeding and dwelling behaviour. This assemblage is characteristic of a diverse *Cruziana* ichnofacies. Sandstone beds are typically devoid of trace fossils, but locally display moderate degrees of bioturbation characterized by *Macaronichnus*, *Rosselia*, *Teichichnus*, and *Asterosoma*. The primary sandstone assemblage consists of deposit-feeding structures characteristic of the *Cruziana* ichnofacies. *Diplocraterion habichi* is found in one location is associated with a pebble and coarse-grained sandstone lag. The burrow fill of coarse-grained sand shows no structure and indicates a passive fill. The overlying pebbles are 1-2 cm diameter, and well rounded.

The laminated sandstone facies of FA3 is similar to the laminated portion of the laminated to burrowed facies of FA2. Amalgamated beds of sharp-based, low angle cross-stratified, vfU-mL sandstone comprise the laminated sandstone facies (Figure 27 b,c,d, Figure 28). Accessories include dispersed pebbles, mudstone rip-up clasts, coal detritus,

Figure 27. Facies photographs for FA3.

A) The bioturbated, interbedded sandstone and shale facies in 7-3-75-13w6 at 1769.5 m. This facies contains a diverse *Cruziana* assemblage associated with shale laminae. The trace fossils present in this facies include *Rosselia* (Ro), *Planolites* (Pl), *Teichichnus* (Te), *Asterosoma* (As), and *Palaeophycos* (Pa). Sandstone beds are 1 to 2 cm thick and typically unburrowed.

B) Wavy parallel laminated sandstone with truncated *Palaeophycos* (Pa) and associated fugichnia (fu) in the 3-28-74-11w6 well (1794.4 m). Erosion and deposition of the upper bed occurred as two discrete events since the truncated fugichnia does not continue upward into the overlying sand.

C) Laminated sandstone facies in the 14-15-73-9w6 well (1765.2 m).

D) Laminated sandstone facies with fugichnia (black arrows) in the 14-15-73-9w6 well (1771.7 m).

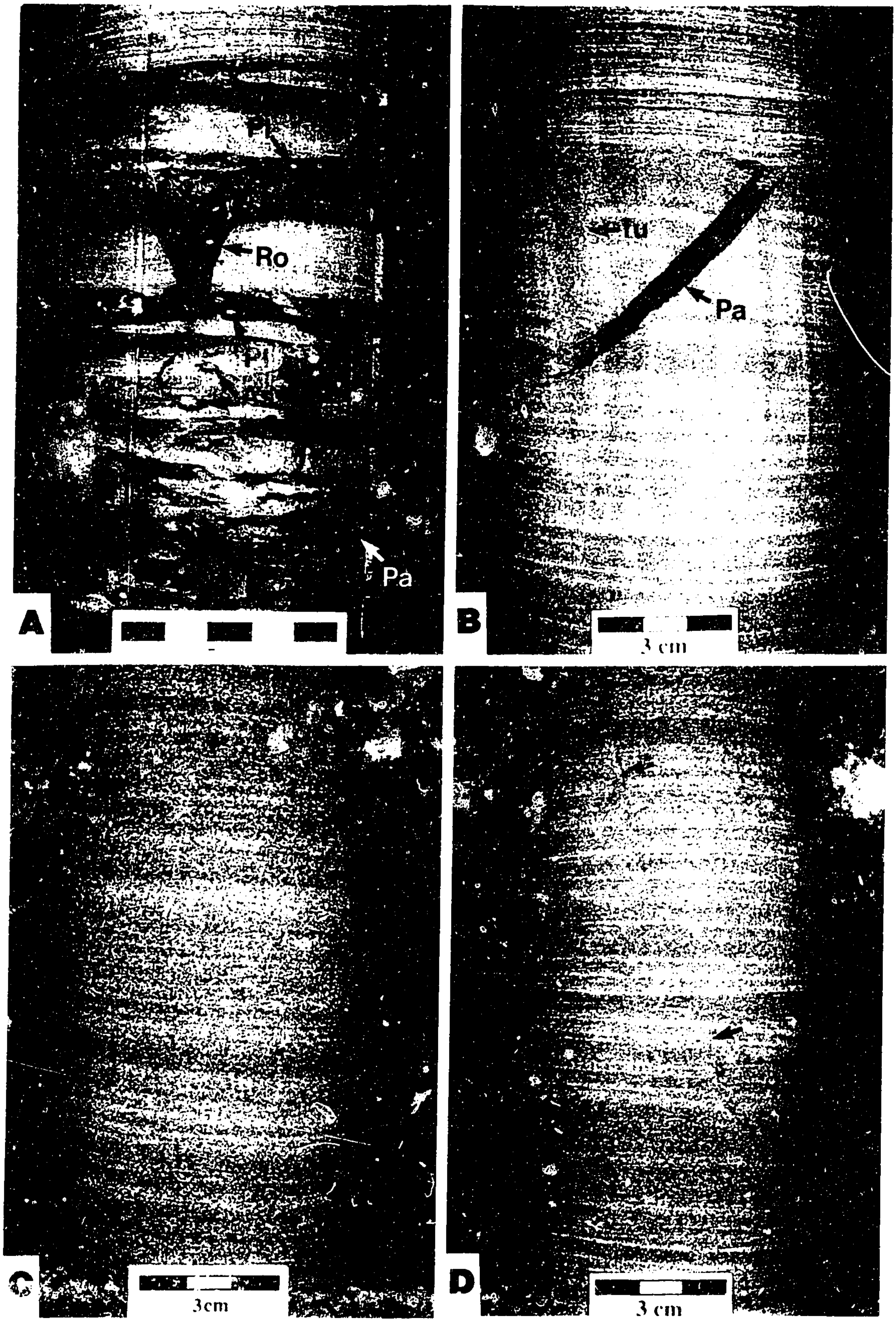

A
Pl
Ro
Pl
Pa
B
Tu
Pa
3 cm
C
3cm
D
3 cm

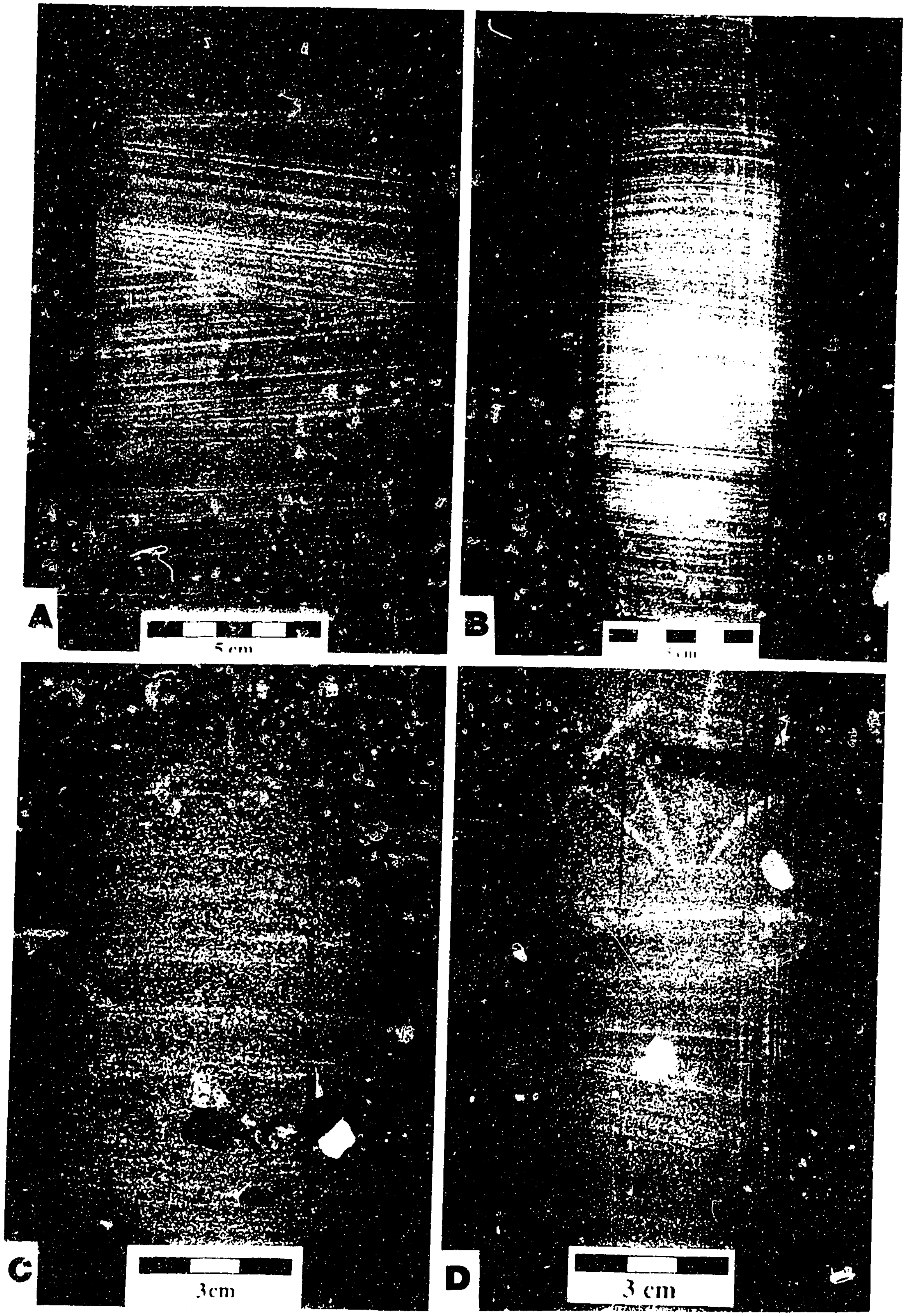
Figure 28. Facies photographs for FA3.

A) Laminated sandstone facies in the 3-28-74-11w6 well (1565.5 m). Truncation by successive storm events results in bedsets ~ 5 cm thick.

B) Laminated sandstone facies shows laminations characteristic of SCS in the 3-28-74-11 well (1797.7 m).

C) Pebble-rich layer in the laminated sandstone facies in the 7-27-72-13w6 well (2158.6 m).

D) Mudstone rip-ups in the laminated sandstone facies (11-18-74-13w6 at 1953.3 m) are interpreted to have been derived from nearby marine shales. An interbedded sandstone and shale facies directly underlies the thin laminated sandstone facies.


A
5 cm
B
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3cm
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3 cm

glauconite, shale laminae, organic shale laminae, pyrite, and shell fragments. This facies was encountered in twelve wells throughout the study area, and ranges from 2.5 to 9.8 m thick, averaging 6 to 7 m thick. The laminated sandstone facies sharply overlies the interbedded sandstone and shale facies of FA2 and FA3, as well as sandstones of FA2 and FA4. Bedsets range from 5 to 30 cm thick, but are generally 10 to 15 cm thick. Individual laminae sets are typically on the order of 3 to 5 cm thick, and are erosionally based. Beds display low angle (typically <15°), wavy parallel lamination. Burrowing within the laminated sandstone facies consists of rare *Palaeophycus*, *Skolithos*, and fugichnia (Figure 27b,d).

Three wells show an alternation between the laminated sandstone facies and the laminated to bioturbated facies, and represent a midpoint between these FA2 and FA3 end members. Trace fossils in these wells include: *Macaronichnus* (c-r), *Diplocraterion* (c-r), *Teichichnus* (c-r), *Rosselia* (m-r), *Planolites* (m-r), *Palaeophycus* (m-r), *Chondrites* (r), *Asterosoma* (r), *Terebellina* (r), *Bergaueria* (r), and *Lockeia* (r).

The sharp-based interbedded shale and sandstone facies was encountered in three cores in the northern portion of the study area. The facies contrasts with the typical bioturbated interbedded sandstone and shale facies of FA2 and FA3. Unlike other interbedded facies, this facies is only rarely burrowed, and sharply overlies laminated sandstones of FA3. The typical bioturbated interbedded shale and sandstone facies underlie the laminated sandstone facies. The sharp-based interbedded shale and sandstone facies is shale-dominated and thinly bedded. Sandstone and shale beds range from 0.5 to 3.0 cm thick, and are typically 0.5 to 1.0 cm thick. The sharp-based interbedded shale and sandstone facies is thin and ranges from 30 to 50 cm in thickness. The facies consists of vfL sandstone and shale with rare allochthonous coaly detritus. Primary physical sedimentary structures in the sandstone include low angle parallel laminations and rare ripples. Burrowing intensity may be locally moderate, but is typically rare to unbioturbated. *Planolites* (m) and *Macaronichnus* (m) are present in one thick sandstone bed. The only trace fossil typically present in this facies is *Planolites* (r). *Planolites* is a deposit-feeding structure and is an ichnofacies-crossing form. Consequently, its presence is not diagnostic of specific environmental conditions. The reduced trace fossils abundance and diversity are indicative of a stressed environment.

Environmental Implications of FA3

FA3 represents a vertical succession of facies passing from bioturbated silty shale and bioturbated sandy shale through bioturbated interbedded sandstone and shale, capped by the laminated sandstone facies, and locally interstratified with the sharp-based interbedded sandstone and shale facies. This facies association overlies FA1, although it locally overlies FA2. The FA3 succession is dominated by biogenic reworking near the base, and laminated sandstone towards the top.

The bioturbated silty shale and bioturbated sandy shale facies are similar to the lower facies of FA2. These facies represent deposition in a low energy marine environment interpreted to be an offshore to upper offshore setting. The bioturbated interbedded sandstone and shale facies is interpreted to have been deposited in an offshore-shoreface transition. This facies has a higher sand content than the bioturbated interbedded sandstone and shale of FA2. The increased sandstone content is typically unburrowed, laminated, vf-f sandstone beds interpreted to be tempestites. The higher sandstone content is due to a greater degree of storm influence in an upper offshore to lower shoreface transitional setting.

The laminated sandstone facies was deposited in a storm-dominated lower to middle shoreface. The sandstone bedsets are the amalgamation of numerous individual HCS, SCS, and QPL beds. The lack of bioturbation reflects high energy conditions during deposition. This may have been caused by two mechanisms (Figure 29). Either storm frequency was high enough to either prevent the colonization of the substrate, or storm energy was great enough to erode any evidence of biogenic activity.

The sharp-based interbedded shale and sandstone facies is interpreted to represent deposition in the lower to middle shoreface. This is based on the stratigraphic position and recurring facies relationship with the laminated sandstone facies. The sharp-based interbedded shale and sandstone facies may have been deposited as the result of flooding due to storm activity on land (Saunders, pers. comm., 1994). This facies is problematic since bioturbation intensity should be higher, and marine shale beds are typically deposited in an offshore setting.

FA3 Summary

The general succession of facies passes from bioturbated silty shale and bioturbated sandy shale to bioturbated interbedded sandstone and shale, and is capped by the laminated sandstone facies. An overall coarsening upward succession and corresponding shift in energy from the distal *Cruziana* ichnofacies to amalgamated sandstone lower to middle shoreface is observed in FA3. This vertical succession is interpreted to reflect the progradation of storm-dominated, lower to middle shoreface sands over shelfal and offshore sediments. This is interpreted to represent a relative drop in sea level due to an increase in sediment input.

Figure 27 Facies Association 3 Development.

A) Depicts low frequency, high energy storms resulting in a swaley cross-stratified sandstone facies. The inital event deposits low angle, wavy laminated sandstone with assorted detritus. A typical marine assemblage of organisms inhabits the substrate after fairweather conditions return in the long inter-storm periods. Subsequent storm conditions remove most ichnofossils, and deposit a new layer of swaley cross stratified sandstone.

B) The same facies may be generated by frequent, relatively low energy storm events. Storms are frequent enough to stress the depositional setting and prevent colonization of the substrate. Storm erosion does not cut deeply into the substrate and wave ripples at the top of the previous bed may be preserved.

The second (B) model may be positively identified if wave ripples are preserved and trace fossils are absent in the amalgamated SCS facies.

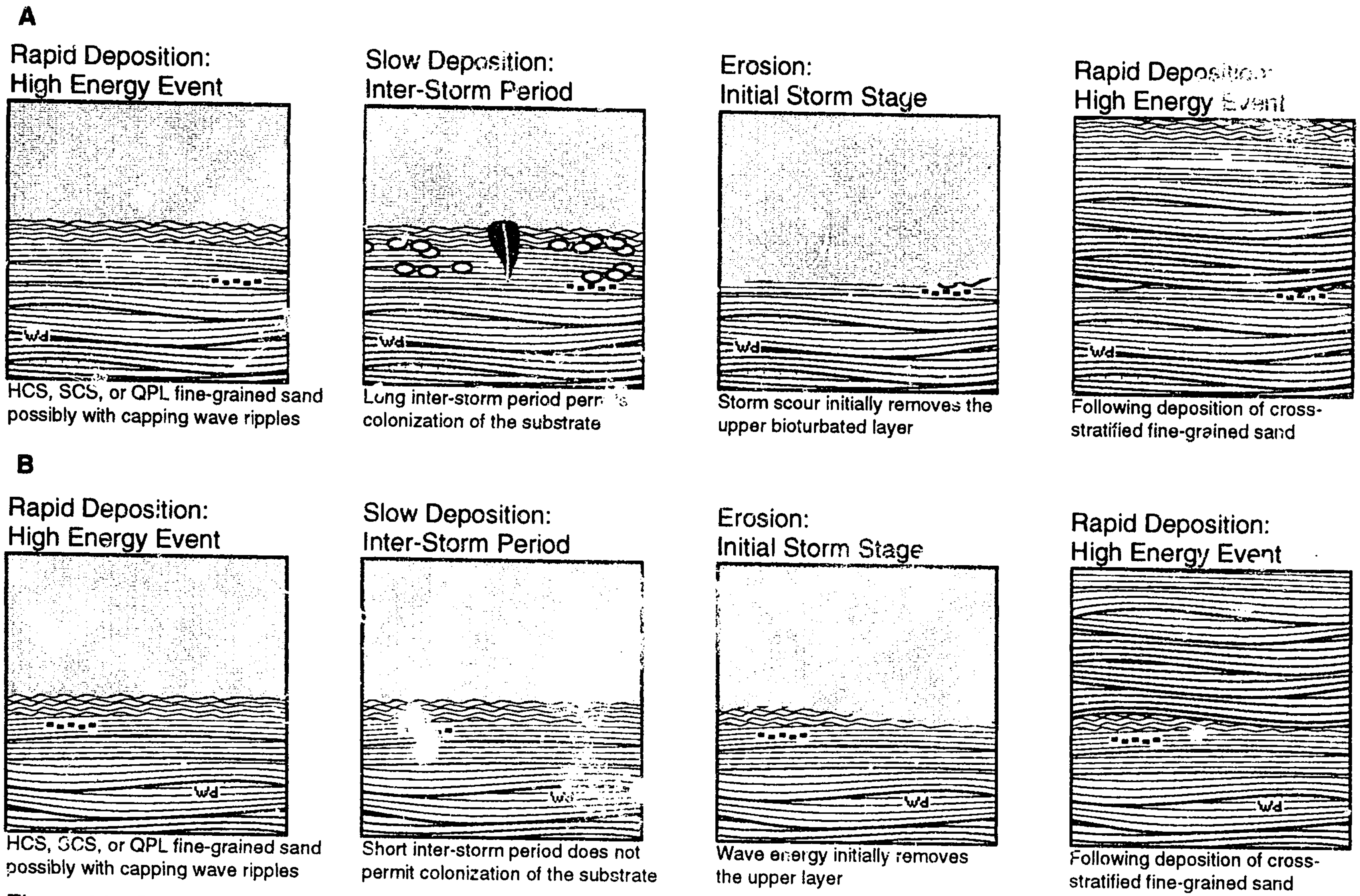


Figure 29. Facies Association 3 Development.

Facies Association Four (FA4): Cross-bedded to Structureless Sandstones

Sedimentology and Ichnology

Facies Association 4 is a common facies association and was observed in nine cored wells (Figure 30). The facies association is dominated by cross-bedded to structureless sandstone with secondary intervals of bioturbated and low-angle planar laminated sandstone, and overlies FA2 and FA3. This facies association includes three facies, in ascending order; conglomerate, trough cross-bedded sandstone, and bioturbated to parallel laminated sandstone (Figure 24). Facies Association 4 ranges in thickness from 0.1 m (an isolated conglomerate) to >10 m (an incomplete succession of trough cross-bedded sandstone and bioturbated and low-angle planar laminated sandstone). The average thickness of a complete FA4 succession is about 5 m, but is difficult to determine because few cores recover the entire association. The wireline log response of FA4 in 14-15-73-9w6 is illustrated in Figure 26.

The conglomerate facies of FA4 is present in two cores and is observed exclusively in the southwestern portion of the study area (Figure 30). These conglomerates are clast supported and consist of rounded to well rounded, subangular to equant, lithic chert pebbles in a sandy matrix (Figure 31a,b). Clast size ranges from granules to pebbles, up to 2.0 cm diameter, whereas the matrix ranges from medium-grained sand to granules. This facies sharply overlies sandstones of FA3, and was observed to be erosional in one well. The conglomerate facies is thin compared to most other facies, and is 10 to 20 cm thick. No trace fossils or physical sedimentary structures are present in this facies.

Trough cross-bedded sandstones comprise the most common facies of FA4. The trough cross-bedded sandstone facies is widespread and occurs in eight wells. It normally sharply overlies the laminated sandstones and the laminated to bioturbated facies, but in a single well it overlies FA4 conglomerate. The trough cross-bedded sandstone facies ranges from fU to mU, but is typically medium-grained. Physical sedimentary structures consist of high-angle, steepening upward, cross-laminations (Figure 31c,d). The facies is dominated by trough cross-bedding, although thin zones of low angle planar laminations, tabular cross-bedding, and current ripple lamination are also intercalated. Coal and mafic detritus accentuate sedimentary structures, and are ubiquitous within this facies. Other accessories include dispersed mud, pebbles, and rare mudstone rip-up clasts. This facies varies in thickness from 0.5 to 5.7 m, averaging 3 m, and has foreset thicknesses 0.5 to 1.0 cm. Cores through this facies are typically brecciated and bed thicknesses cannot be accurately measured.

Bioturbation in the trough cross-bedded sandstone facies is limited to rare fugichnia and *Skolithos*. The *Skolithos* are dominichnia representing the colonization by a

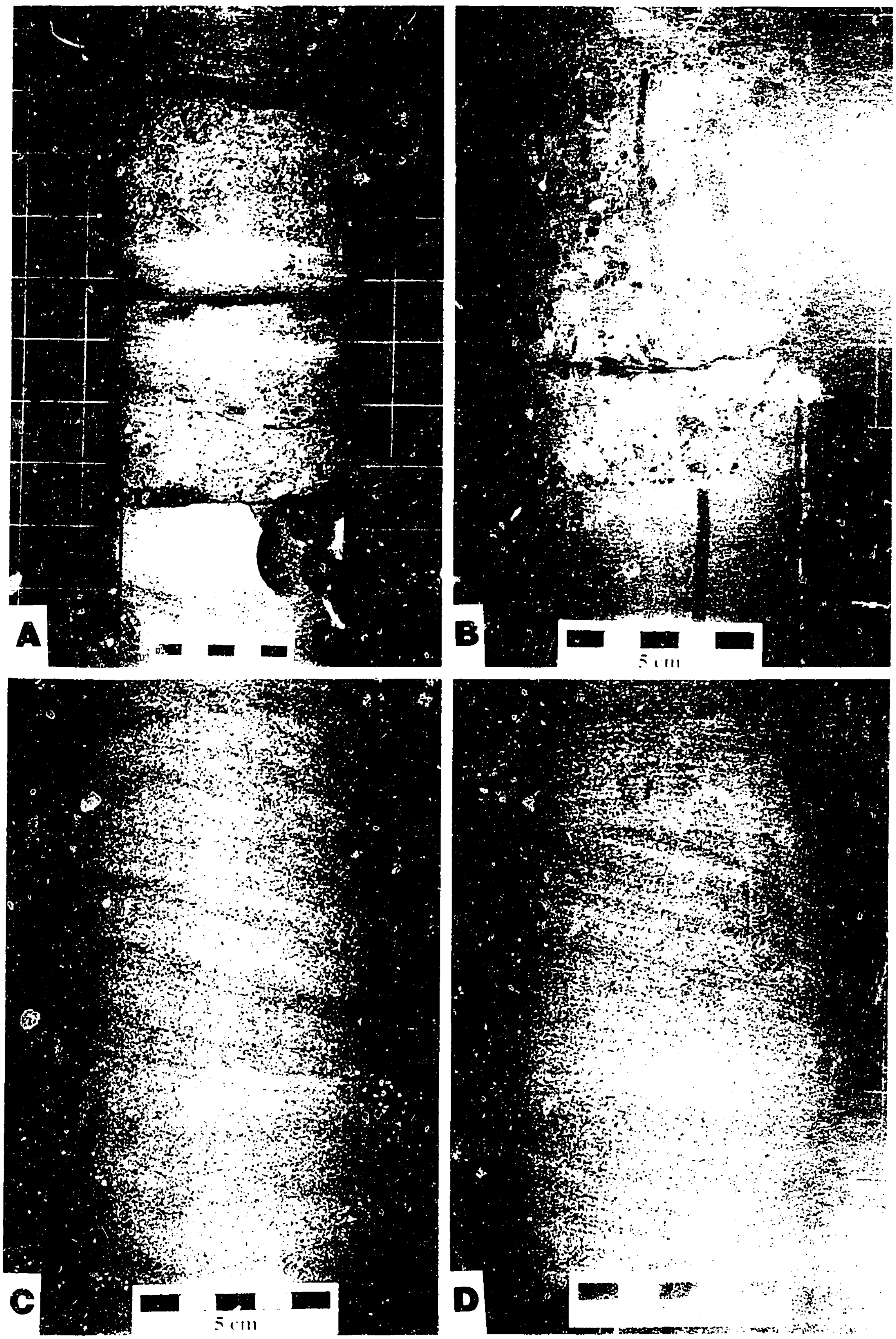
Figure 31. Facies photographs for FA4.

A) The conglomerate facies consisting of well rounded lithic pebbles and a sandstone matrix in the 10-35-71-13w6 well (2204.4 m).

B) The conglomerate facies consisting of well rounded lithic pebbles up to 2 cm in diameter, from the 10-34-70-13w6 well (2374.2 m).

C) Trough cross-bedded sandstone facies in the 10-35-71-13w6 well (2201.2 m).

D) Trough cross-bedded sandstone facies in the 10-34-70-13w6 well (2365.7 m). Bedsets are thin and indicate variable flow directions.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5 cm
D

suspension-feeding organism. Fugichnia are the trace fossil of an organism that was rapidly buried, and consequently escaped to the sediment-water interface. These trace fossils are representative of biogenic activity in a high energy, non-cohesive, shifting substrate with rapid sedimentation. The *Skolithos* and fugichnia are indicative of a limited *Skolithos* ichnofacies. This restricted ichnofacies has a low diversity due to the high energy of the depositional environment.

Additional biogenic activity observed in this facies includes rhizoliths (root traces) at the top of one cross-bedded sandstone. The rhizoliths are moderate in abundance and subtend from an overlying organic shale facies, cross-cutting trough cross-beds.

The bioturbated and low-angle planar laminated sandstone facies is another common component of FA4 and occurs in seven wells in the western portion of the study area (Figure 30). This facies commonly overlies the trough cross-bedded sandstone facies of FA4, although it may directly overlie the laminated sandstone facies of FA2. It ranges in thickness from 0.3 to 2.9 m, and is made up of completely burrowed to low-angle planar laminated sandstone (Figure 32). The sand is very well-sorted, vfU to mL grained, typically fU-mL, and contains rare coaly detritus. The lower contact with the trough cross-bedded sandstone facies is typically gradational, but is locally erosional. Primary physical sedimentary structures are low-angle planar laminations with subparallel bedsets. Bioturbation intensity is locally abundant to common, and trace fossils rarely disrupt physical sedimentary structures.

Trace fossils within this facies are limited to *Macaronichnus segregatis*, or *Macaronichnus spiralis* (*cf.* Clifton and Thompson, 1978; Saunders, 1986; Saunders *et al.*, 1994). These species differ from the *Macaronichnus* sp. of FA2 and FA3 in size, character of the outer mantle, and associations with other trace fossils. The *Macaronichnus* of FA4 range in size from 1 to 2 mm in diameter, and have a mantle ~0.2 mm thick (Figure 32). *Macaronichnus* sp. of FA2 and FA3 are considerably larger, typically >5 mm in diameter, and typically range from 3 to 9 mm in diameter (Figure 22) with an outer mantle 0.5 to 1.0 mm thick. Additionally, *M.* sp. is closely associated with *Rosselia* and *Palaeophycus* whereas *M. segregatis* and *M. spiralis* occur exclusive of other ichnogenera. *Macaronichnus segregatis* and *M. spiralis* are interpreted as the trace fossils of a grain-selective, epigranular deposit-feeding organism (fodinichnia) in a high-energy (stressed) environment. This assemblage is typical of a shifting, non-cohesive substrate, deposited in a very high energy marine environment. No formal ichnofacies yet exists to encompass this monospecific trace fossil association, but the *Macaronichnus* ichnofacies has been suggested by Pemberton (pers. comm. 1994).

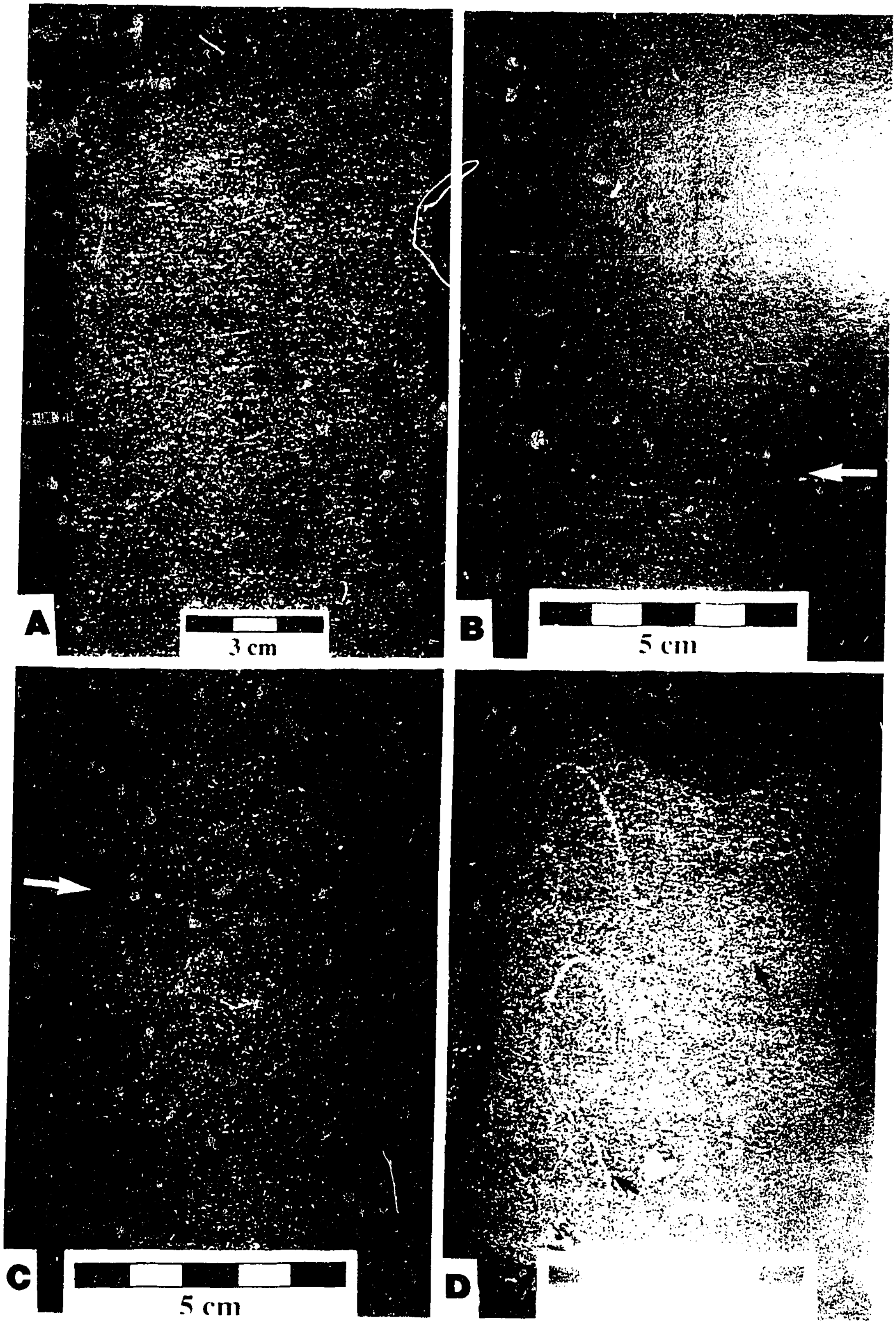
Figure 32. Facies photographs of FA4.

A) *Macaronichnus segregatis* or *Macaronichnus spiralis* (black arrows) obscuring the laminae present in a fine-grained, swash-stratified sandstone in the 14-15-73-9w6 well (1760.3 m). *Macaronichnus* is common to abundant and occurs exclusively in the swash-stratified sandstone.

B) *Macaronichnus* (black arrows) in a swash-stratified sandstone. Laminations are present (white arrow) in the 10-34-70-13w6 well (2364.2 m).

C) *Macaronichnus* (black arrows) in a swash-stratified sandstone with faint swash laminations (white arrow) in the 6-6 72-12w6 well (2179.6 m).

D) *Macaronichnus* (black arrows) in a swash-stratified sandstone. Few burrows have significant horizontal component and cross-cut swash laminations (white arrow) in the 10-34-70-13w6 well (2364.4 m).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5 cm
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Environmental Implications of FA4

The idealized vertical succession of facies in FA4 typically consists of a localized conglomerate overlain by trough cross-bedded sandstone which is overlain by the bioturbated and low-angle planar laminated sandstone facies.

The conglomerate facies is interpreted as a lag deposit overlying the FA3 deposits. The lag deposit underlies the trough cross-bedded sandstone facies of FA4 and demarcates the base of the upper shoreface. Pebble veneers are created on erosional surfaces (ravinement, TSE) by winnowing from deposits and concentration as a lag (Van Wagoneer *et al.*, 1990). The trough cross-bedded sandstone facies is interpreted as being deposited in the upper shoreface. The physical sedimentary structures and rare trace fossils present are consistent with deposition in a high energy environment.

The bioturbated and low-angle planar laminated sandstone facies is variable in thickness and is closely associated with the trough cross-bedded sandstone facies. Primary physical sedimentary structures are low-angle planar laminations with subparallel bedsets and are interpreted to represent swash stratification. Trace fossils display a deposit-feeding behaviour characteristic of a high energy, non-consolidated, shifting sandy substrate. This facies is interpreted to represent a foreshore setting.

The typical FA4 succession consists of a localized pebble lag overlain by trough-crossbedded sandstone of the upper shoreface, and swash-stratified and bioturbated sandstone of the foreshore.

3.5.3 Upper Deposits

Facies Association Five (FA5): Mud Rip-Up Breccias and Sandstones

Sedimentology and Ichnology

Facies Association 5 is a highly variable facies association, which was observed in several locations throughout the study area (Figure 30). Facies Association 5 consists of ten facies; mudstone rip-up breccia, coaly trough cross-bedded sandstone, pebbly sandstone, organic-rich shale, pinstripe laminated shale and sandstone, coal, structureless coaly sandstone, rippled sandstone, disrupted sandstone, and a salt and pepper sandstone. This facies association ranges from 2.35 to >5.5 m thick, and averages 4 to 5 m thickness. This facies overlies sandstones of FA2, FA3, and FA4, and is overlain by FA1 deposits. The wireline log response of FA5 is illustrated for the 2-23-75-13W6 well in Figure 33.

A single, three facies succession occurs in one well and consists of a mudstone rip-up breccia, coaly trough cross-bedded sandstone, and a pebbly sandstone facies. The lowermost facies in this succession is a matrix-supported mudstone rip-up breccia (Figure 34a,b). It is 40 cm thick and erosively overlies the laminated to burrowed sandstone

Chiefco Texaco Sinclair
2-23-75-13w6

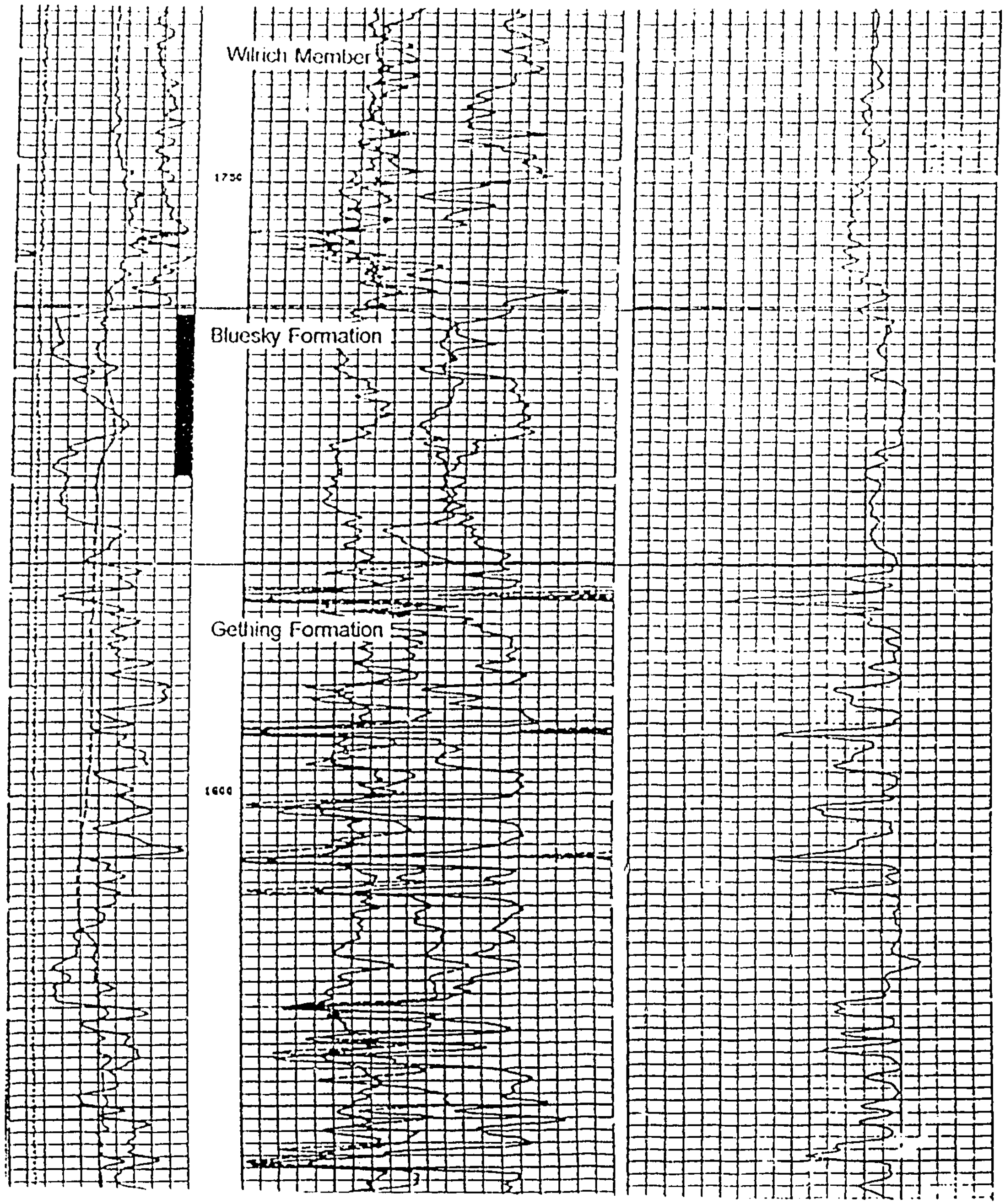


Figure 33. Wireline log (GR, CNL, FDC, BHC) showing the Wilrich Member, the Bluesky Formation, and the Gething Formation. The Bluesky Formation shown here consists of one coarsening upward cycle including lower-middle shoreface to tidal channel and transgressive deposits.

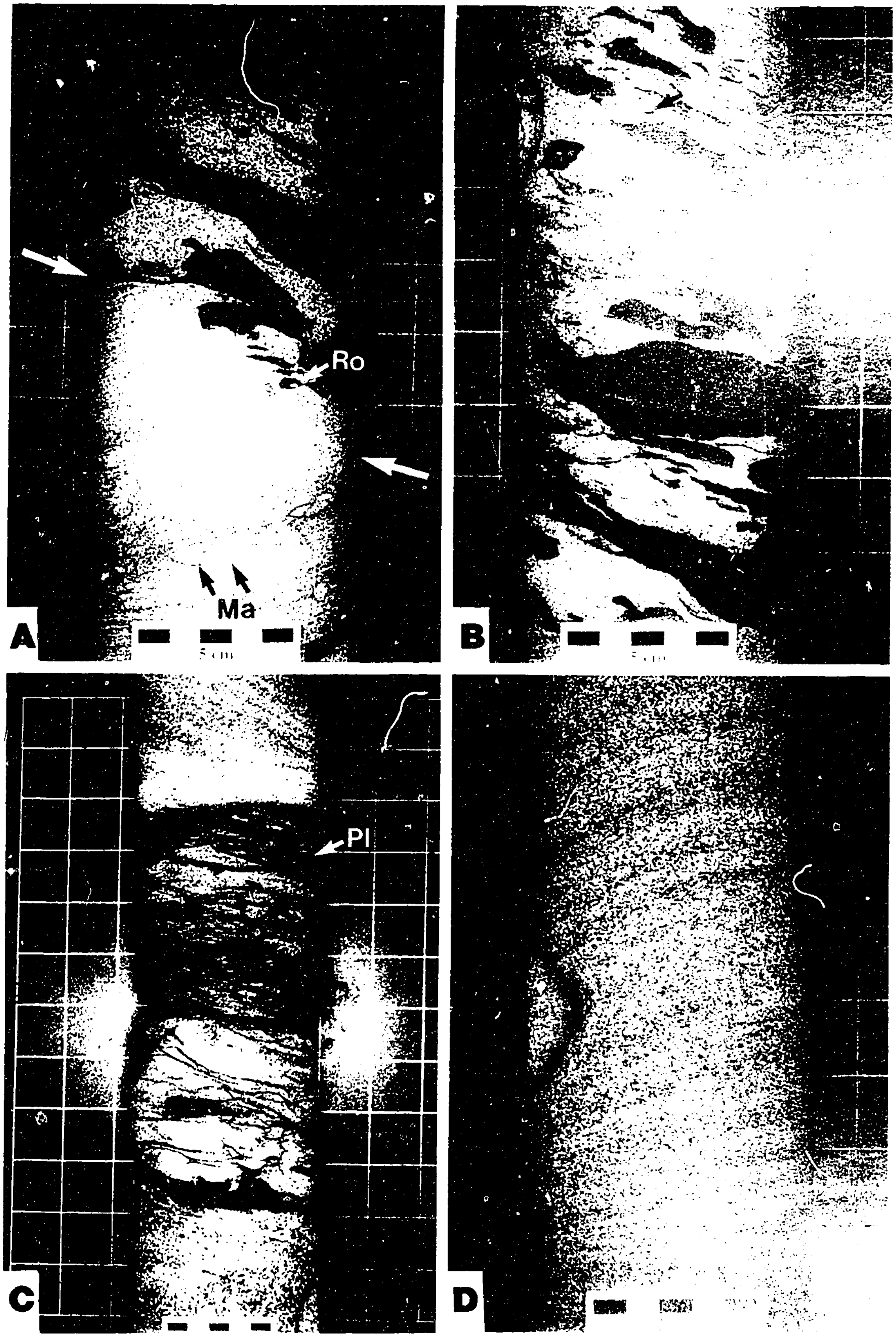
Figure 34. Facies photographs of FA5.

A) Erosive contact of the mudstone rip-up breccia with the underlying laminated to bioturbated sandstone facies in the 2-23-75-13w6 well (1767.5 m). The breccia cross-cuts *Macaronichnus* sp. (Ma) and laminations in the underlying facies. Small *Rosselia* fragments (Ro) are included in the rip-up breccia and indicate a marine origin for the unit.

B) Large tabular clasts are angular and indicate a proximal sediment source in the 2-23-75-13w6 well (1767.4 m). Small *Rosselia* fragments (small black arrow) make up the smaller size fraction of the breccia facies.

C) The trough cross-bedded sandstone facies locally contains abundant coal laminae in the 2-23-75-13w6 well (1767.0 m). Rare Planolites (Pl) are present and indicate an environmental stress.

D) The upper, trough cross-bedded sandstone facies of FA5 in the 2-23-75-13w6 well (1766.1 m).


A
Ro
Ma
B
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facies, truncating both stratification and trace fossils. Mudstone rip-up clasts are made up of two distinct size populations. The larger rip-up clasts are angular, tabular to sub-tabular in shape, and range from 1 to 8 cm in length. The smaller 'rip-ups' are allochthonous, cylindrical fragments of *Rosselia* and *Asterosoma*, approximately 0.5 x 1.0 cm in size. The amount of rip-up clasts decreases as the breccia grades upward into a coarse-grained sandstone with dispersed rare chert granules. An increase in matrix grain size from mU to cL accompanies the decrease in the abundance of rip-up clasts.

A medium-grained, coaly trough cross-bedded sandstone facies erosively overlies the breccia facies (Figure 34c,d). The sandstone facies is 3.4 m thick with abundant, large (2 cm long) coal clasts and dispersed coaly detritus in the basal 20 cm. Dispersed chert pebbles, rare coaly detritus, and mud laminae are present throughout the upper 3.2 m of the facies. Cross-beds are 5-15 cm thick and amalgamated into bedsets up to 1.5 m thick, which pass upward into current ripples. A massive, apparently structureless sandstone containing mudstone rip-up clasts directly overlies the ripple lamination. Rip-up clasts are tabular, angular, locally sideritized, and range from 1-5 cm long.

The uppermost facies in this association is the pebbly sandstone facies, which erosively caps the coaly trough cross-bedded sandstone facies. The pebbly sandstone facies is medium grained and fines upward from mL to vcU. Dispersed granules are abundant at the base and towards the top of the unit, and range in size from 0.5 to 1.0 cm in diameter. Coal clasts occur near the top of the sandstone, directly underlying the upper granule-rich zone. A thin shale layer occurs at the top of this facies association. No trace fossils were observed in this facies.

The remaining facies in FA5 are rare and do not occur in any observed successions. The organic-rich shale facies occurs in one cored well in the southwest portion of the study area. This facies is 30 cm thick, highly organic, and contains pyrite and subordinate sand and silt laminae (Figure 35a). Trace fossils are limited to *Planolites* (m), and *Teichichnus* (r) associated with sand and silt laminae. Root traces subtend from the organic-rich shale facies into the underlying bioturbated and low-angle planar laminated sandstone facies of FA4.

A pinstripe laminated shale and sandstone facies occurs in two wells. This facies is shale-dominated and made up of 0.5 to 4.0 cm thick beds of thinly laminated shale and sandstone with abundant pyrite, and rare pebbles (Figure 35b). Sandstone laminae are 1.0 to 2.0 cm thick, fine-grained, and typically occur as sharp-based current ripples. In one well this facies is 0.7 thick and sharply overlies a coaly, structureless sandstone of FA5. In the second well, the pinstripe laminated shale and sandstone facies is 1.7 m thick and overlies sharply the bioturbated and low-angle planar laminated sandstone facies of FA4.

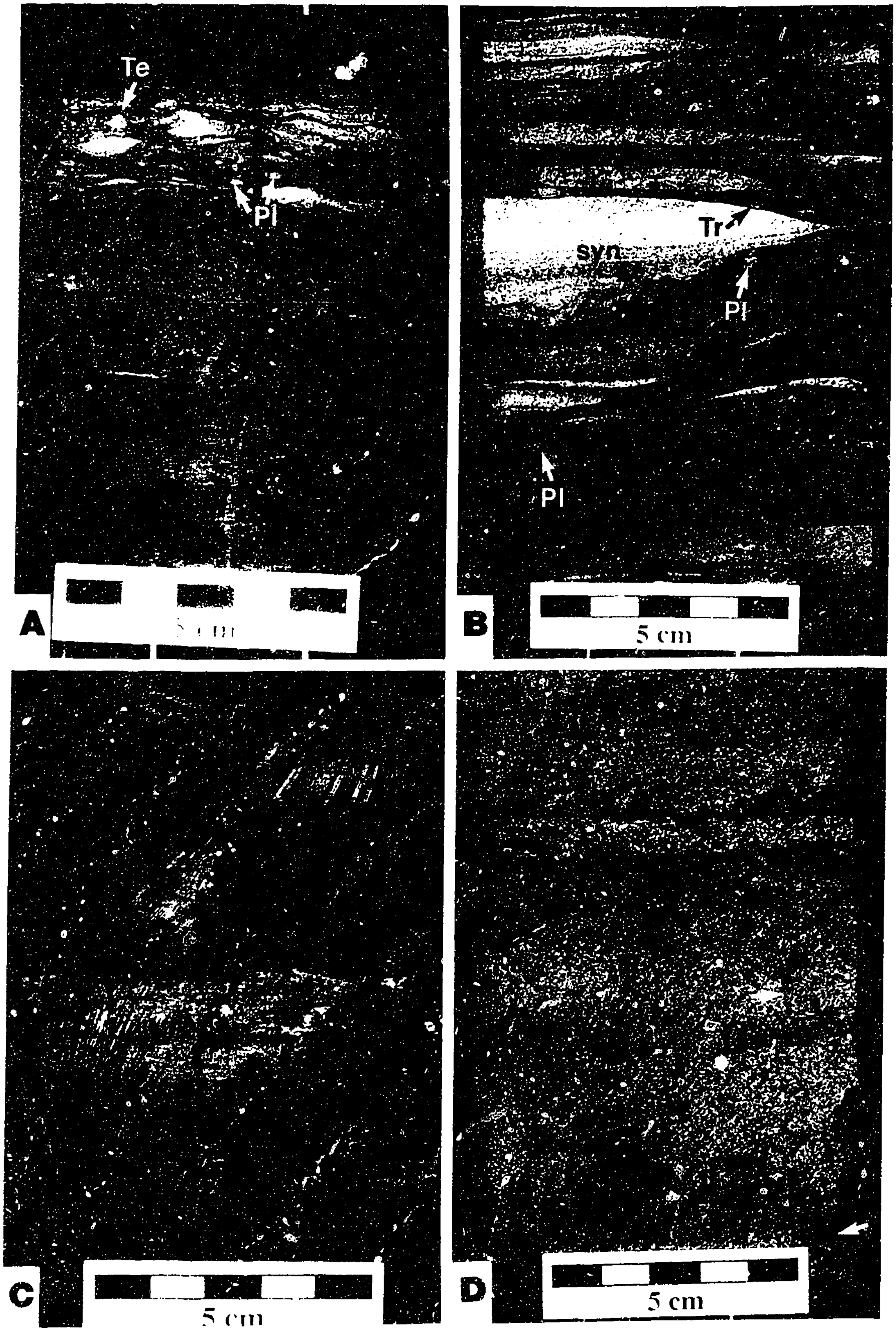
Figure 35. Facies photographs of FA5.

A) The organic-rich shale facies with rare silt in the 10-35-71-13w6 well (2198.2 m). *Teichnichnus* (Te) and *Planolites* (Pl) are diminutive and rare, indicative of a stressed environment.

B) The pinstripe laminated shale and sandstone facies in the 11-36-70-11w6 well (2107.1 m). Bioturbation is rare and consists of *Planolites* (Pl) and small *Terebellina* (Tr). The rare trace fossils and small size are indicative of an environmental stress. Synaeresis cracks (syn) are present and, combined with the stressed trace fossil assemblage, are interpreted to have been caused by fluctuating salinity.

C) Coal (vitrain) with silt laminae in the 11-36-70-11w6 well (2108.9 m).

D) The structureless, rooted sandstone in the 11-36-70-11w6 well (2107.9 m). Rhizoliths (white arrows) indicate the sandstone was deposited in a subaerial to very shallow marine environment.


Te
Pl
A
Tr
syn
Pl
Pl
B
5 cm
C
5 cm
D
5 cm

Sand-filled synaeresis cracks and contorted sandstone and shale beds are common in the pinstripe laminated shale and sandstone facies. Trace fossil abundances are typically rare to moderate in the shale beds, and absent in the sandstone beds. *Planolites* (m-r) dominates the suite with *Terebellina* (r) and *Chondrites* (r) in the thicker shale beds. *Planolites* are small in this facies (3 to 5 mm diameter) compared to typical forms observed throughout the Bluesky Formation (6 to 8 mm diameter). Trace fossils are representative of a deposit-feeding behaviour. Although the trace fossils are facies-crossing, and not indicative of a particular ichnofacies, the reduced size of *Planolites* and diminished abundances of other forms may indicate a stressed environment.

The coal facies occurs in two wells and sharply overlies the bioturbated and low-angle planar laminated sandstone facies. The coal is black, glassy (bright), brittle, vitrain, and typically thin, ranging from 20 to 60 cm in thickness (Figure 35c). It overlies the sandy facies of FA4, and is in turn sharply overlain by the disrupted sandstone facies and the structureless coaly sandstone facies of FA5.

A mU-fU, rooted, structureless, coaly sandstone comprised the structureless coaly sandstone facies (Figure 35d). This facies contains allochthonous coaly laminae at the base of the facies, and coaly detritus throughout the remainder of the facies. It also has carbon-lined root traces (rhizoliths) and rare thin mud laminae. It occurs in one well, is 1.3 m thick, and sharply overlies the coal facies. This facies is devoid of burrows, except for the upper few centimetres where *Palaeophycus* (r) is present. *Palaeophycus* is associated with biogenic activity related to the overlying pinstripe laminated shale and sandstone facies.

The rippled sandstone facies occurs in two wells, and sharply overlies the bioturbated and low-angle planar laminated sandstone facies of FA4, and the organic-rich shale facies of FA5. The rippled sandstone facies is fL-fU grained, contains subordinate amounts of coal detritus and wood fragments, and is rarely to abundantly bioturbated in thin zones (Figure 36a,b). This facies is 3.0 and >5.0 m thick in the two cored intervals. Current ripples are 1.0 to 4.0 cm thick with mm scale laminae, and occur throughout the facies. Low angle wavy laminations are locally present but rare. A thick zone in the upper portion of one well is massive (apparently structureless). Zones of bioturbation range from 10 to 50 cm thick and trace fossils are *Macaronichnus* sp. (m) and fugichnia (r). The trace fossil assemblage of the "*Macaronichnus* sp." represents a feeding behaviour.

The disrupted sandstone facies occurs in two wells and consists of fL-fU grained with subordinate amounts of coal detritus and shale laminae. Large zones of convoluted and disrupted bedding and laminae cross-cut the primary sedimentary structures (Figure 36c). Disrupted bedsets range from 15-20 cm thick. It is rarely to moderately bioturbated in thin zones 10 to 50 cm thick. Trace fossils consist of *Macaronichnus* sp. and fugichnia.

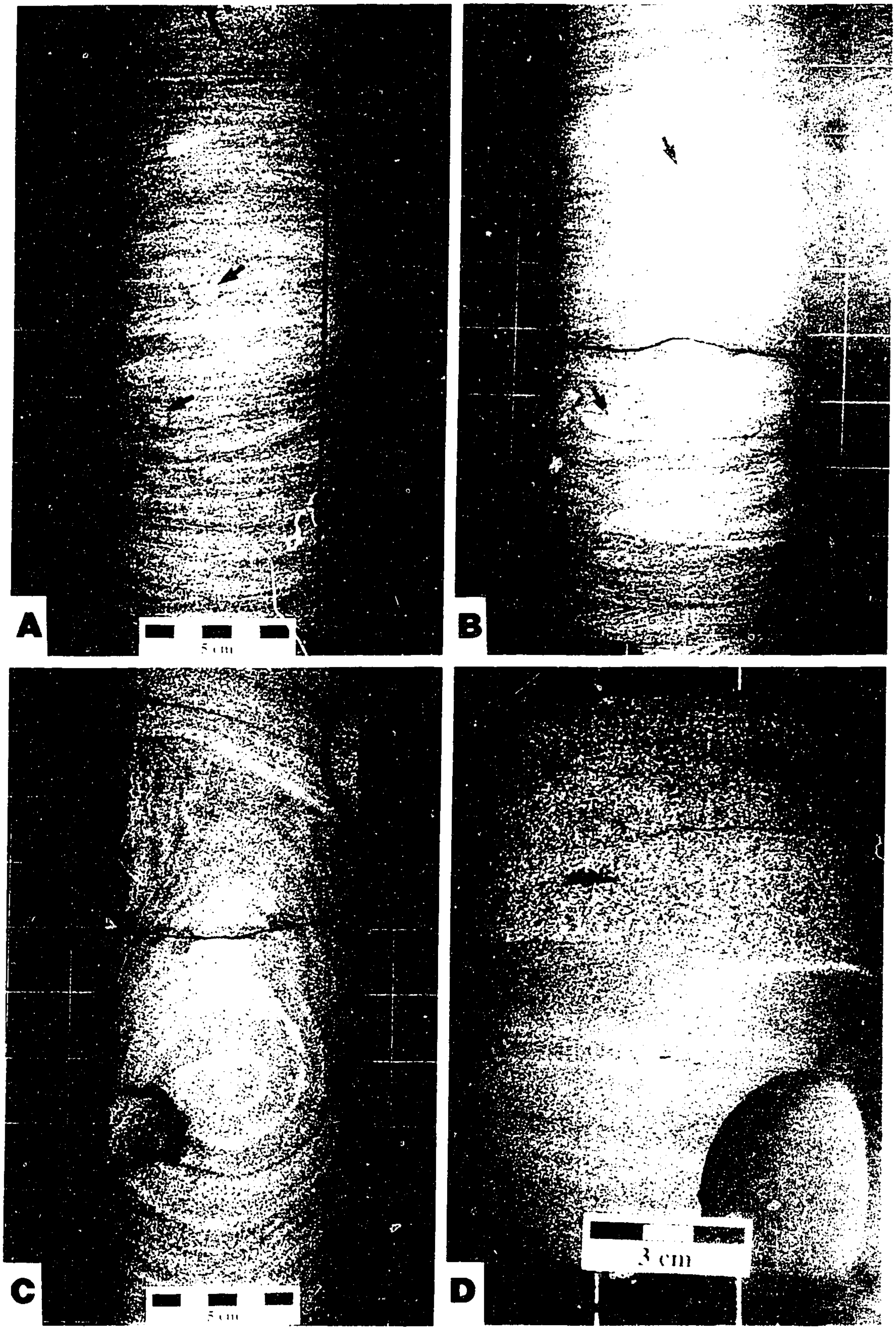
Figure 36. Facies photographs of FA5.

A) The rippled sandstone facies in the 6-6-72-12w6 well (2176.0 m). *Macaronichnus* sp. (black arrows) and the ripples indicate a moderate energy marine environment.

B) The rippled sandstone facies in the in the 6-6-72-12w6 well (2176.4 m). Robust *Macaronichnus* sp. (black arrows) are moderate in abundance.

C) The disrupted sandstone facies with large convolute structures in the 10-34-70-13w6 well (2361.7 m). These structures are interpreted to be dewatering structures.

D) The 'salt and pepper' sandstone facies consists of a medium-grained, trough cross-bedded sandstone with abundant dark-grained, detrital mafic material. The lower contact is erosive in the 11-18-74-13w6 well (1952.8 m).


A
5 cm
B
C
5 cm
D
3 cm

This facies is >2.5 and 3.0 m thick in the two cored intervals. It sharply overlies the coal facies and gradationally overlies the rippled sandstone facies.

The salt and pepper sandstone facies occurs in the 11-18 well in the northwest portion of the study area. The salt and pepper sandstone facies comprises mU quartzose and dark-grained (detrital mafic material) sandstone with abundant coal, and is trough cross-bedded (Figure 36d). The 'salt and pepper' appearance is due to abundant mafic minerals which are anomalous in other facies within the study area. It is locally massive and apparently structureless over most of the facies, but has some trough cross-bedding in the lower portion of the unit. No trace fossils are present in this facies. This facies occurs at the top of the cored interval, is over 1.8 m thick, and erosively overlies a laminated sandstone of FA3.

Environmental Implications of FA5

Facies Association 5 displays a large variation in facies and several incomplete successions were observed. It consists of ten facies; mudstone rip-up breccia, coaly trough cross-bedded sandstone, pebbly sandstone, organic-rich shale, pinstripe laminated shale and sandstone, coal, structureless coaly sandstone, rippled sandstone, disrupted sandstone, and a salt and pepper sandstone.

The first vertical succession of FA5 consists of a mudstone rip-up breccia overlain by coaly sandstone, trough cross-bedded to structureless sandstone, and capped by pebbly coaly sandstone. This succession erosively overlies the FA2 laminated to burrowed sandstone facies. The large angular rip-up clasts are interpreted to have been derived from nearby shales. The smaller 'rip-up' clasts which are remnants of *Rosselia* and *Asterosoma* indicate a marine origin for the clasts. Trace fossils of this type were observed *in situ* in the lower-middle shoreface deposits of FA2, suggesting deep excavation into earlier Bluesky deposits. McCubbin (1981) states that the depth of deep tidal channels may locally surpass the thickness of shoreface deposits, and cut into the underlying offshore facies. The overlying coaly trough cross-bedded sandstone facies indicates erosion and transportation of terrestrially derived deposits at the time of deposition. The trough cross-bedding shows a largely unidirectional orientation, and indicates a high-energy environment with a relatively stable flow direction. Mudstone rip-up clasts also occur near the top of this facies, and indicate recurring erosion of nearby shales.

The rippled sandstone facies overlies the trough cross-bedded sandstone facies of FA4 and the organic-rich shale facies. The rippled sandstone facies and the organic shale facies are locally overlain by the disrupted sandstone facies. The stressed shale facies is interstratified with the massive sandstone facies and represents a third vertical succession present in FA5. Each remaining facies will be individually interpreted since successions consist of many facies and are variable.

The organic-rich shale facies contains abundant organic matter and coaly detritus, and is associated with root traces. Deposition of very fine (shale) and hydraulically light (coal) material occurred from suspension, and the thin silt and sand laminae record the effects of episodic high energy events. Pyrite indicates the presence of reducing conditions. This facies is interpreted to be proximal to the shoreline, and represents the upper portion of a back barrier complex, interpreted as a marsh environment.

The pinstripe laminated shale and sandstone facies sharply overlies the structureless coaly sandstone facies, and the bioturbated and low-angle planar laminated sandstone facies. It is interpreted to have been deposited in a low energy environment. The shale portion of the facies deposited from suspension in a low energy environment. The fine-grained sand laminae were reworked from nearby sand bodies into thin current ripples and are interpreted to be produced by wind-waves. Sand-filled synaeresis cracks and contorted sandstone and shale beds are common. Trace fossil abundances are typically rare to moderate in the shale beds, and absent in the sandstone beds. Synaeresis cracks, and the reduced size and diversity of ichnogenera are interpreted to be the result of fluctuating salinity. This facies is interpreted to be the result of deposition in a stressed lagoonal environment.

The coal facies sharply overlies the bioturbated and low-angle planar laminated sandstone facies, and the trough cross-bedded sandstone facies. In turn it is sharply overlain by the disrupted sandstone facies, and the structureless coaly sandstone facies. The thin coal facies is interpreted to be the result of deposition of organic material in a marsh.

The structureless coaly sandstone facies sharply overlies the coal facies, and is sharply overlain by a pinstripe laminated shale and sandstone. Abundant coaly detritus and coal laminae indicate a terrestrial source nearby, and carbon-lined rhizoliths indicate a subareal setting. This facies is interpreted as a washover fan deposit.

The rippled sandstone facies sharply overlies the bioturbated and low-angle planar laminated sandstone, the organic-rich shale, and the pebbly coaly sandstone facies. Current ripples occur throughout this facies, and low angle wavy laminations are locally present. The trace fossil assemblage is indicative of a deposit-feeding behaviour in a moderate energy marine setting. The stratigraphic position of this facies places it in a shallow subtidal to intertidal zone. This nearshore environment is interpreted as a flood tidal delta.

The deformed sandstone facies is dominated by water escape structures indicating that this facies was rapidly deposited, and loaded to cause the plastic deformation of watersaturated sediments. Undisturbed sedimentary structures and trace fossils are similar to those of the rippled sandstone facies. This facies is interpreted as being deposited in a flood tidal delta.

The 'salt and pepper' sandstone facies is interpreted to be a transgressive upper shoreface deposit. This facies comprises a trough cross-bedded, mU sandstone with abundant dark-grained detrital mafic material and coaly detritus. The relatively coarse grain size and sedimentary structures are consistent with upper shoreface deposition. The mafic material and coaly detritus may be indicative of a nearby back barrier sediment source.

FA5 Summary

Facies Association 5 displays a large variation in facies in several incomplete successions. Facies Association 5 is interpreted to reflect back barrier facies in the Bluesky Formation. The succession of the first three facies is interpreted to represent a tidal channel incised into lower to middle shoreface deposits. Lack of *in situ* burrows within the tidal channel deposits indicate a stress due to salinity or a high energy channelized flow. The mudstone breccia indicates a local derivation as large angular components were not transported far from their source.

The overlying back barrier deposits display a variety of settings including flood tidal delta, lagoon, washover fans, marsh, and swamp. The salt and pepper sandstone facies is interpreted to indicate a transgressive upper shoreface deposit derived from nearby back barrier sediments.

IV DEPOSITIONAL MODEL AND FACIES SUCCESSIONS

4.1 Introduction

The "classical" method for interpreting depositional environments is to compare ancient deposits with analogous modern environments. In clastic studies these environmental reconstructions have often been limited to comparison of lithology and bedforms. In this study, reconstructions of Bluesky Formation environments have been strengthened by the addition of ichnological observations.

The second purpose of this study was to use paleoenvironmental interpretations, combined with subsurface mapping, to determine sequence stratigraphic patterns and establish a depositional model for the Bluesky Formation.

4.2 Depositional Environments and Model

Depositional settings of the Bluesky Formation range from offshore to backshore (Figure 37). The typical vertical succession is a coarsening upward cycle from offshore shales to shoreface sandstones. Lateral relationships indicate that this coarsening upward cycle is wedge-shaped and thins to the northeast (Figure 38). The sandbody trends northwest-southeast (Figure 39). A complete offshore to upper shoreface cycle is preserved in the western portion of the study area (Figure 38). The facies associations present are dominated by offshore to shoreface transitional deposits in the northeast. Along this cross-section, the Bluesky Formation thins from 26 metres to 6 metres. Along strike, facies associations vary in thickness but are dominated by sandstones of the lower to middle shoreface (Figure 39). The tidal channel facies are present in the northwest, and were incised into laminated to bioturbated sandstones. A similar wedge-shaped geometry continues to the southeast (Figures 40, 41).

The base of the Bluesky Formation consists of a transgressive unit that was deposited in an offshore setting. These facies typically fine upward from a muddy sandstone to a silty shale facies. This is overlain by sandy shale and interbedded sandstone and shale of the offshore-shoreface transitional setting. This is overlain by the erosively based laminated to bioturbated sandstone (Figure 19) and laminated sandstone facies (Figure 25) of the lower to middle shoreface. Lower to middle shoreface deposits vary in the degree of storm influence, but largely consist of amalgamated storm deposits. Upper shoreface deposits are common in the southern and western portions of the study area (Figure 30), and overlie the amalgamated storm deposits of the lower to middle shoreface. These are locally overlain by the variable facies of the back barrier setting (Figure 30). Facies include washover fan, flood tidal delta, tidal channel, marsh, and lagoon facies.

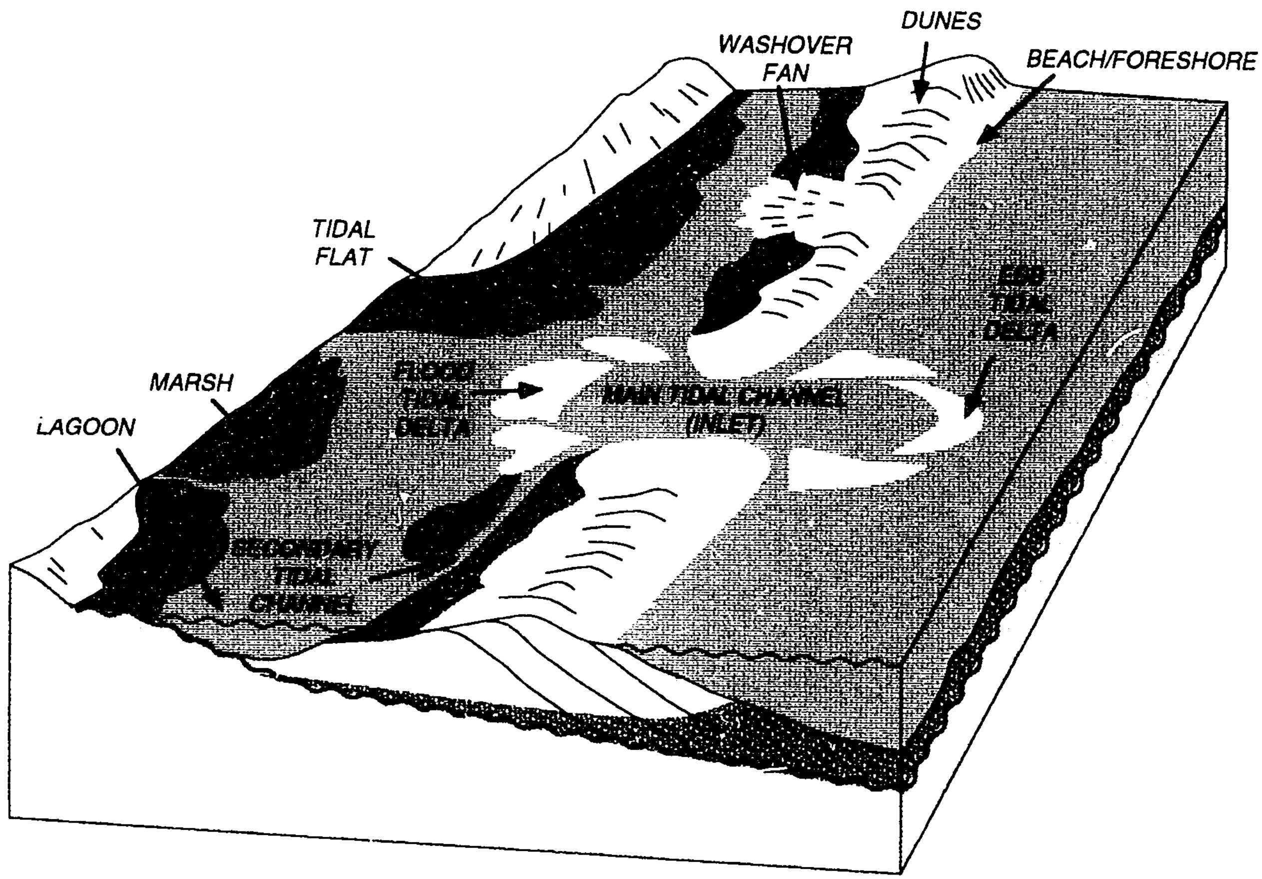
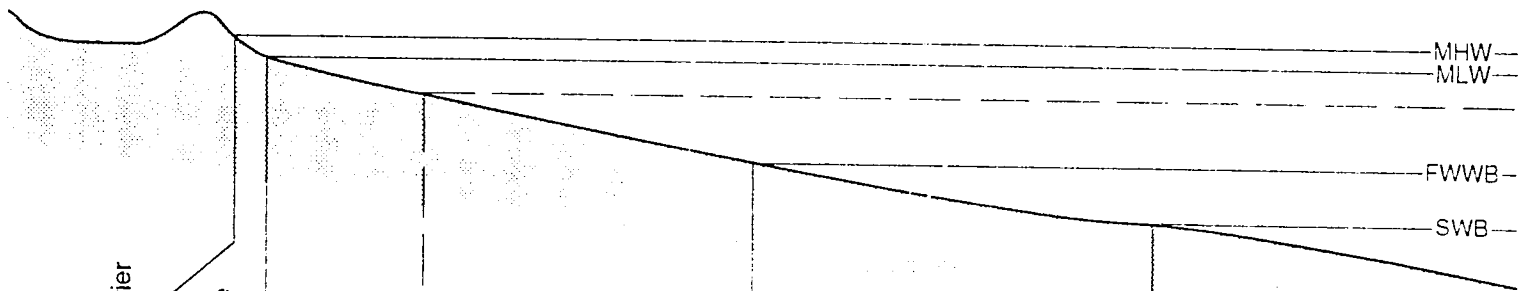


Figure 37. Schematic diagram of the depositional environments of the Bluesky Formation (modified after Reinson, 1984).

This variability is due to erosive removal and reworking during the ensuing transgression. Erosion has also locally removed upper shoreface deposits and resulted in the capping FA 1 deposits. Lithologies, sedimentary structures, and trace fossil assemblages have been characterized for depositional settings in the Bluesky Formation (Figure 42).

Sediments that comprise the shoreface overlie shales of a marine origin, and are in turn overlain by marine shales of the Wilrich Member. The encasing shales indicate that this succession was deposited in a marine setting during an overall rise in sea-level. The coarsening upward succession corresponds to the progradation of shoreface cycles. The vertical facies succession is similar to progradational barrier island sequences described by McCubbin (1981) and Reinson (1984) (Figure 43). Purely transgressive barrier island successions lack the shoreface and offshore deposits observed in the Bluesky Formation. These depositional models coarsen upward from lagoon through other back barrier deposits and contrast sharply with transgressive barrier island sequences. Offshore and shoreface facies are not preserved in transgressive barrier island systems as they are reworked as sea-level gradually rises. Deposition is interpreted to have occurred during a relative sea-level fall during the transgression of the Moosebar Sea (Figure 44).

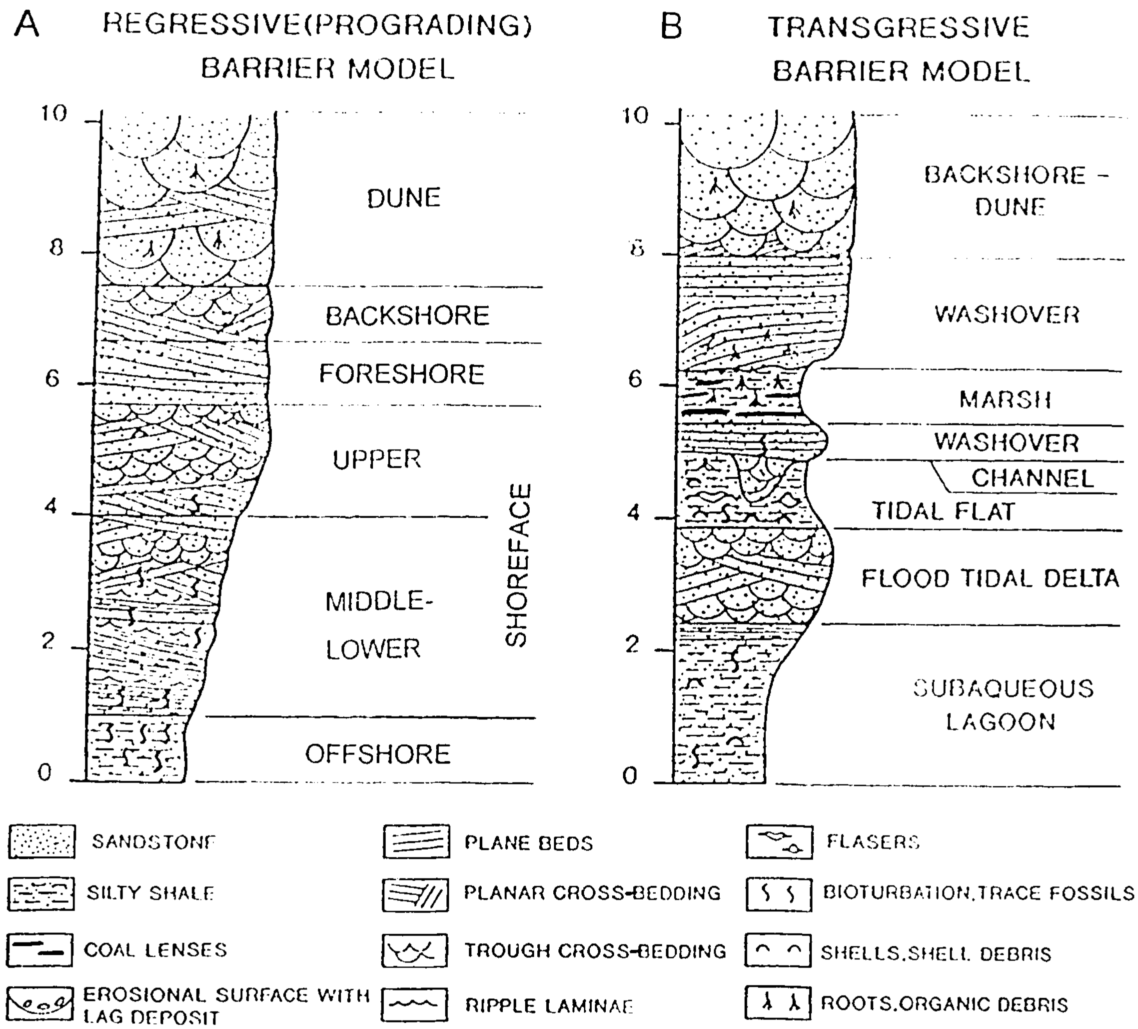
Figure 42. Shoreface model for the storm-influenced to storm-dominated Bluesky Formation in the Sinclair area. Offshore sediments are shale-dominated and thoroughly bioturbated with trace fossils representing the distal *Cruziana* assemblage. The offshore-shoreface transitional zone consists of variably bioturbated, interbedded sandstone and shale with a diverse *Cruziana* to normal *Cruziana* assemblage. The lower to middle shoreface is made up largely of wavy parallel laminated fine-grained sandstone. The laminated sandstone facies lacks bioturbation and represents a storm-dominated setting. The laminated to bioturbated includes bioturbation by a "*Macaronichnus* sp." assemblage (asterisk) and was deposited in a storm-influenced setting. Upper shoreface deposits consist of fine- to medium-grained, trough cross-bedded sandstone and lack evidence of biogenic activity. Fine sandstone with low angle planar cross-stratification and a *Macaronichnus* trace fossil assemblage are characteristic of a foreshore setting. The back barrier facies in this study are variable.



	Back Barrier	Foreshore	Upper Shoreface	Lower to Middle Shoreface	Offshore-Shoreface Transition	Offshore
Texture	variable	f SS	f to m sandstone	f to vf sandstone	f to vf sand and shale	shale w. variable amounts of sand and silt
Structures	variable	low angle planar strat.	planar tabular and trough cross bedding	wavy parallel lamination w. rare ripple lamination	parallel laminated to bioturbated w. rare ripple lamination	bioturbated w. rare remnant tempestites
Ichnology	variable	*Macaronichnus* assemblage		* *Macaronichnus* sp. assemblage * mixed *Skolithos*-*Cruziana* assemblage	diverse *Cruziana* assemblage *Cruziana* Ichnofacies	distal *Cruziana* assemblage
Feeding Strategy	deposit feeding (epigranular)		suspension feeding (includes tube dwelling passive carnivores)		deposit feeding	grazing

Figure 42. Shoreface model for the storm-influenced to storm-dominated Bluesky Formation in the Sinclair area.

Figure 43. Facies profiles for progradational and transgressive barrier island facies. The vertical facies stacking pattern for the Bluesky Formation is similar to the progradational model (A). The preservation potential of the upper shoreface and back barrier facies is relatively low compared to that of the offshore to middle shoreface.



modified after Reinson, 1994

Figure 44. Depositional model of a backstepped barrier island facies produced during a stillstand in an overall transgression. Relative sea-level falls are interpreted to have been caused by an influx of sediment from the Cordillera to the west. At time 1, the barrier island overlies the Gething Formation and progrades basinward. The lower contact between the Gething and the Bluesky formations is an amalgamated flooding surface and sequence boundary (FS/SB). The depocentre is shifted landward with a relative rise in sea-level. A new barrier island succession is produced and portions of the previous barrier island still above fairweather wave base are reworked (degraded). A new FS/SB is generated as well as a flooding surface across the top of the reworked barrier island.

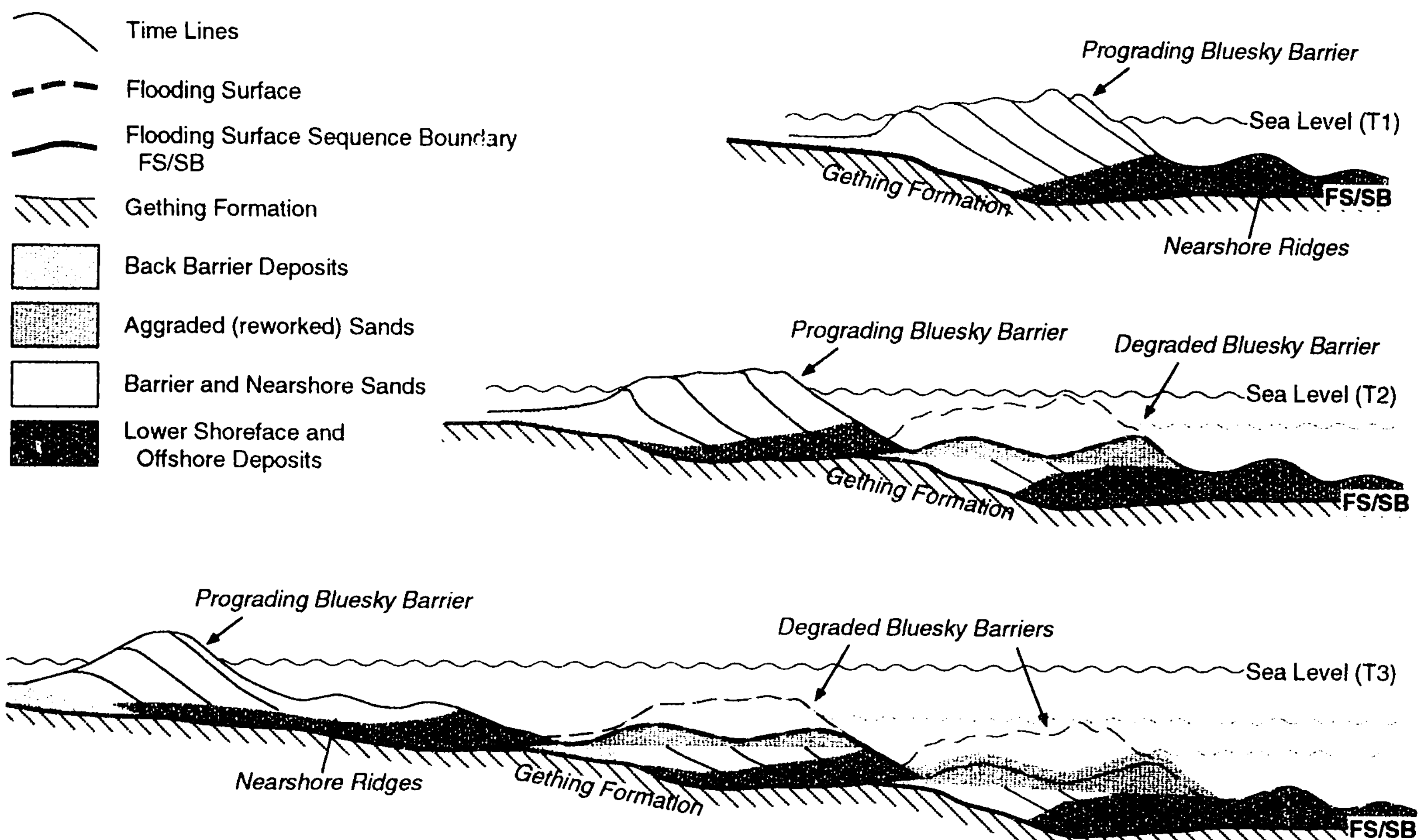


Figure 44. Depositional model of a backstepped barrier island (modified after Rine *et al.*, 1986).

V CONCLUSIONS

This study illustrates the facies and facies associations of the early Albian Bluesky Formation in west-central Alberta. The combination of ichnological and sedimentological data has yielded a detailed model of the depositional environments of the Bluesky Formation within the study area. This can be used for the interpretation of other Bluesky shoreface successions, as well as storm-dominated clastic successions elsewhere.

The Bluesky Formation in the Sinclair field area consists of single barrier island shoreface cycle. This complex is made up of a retrogradational shoreface succession and includes diverse environments from offshore to back barrier.

Difficulty in differentiating Gething and Bluesky deposits stems from their similar depositional conditions. Additionally, Bluesky FA1 deposits overlie a variety of Gething deposits due to the locally erosive nature of the lower contact. Locally, the transgressive deposits are associated with a palimpsest assemblage or a *Glossifungites* surface. This surface is characterized by a glauconitic, pebbly sandstone sharply overlying a 'clean' quartz sandstone. Elsewhere the contact is erosional, but lacks evidence indicative of a hiatus.

The overall coarsening upward shoreface cycle displays a variety of lower to middle shoreface deposits. The laminated to bioturbated sandstone facies are interpreted to have been rapidly deposited in a moderate energy setting influenced by frequent storms. The resident trace fossil suite is dominated by a "*Macaronichnus* sp." assemblage which is indicative of feeding and dwelling behaviours developed in a moderate energy setting. Amalgamated deposits of the laminated sandstone facies are interpreted to have been deposited by more frequent storms. The difference between the laminated to bioturbated sandstone facies and the laminated sandstone facies lies in the presence of a burrowed upper portion of individual sandstone beds. This may be due to highly erosive events removing evidence of biogenic activity, or the frequent storm activity preventing the substrate from being colonized. Rare ripple stratification and fugichnia indicate that the substrate was likely not colonized.

The overlying upper shoreface lag and upper shoreface deposits typically lack biogenic overprinting due to the stressful high energy conditions and shifting substrate in these zones. Trough cross-bedding is the typical physical sedimentary structure present in this setting. Trace fossils are consequently rare in this zone, and sparse fugichnia support interpretations of high energy conditions and rapid sedimentation rates. The foreshore zone is typified by a swash-stratified and or bioturbated zone. The swash stratification, although characteristic, is not always discernible, and the associated *Macaronichnus* assemblage is locally the lone indicator of the depositional setting. It specifically indicates a high energy, non-cohesive, shifting sandy substrate.

The trace fossils observed in the back barrier deposits of the Bluesky Formation are useful in the interpretation of many of the various facies. The transported 'rip-up' clasts, composed of *Rosselia*, found in the breccia facies testify to the marine origin of these sediments. Likewise, the rippled sandstone facies locally has abundance numbers of *Macaronichnus* sp. and is indicative of a marine influence. Rhizoliths, combined with sedimentary context, indicate that the structureless coaly sandstone facies was deposited as a washover fan. that remained exposed after the storm conditions ceased.

The Bluesky Formation in the Sinclair field area is a stratigraphically complex unit that was part of a barrier island complex. This complex was deposited in a series of brief relative sea-level falls during an overall transgression. Some facies present in this study could have been similarly interpreted without the information available from trace fossils. But, when the lithological and sedimentological evidence is combined with the information available from trace fossils, facies and associated successions may be more fully deciphered giving a superior reconstruction of the depositional setting.

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APPENDIX A

Core Logs

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
- pebbly sandstone
- conglomerate
- breccia
- Lost Core

CONTACTS

- Sharp
- Undulating
- Bioturbated
- Uncertain

PHYSICAL STRUCTURES

- Current Ripples
- Climbing Ripples
- Oscillatory Ripples
- Ripple (undifferentiated)
- Dewatering Structure
- Bioturbate Texture
- Convolute Bedding
- Graded Bedding
- Reverse Graded Bedding
- Trough Cross-strat.
- Planar Tabular Bedding
- High Angle Tabular Bedding
- Flaser Bedding
- Low Angle Tabular Bedding
- Low angle truncation
- Gutter cast
- TTT - Synaeresis Cracks
- Br - Brown
- Wavy Parallel Bedding
- HCS/SCS/QPL
- Hummocky Cross-strat
- SCS
- Scour
- Fault
- Slickensides
- Bk - Black
- Gr - Grey

LITHOLOGIC ACCESSORIES

- Sand Lamina
- Pebbles/Granules
- Organic Shale Lamina
- Sid - Siderite
- Gl - Glauconitic
- Silt Lamina
- Coal Lamina
- Rip Up Clasts
- Shell Fragments
- Wd - Wood Fragments
- Shale Lamina
- Breccia Horizon
- Py - Pyrite
- Coal Fragments

ICHNOFOSSILS

- *Anconichnus*
- *Arenicolites*
- *Asterosoma*
- *Bergaueria*
- *Chondrites*
- *Conichnus*
- *Cylindrichnus*
- *Diplocraterion*
- fugichnia (escape trace)
- *Helminthopsis*
- *Macaronichnus*
- *Macaronichnus* sp
- *Monocraterion*
- *Ophiomorpha*
- *Palaeophycus*
- *Planolites*
- *Rhizocorallium*
- rhizolith (rootlets)
- *Rosselia*
- *Skolithos*
- *Teichichnus*
- *Terebellina*
- *Thalassinoides*
- *Zoophycos*

BIOTURBATION INTENSITY

- Abundant
- Common
- Moderate
- Rare
- Absent

FOSSILS

- Brachiopods

CanHunter et al Elmsworth

10-08-070-09w6

Date logged: May 28, 1995

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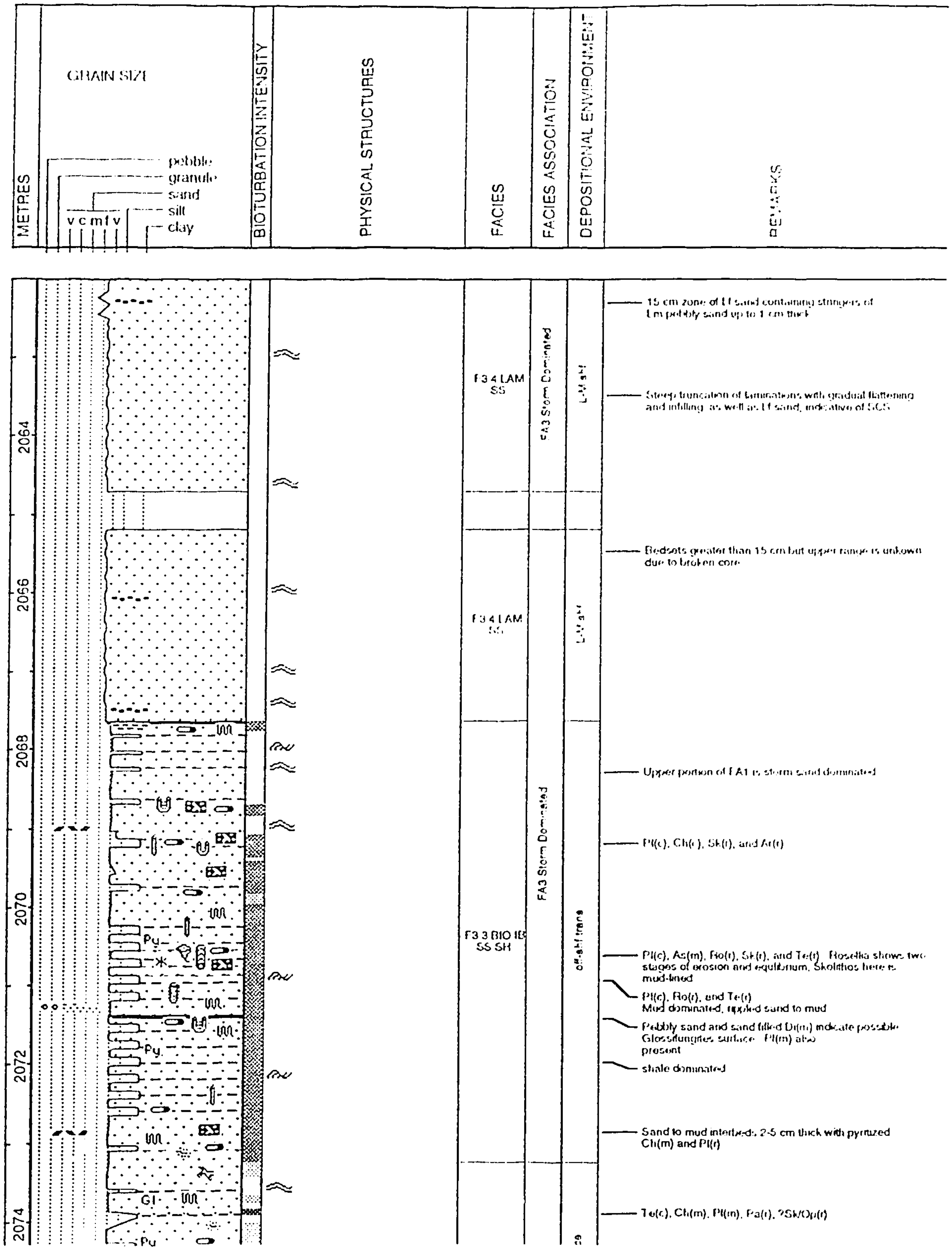

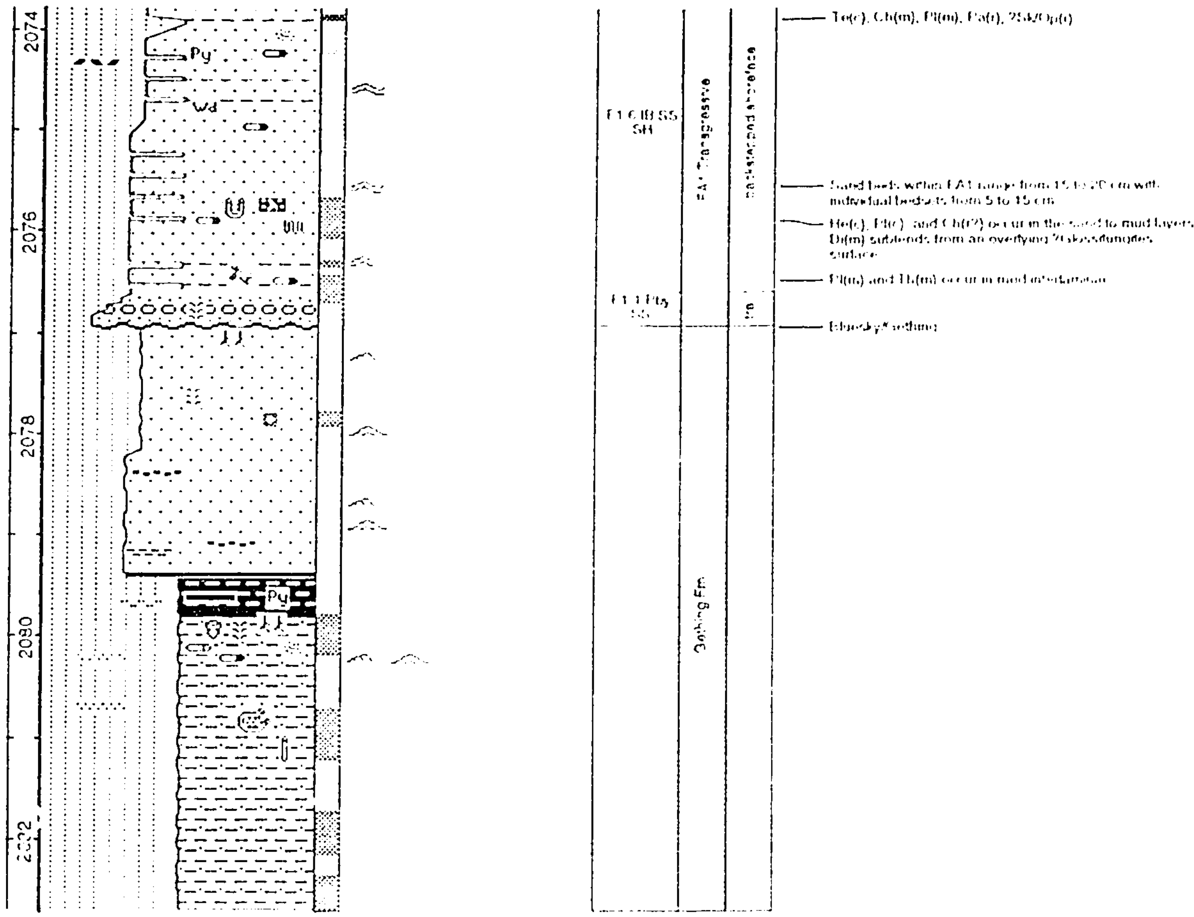

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CanHunter-Texcan Elm
11-36-070-11w6

Date logged: May 29, 1995

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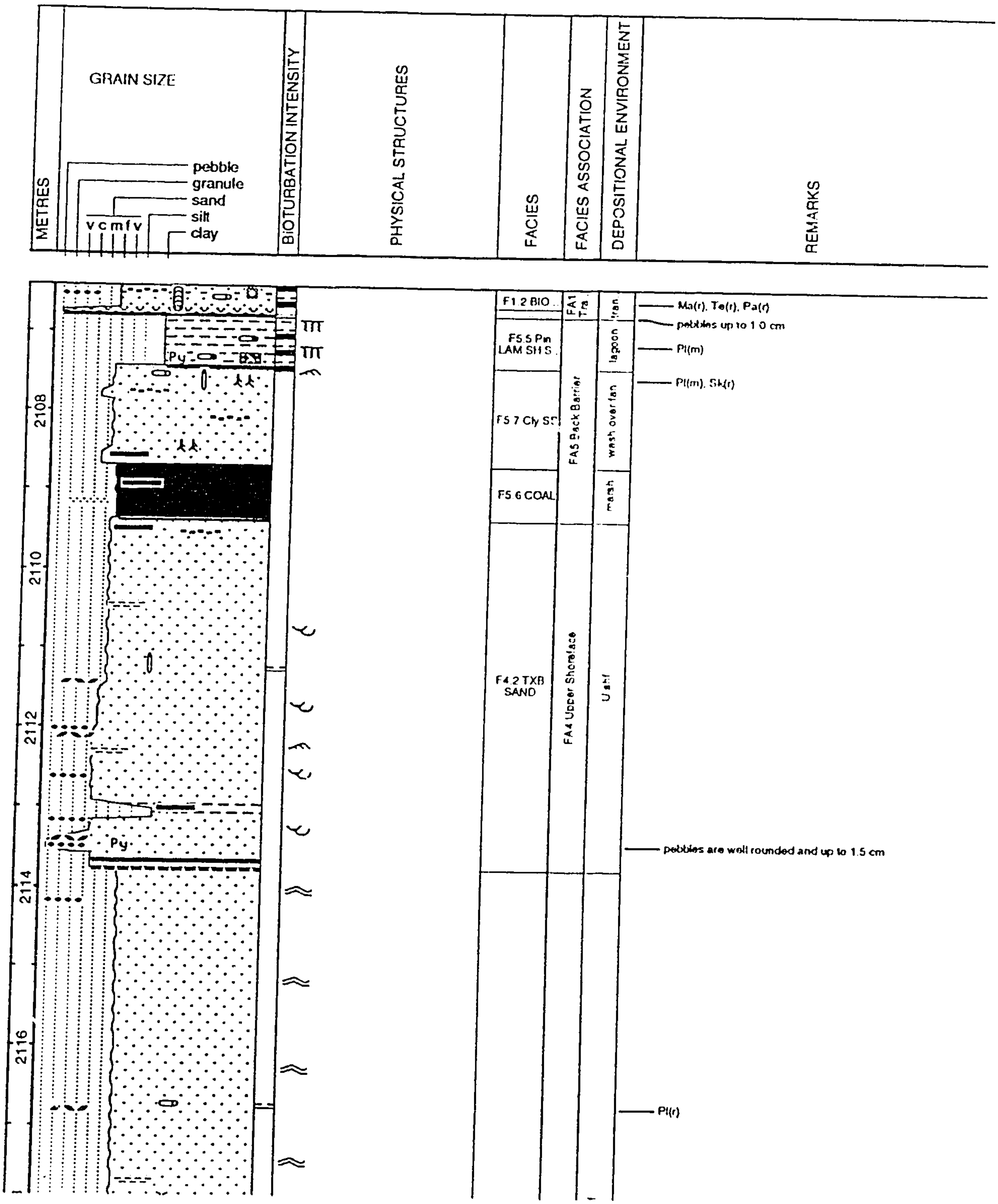

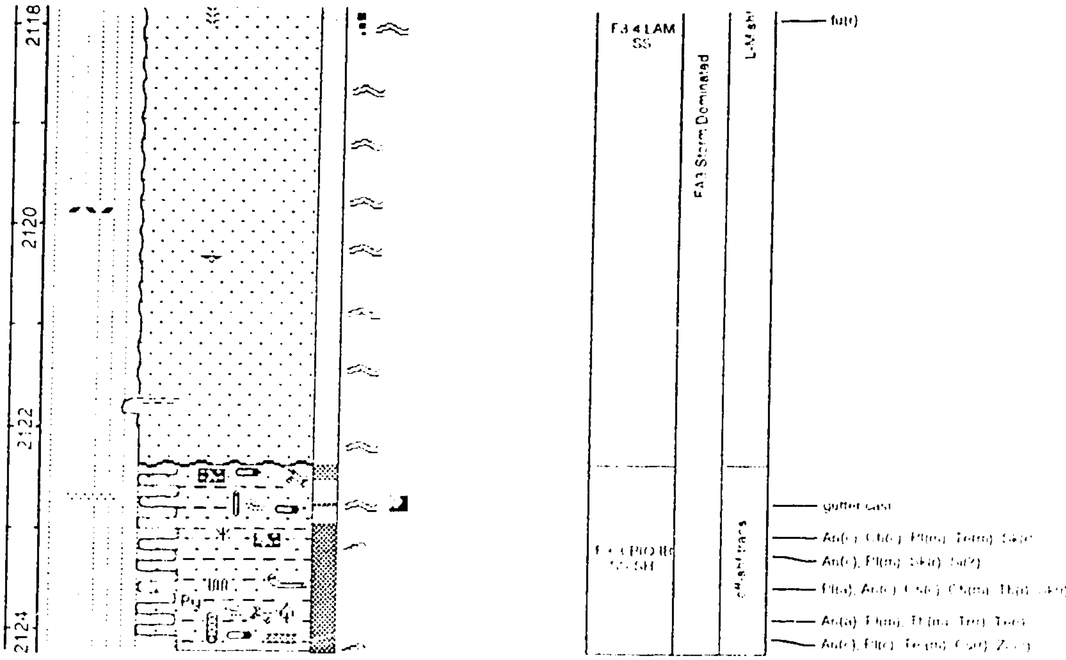

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CanHunter Texaco

10-34-070-13w6

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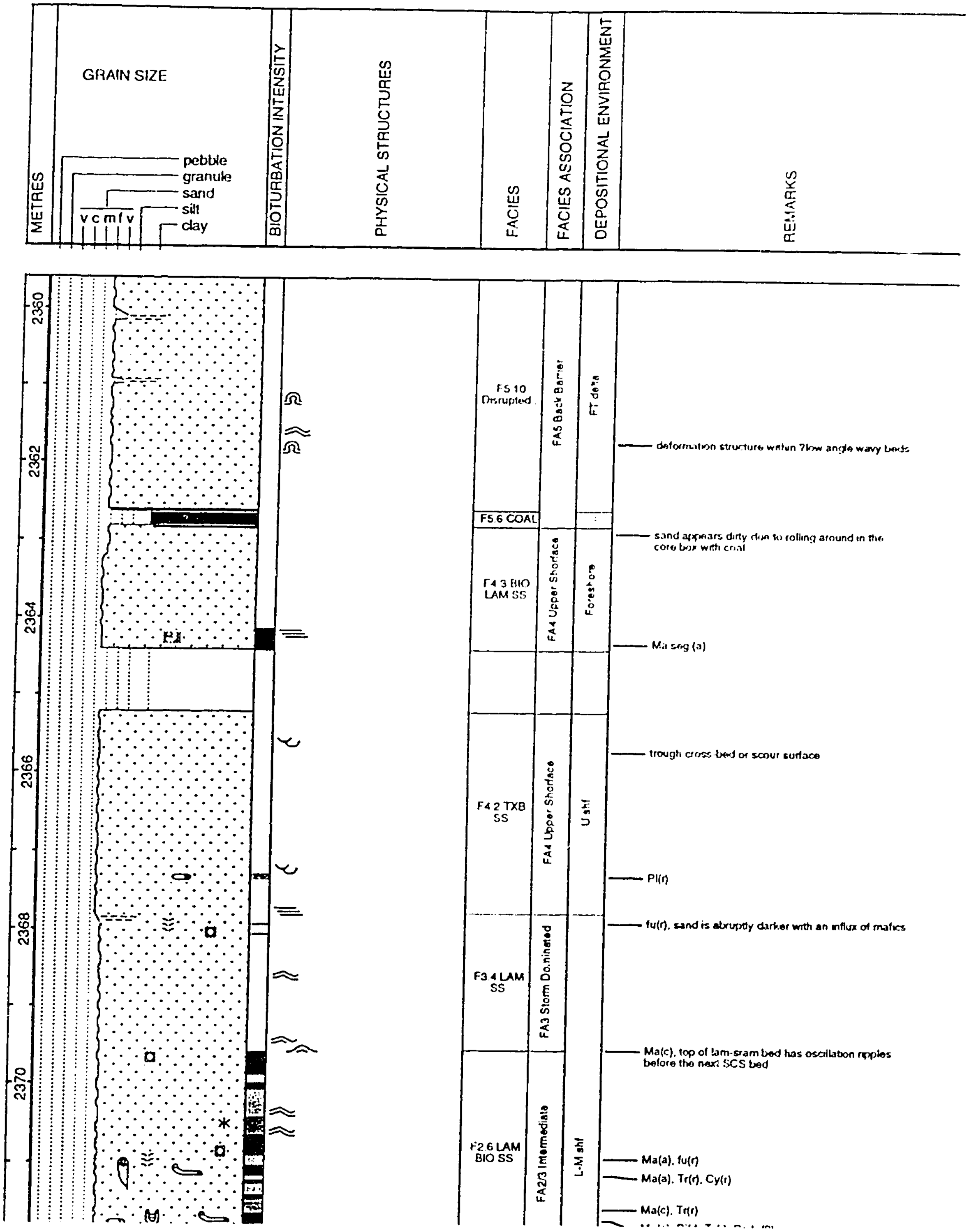

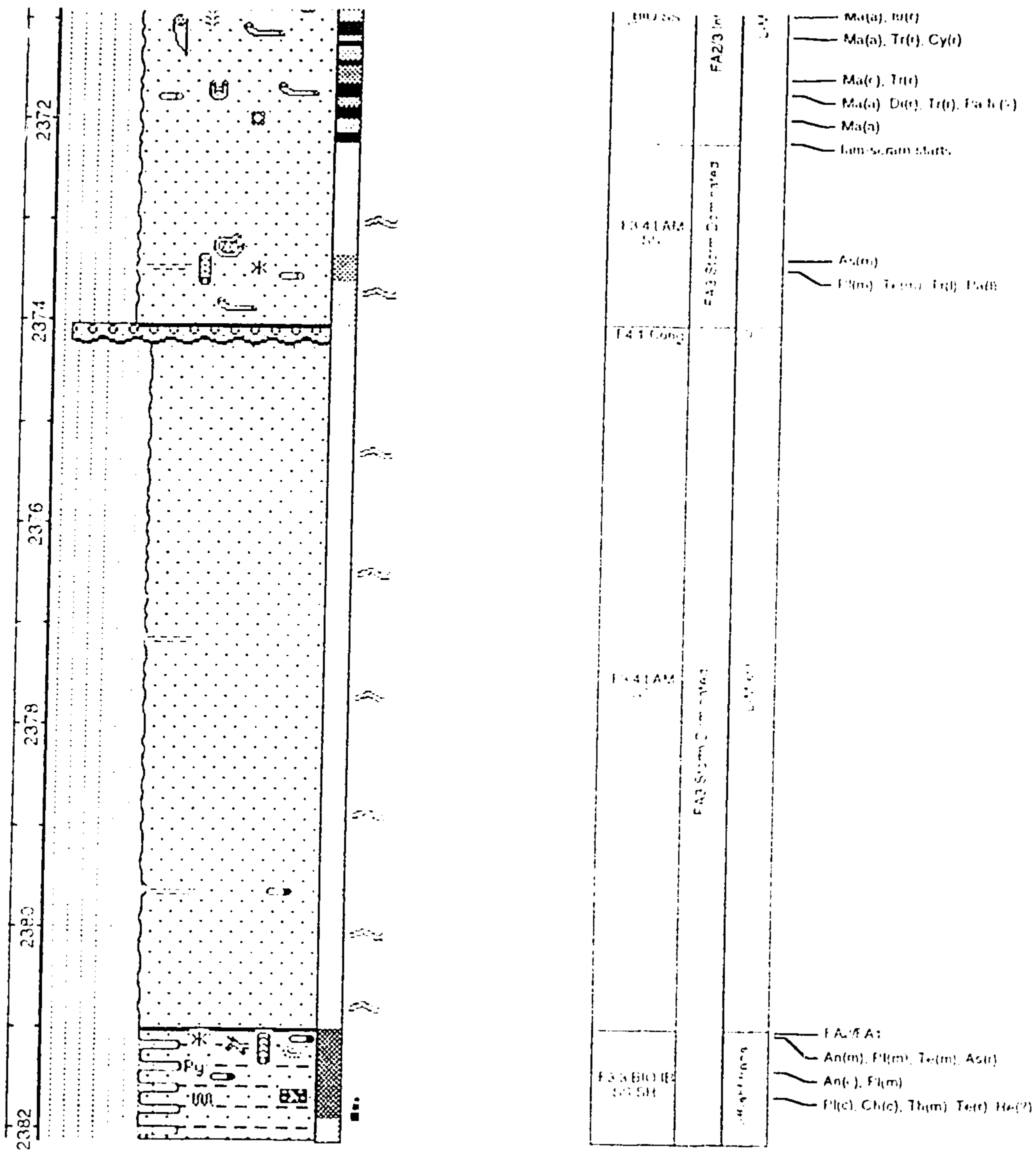

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CanHunter Tex
10-35-071-13w6

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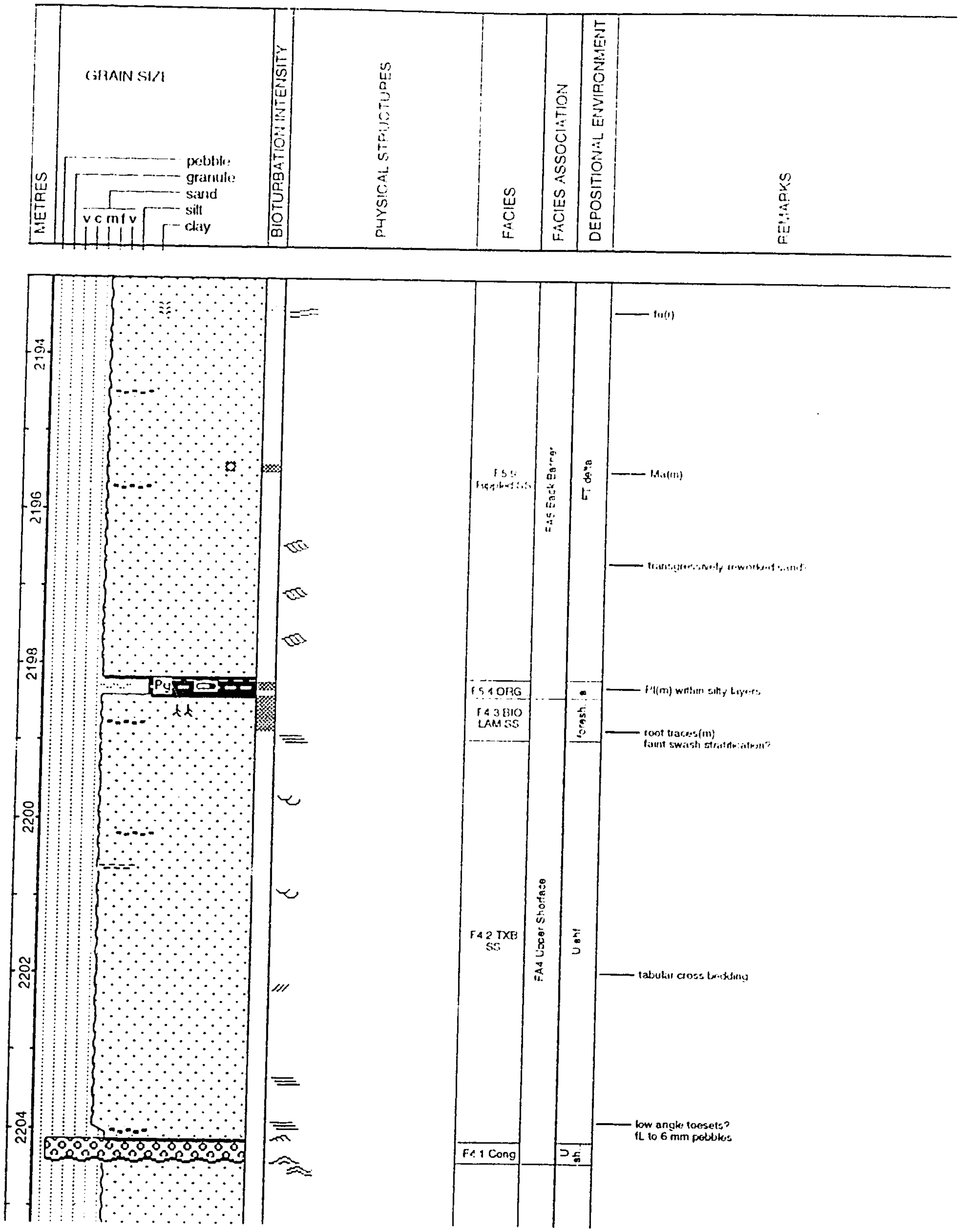

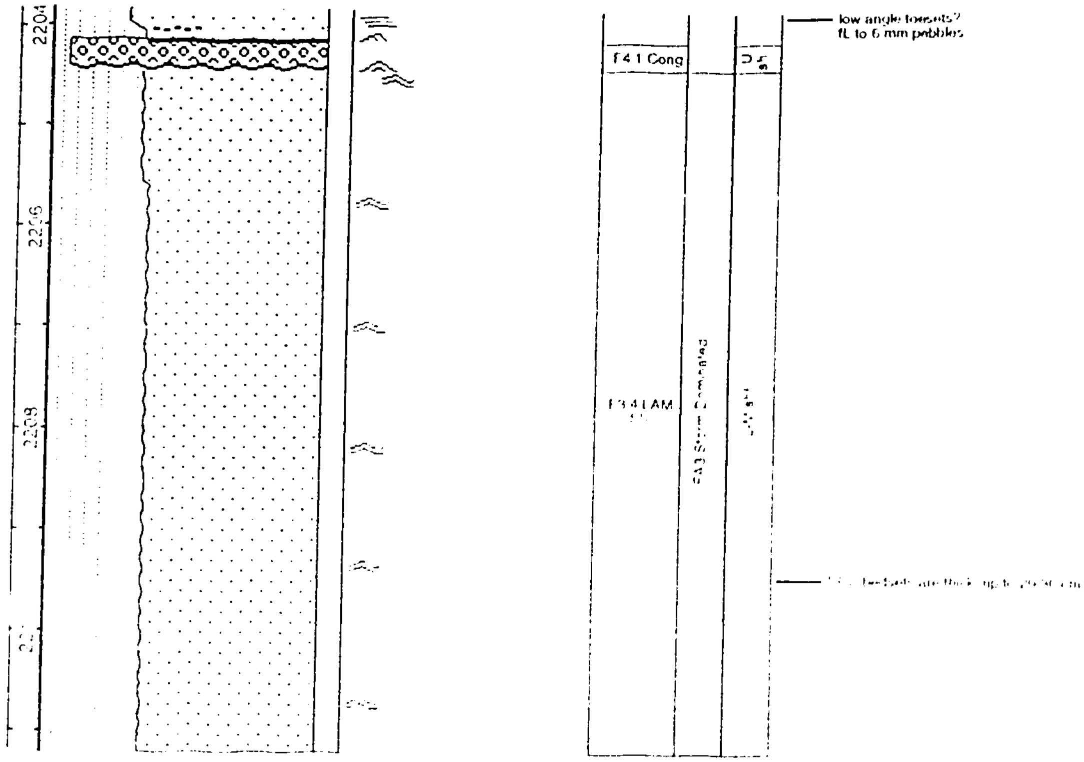

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CanHunter Steeprock
06-06-072-12w6

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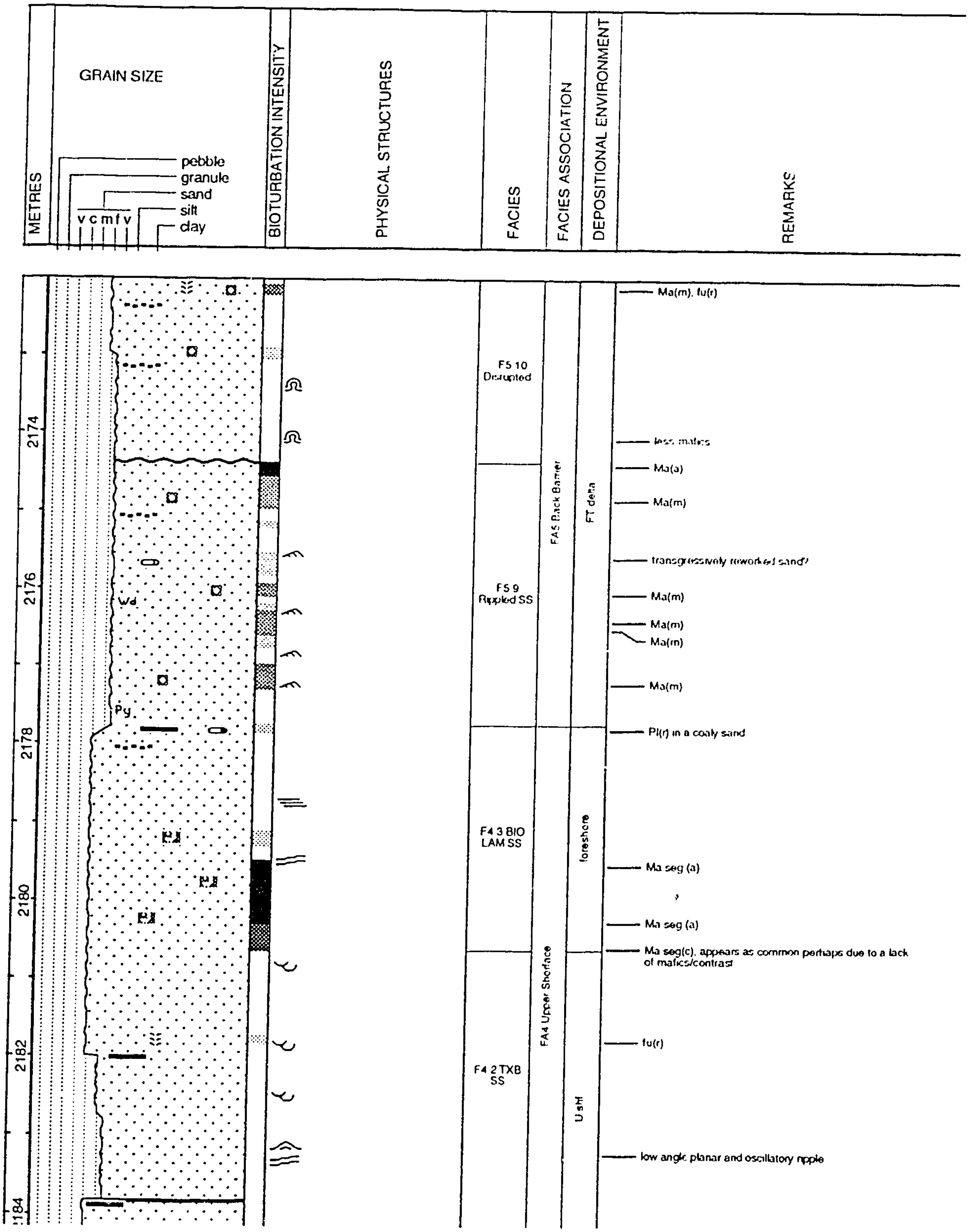

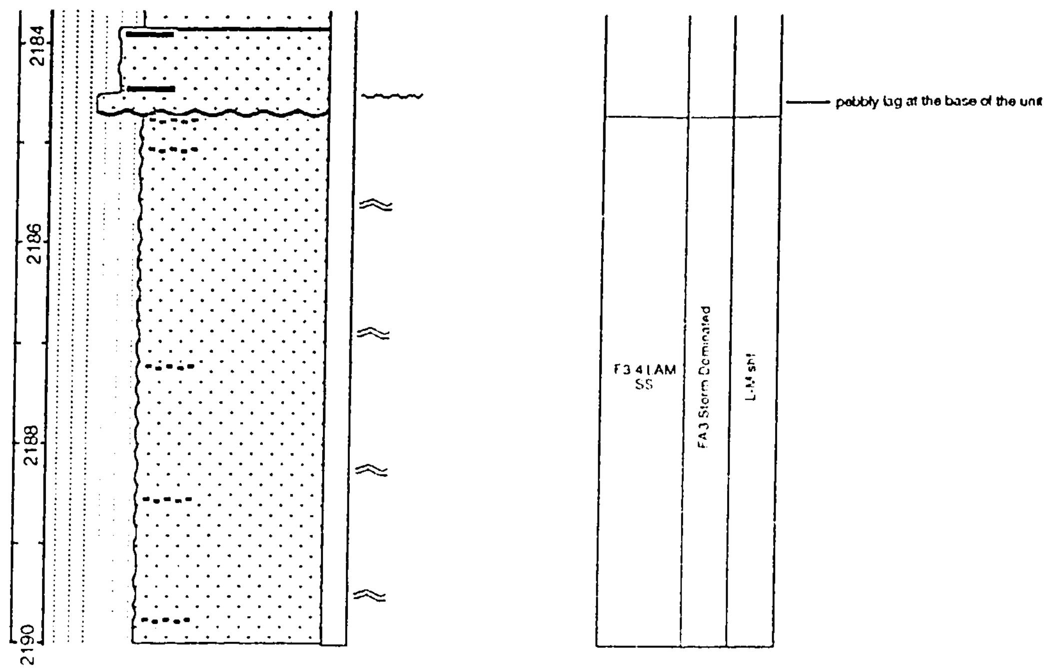

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CanHunter Elmworth
07-27-072-13w6

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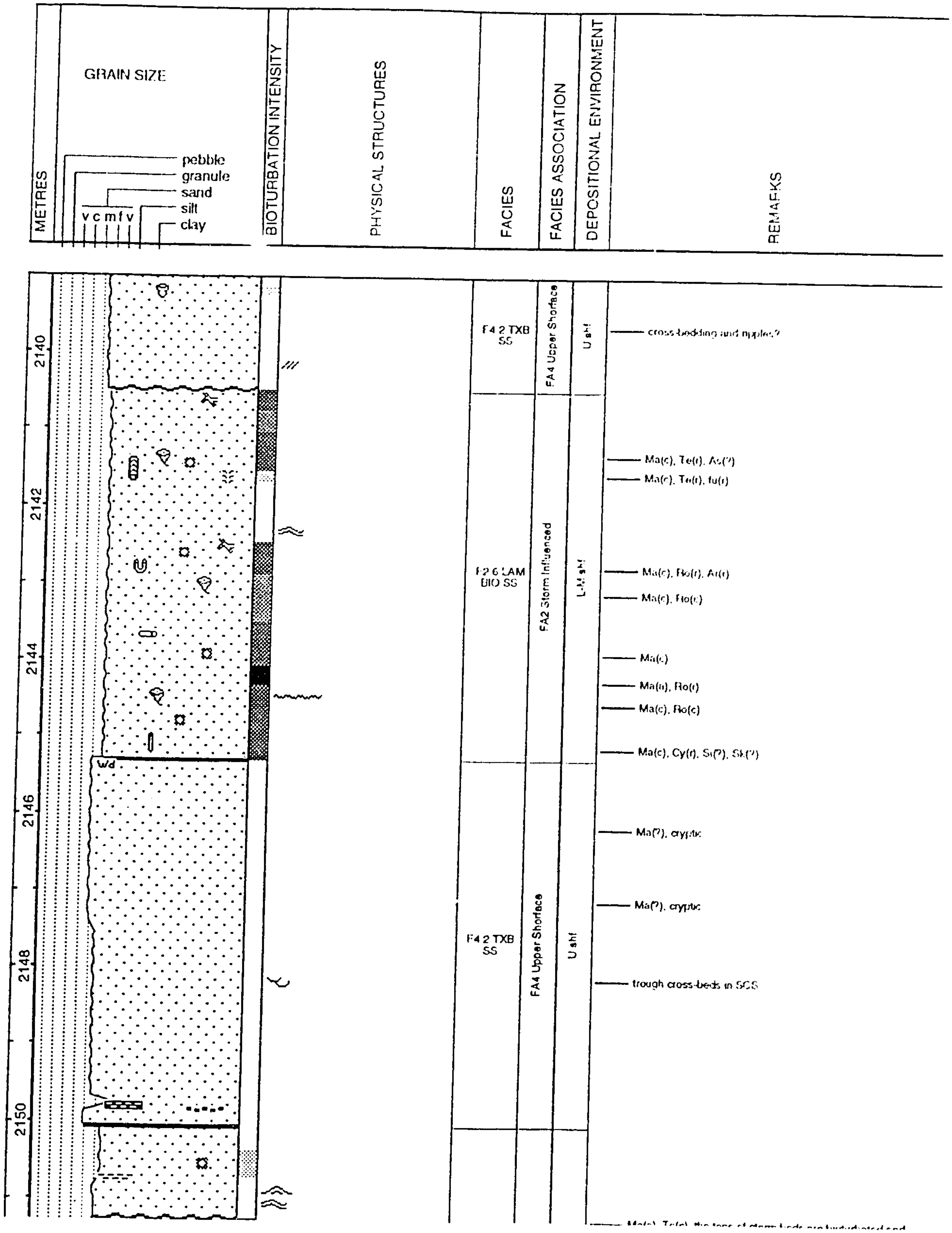

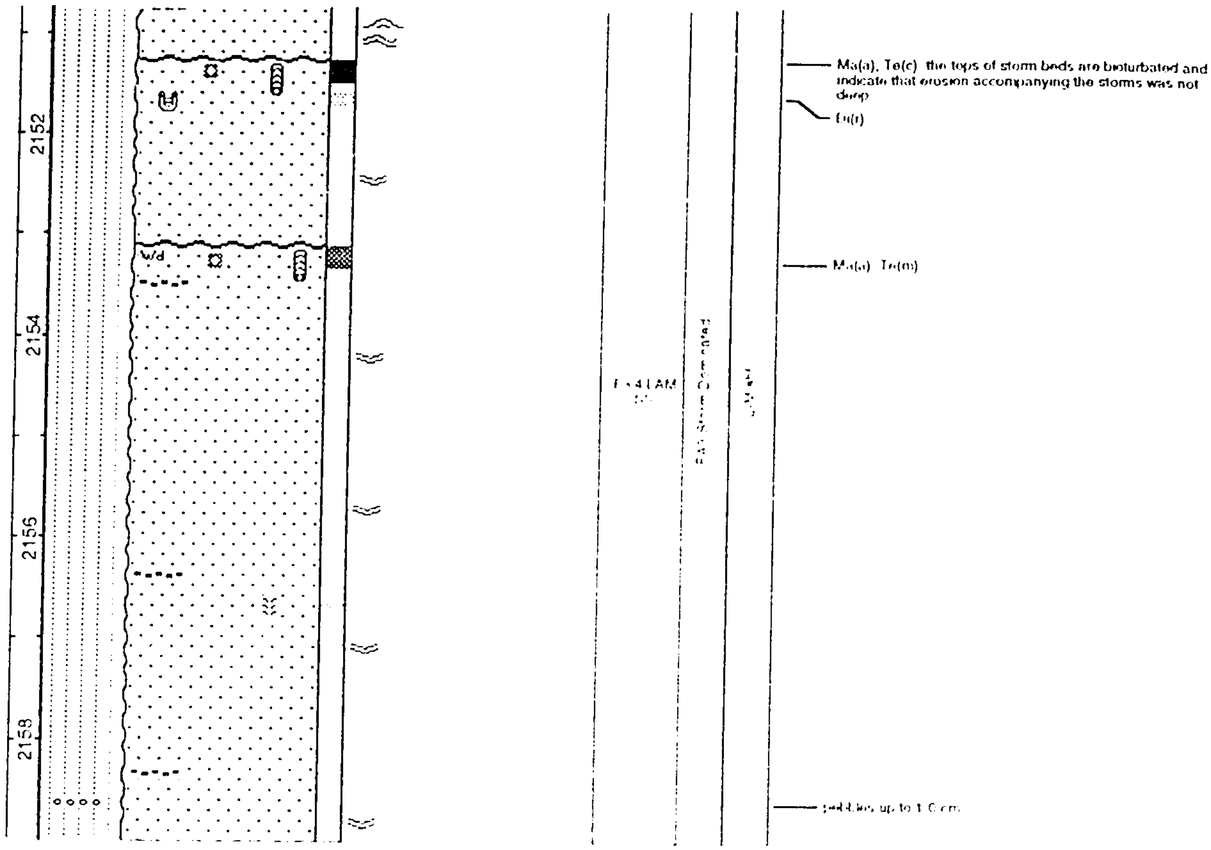
2152
2154
2156
2158
Ma(a), Te(c) the tops of storm beds are bioturbated and indicate that erosion accompanying the storms was not deep
Ma(a) Te(m)

CanHunter Esso Steeprock

06-29-072-13w6

Date logged: May 28, 1995

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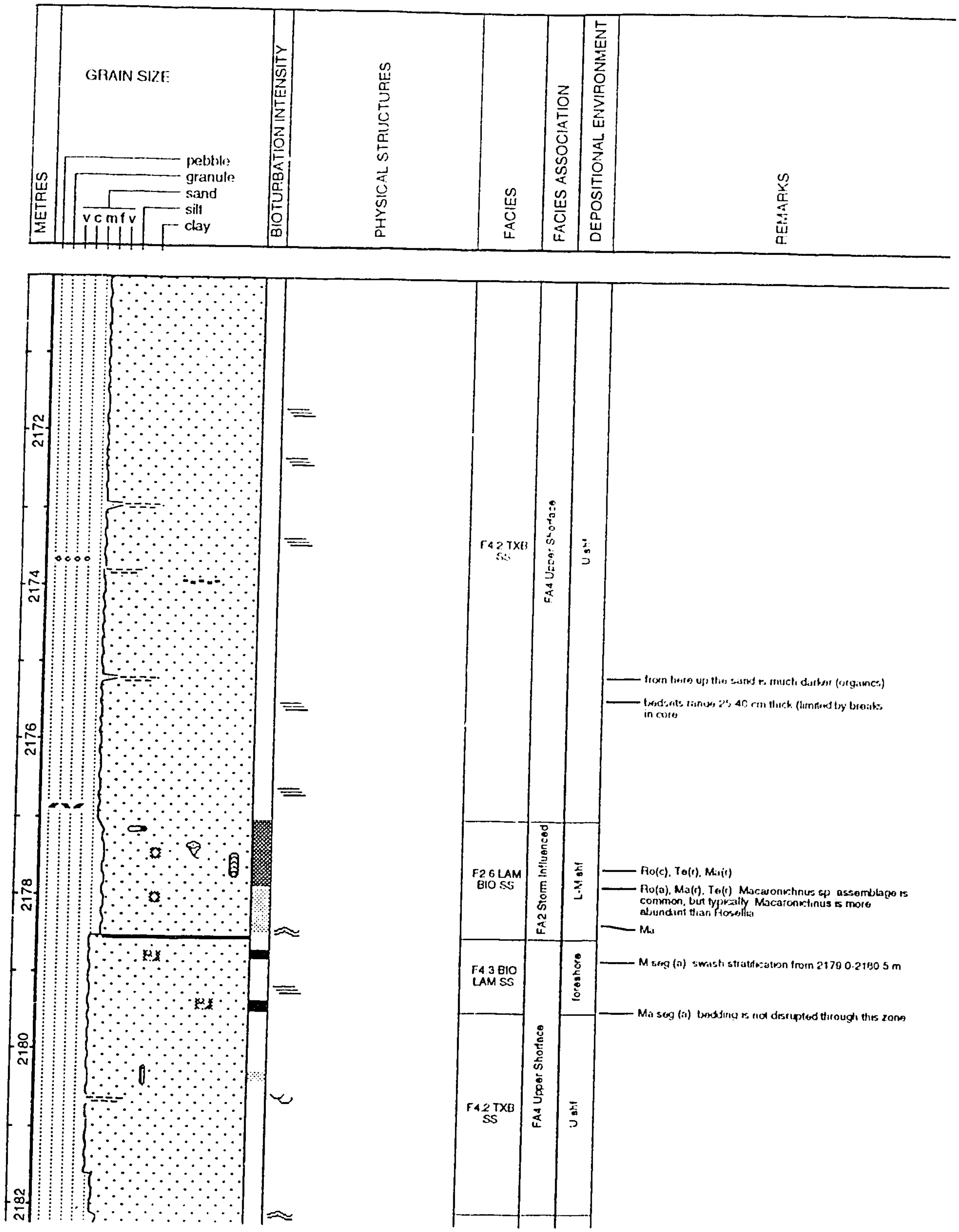

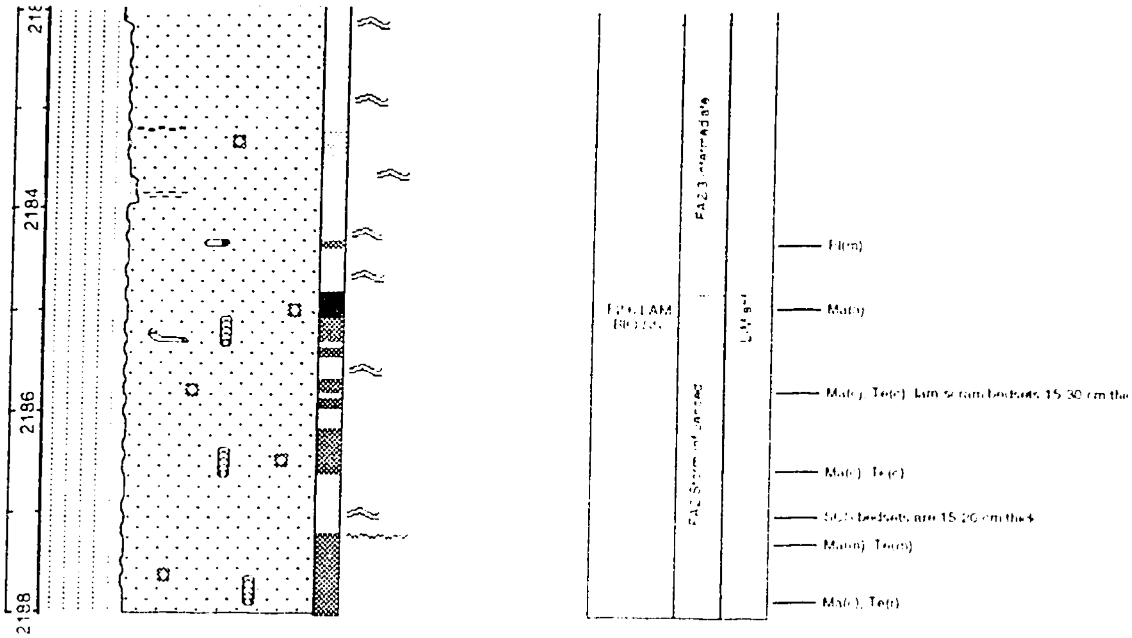

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Enron Hythe

14-15-073-09w6

Date logged: May 29, 1995

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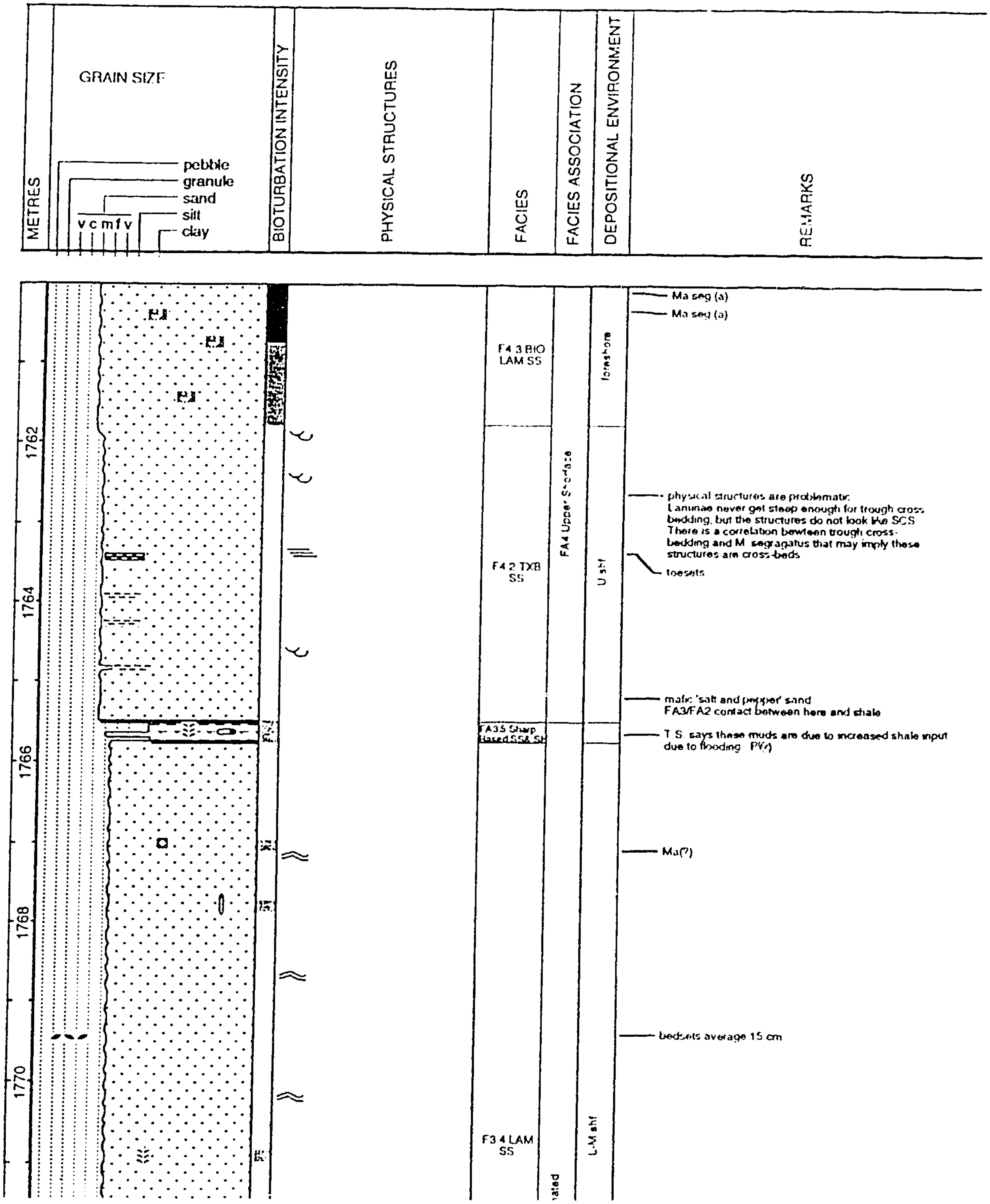

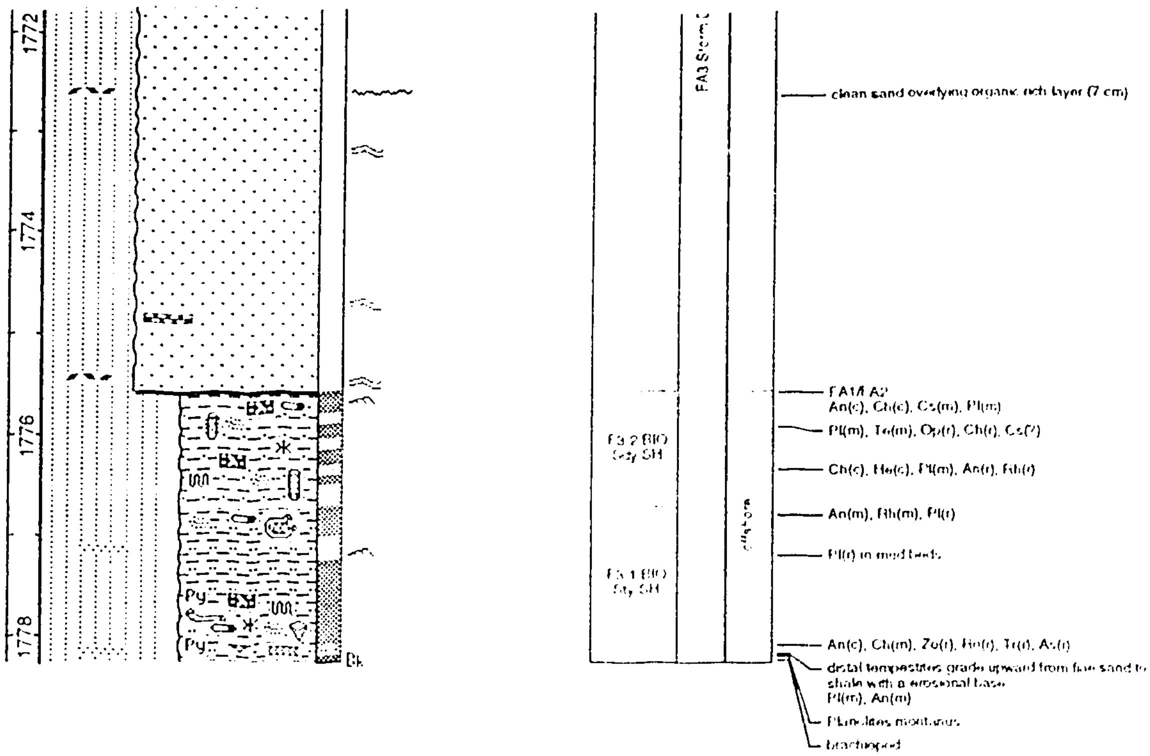

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Enron Hythe

06-31-073-09w6

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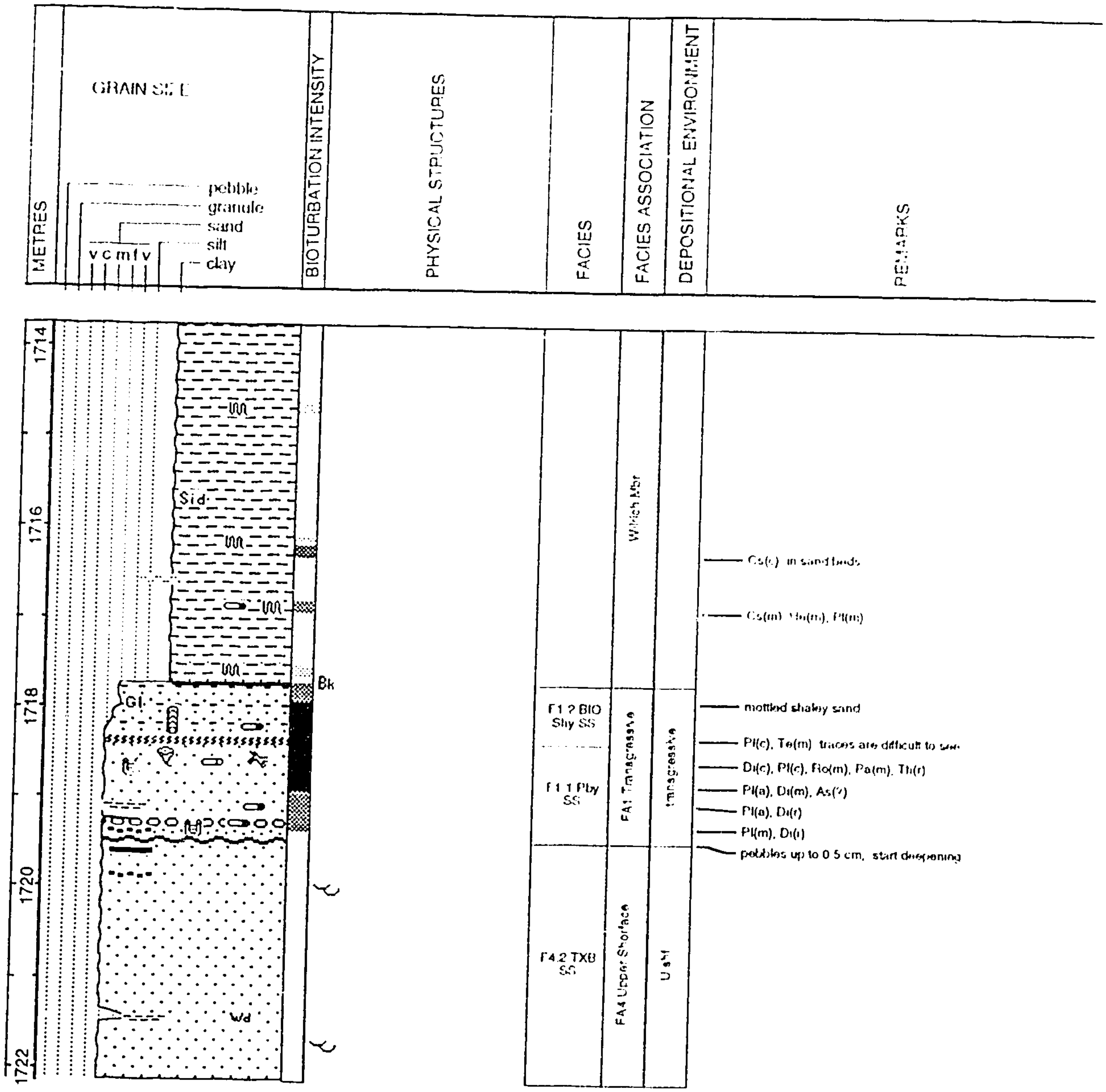

Chiefco Knopcik

05-07-074-11w6

Date logged: May 28, 1995

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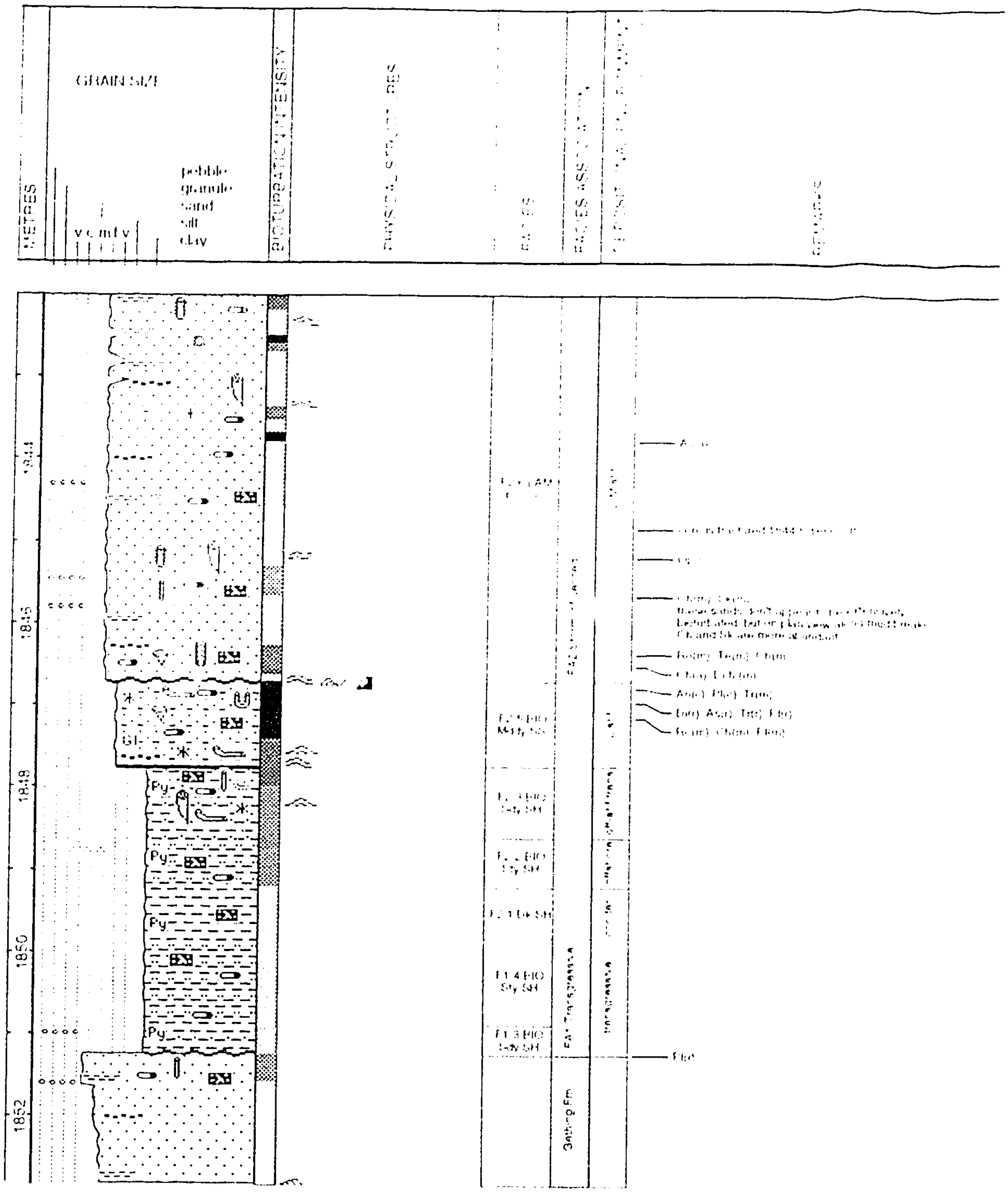

Sulpetero et al Knopcik

03-28-074-11w6

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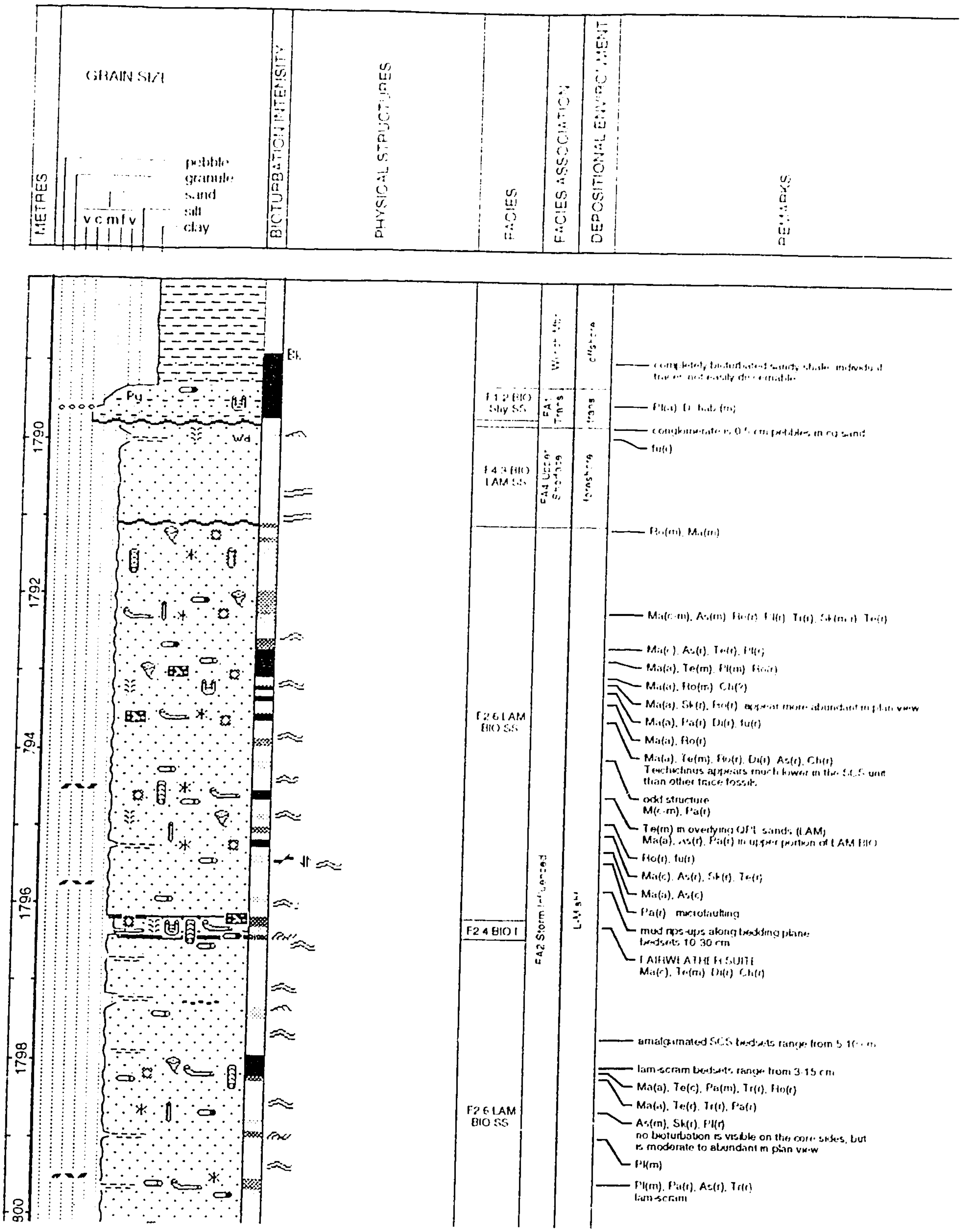

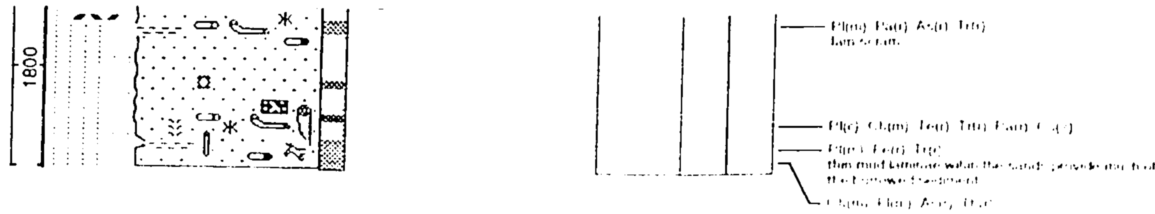

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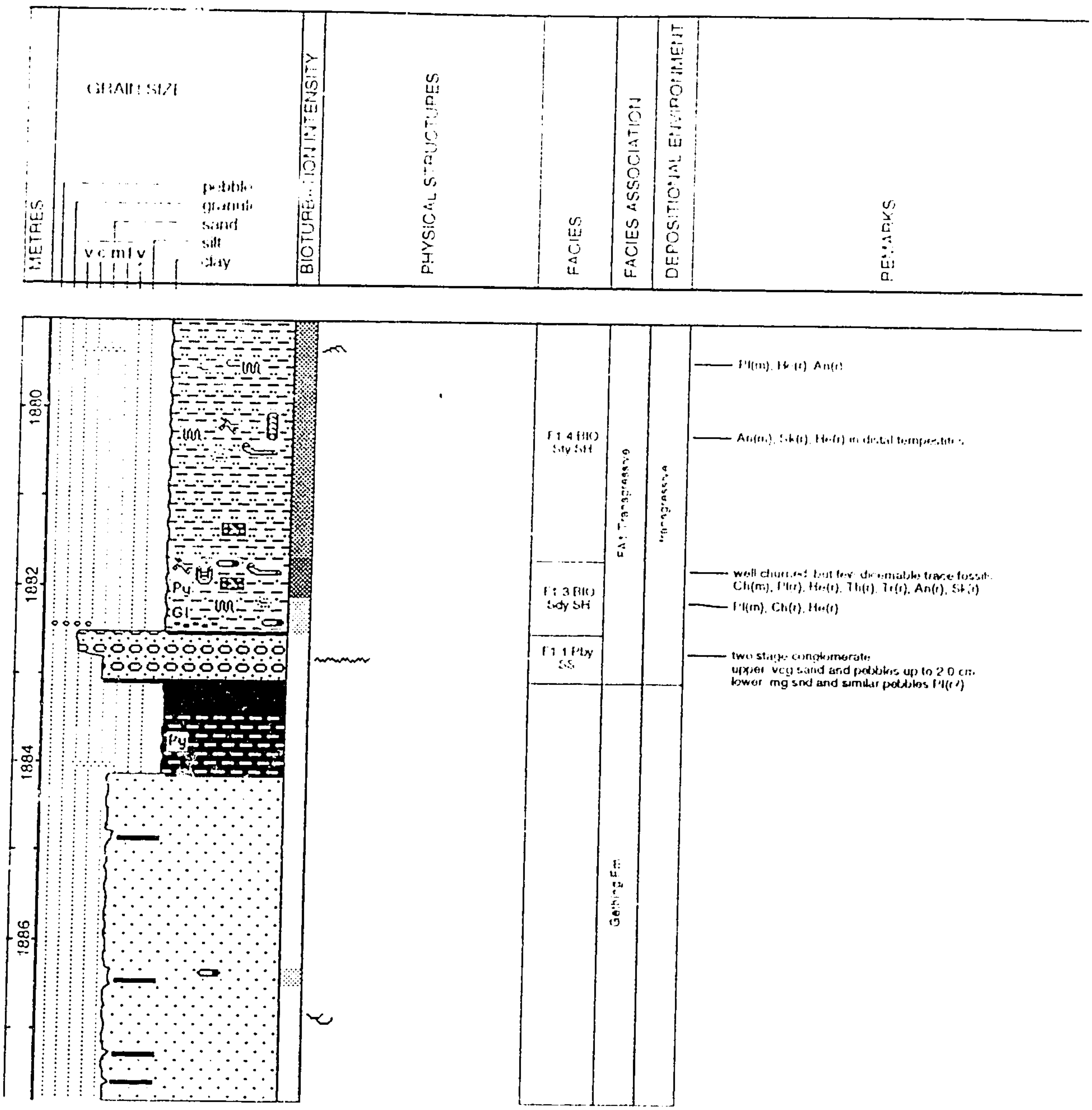
AEC Sinclair

12-01-074-12w6

Date logged: May 29, 1995

Logged by: Howard Brekke © 1995



Dome Total Sinclair

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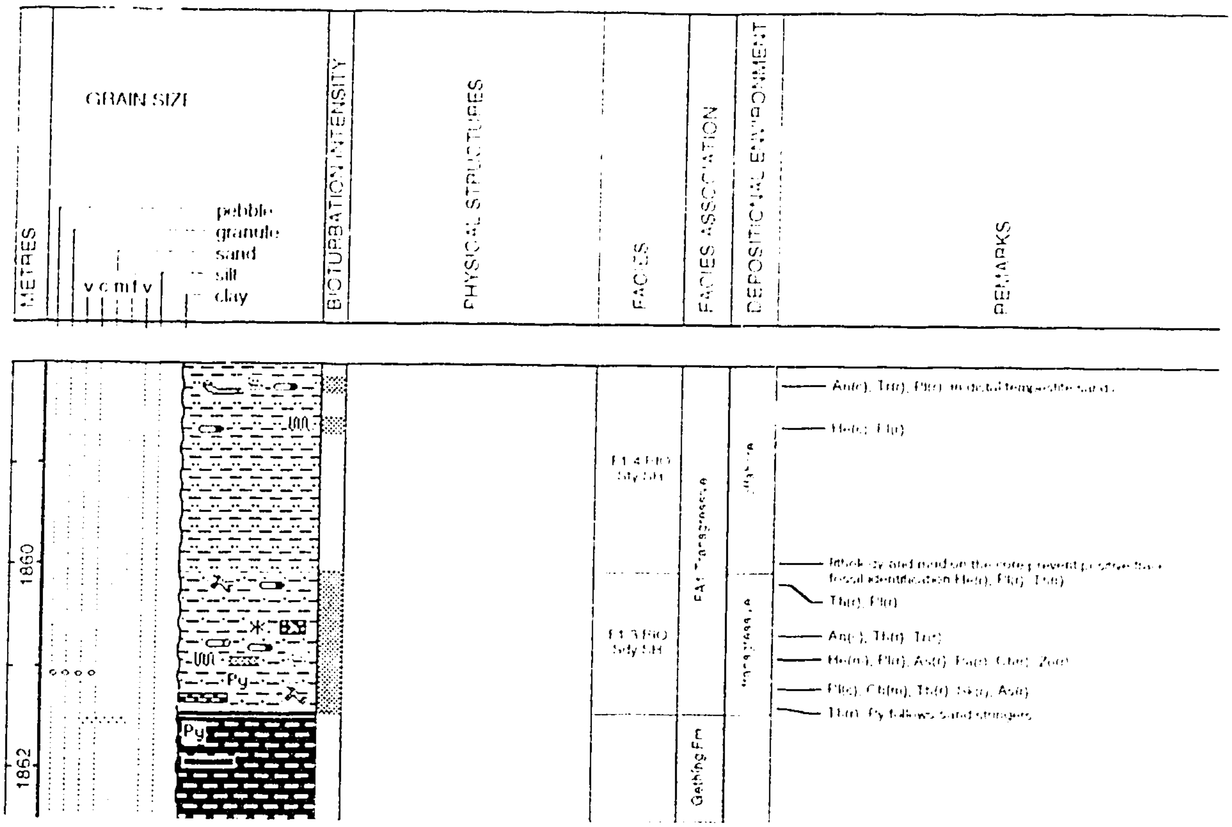

A.E.C. Sinclair
05-12-074-12w6

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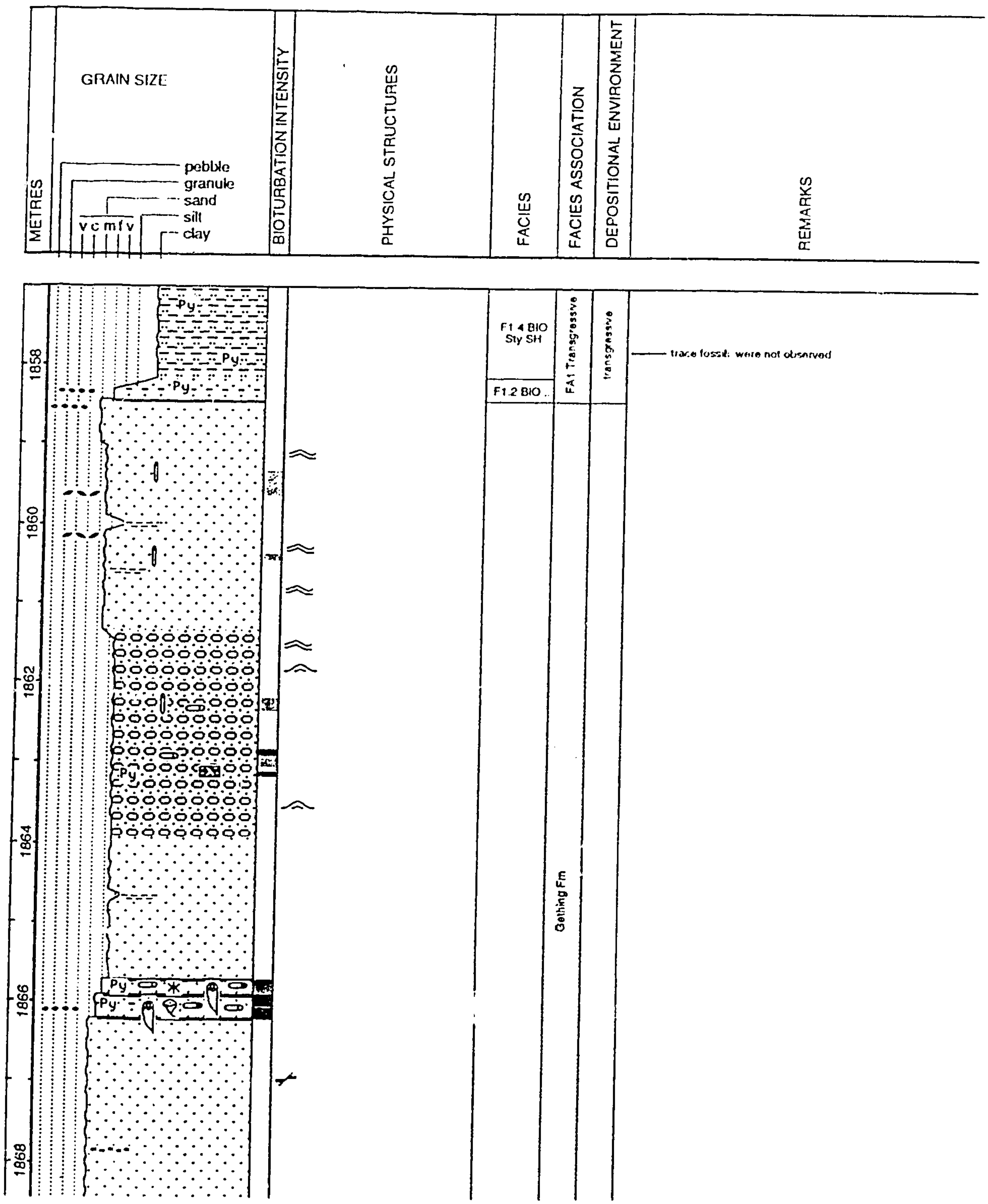

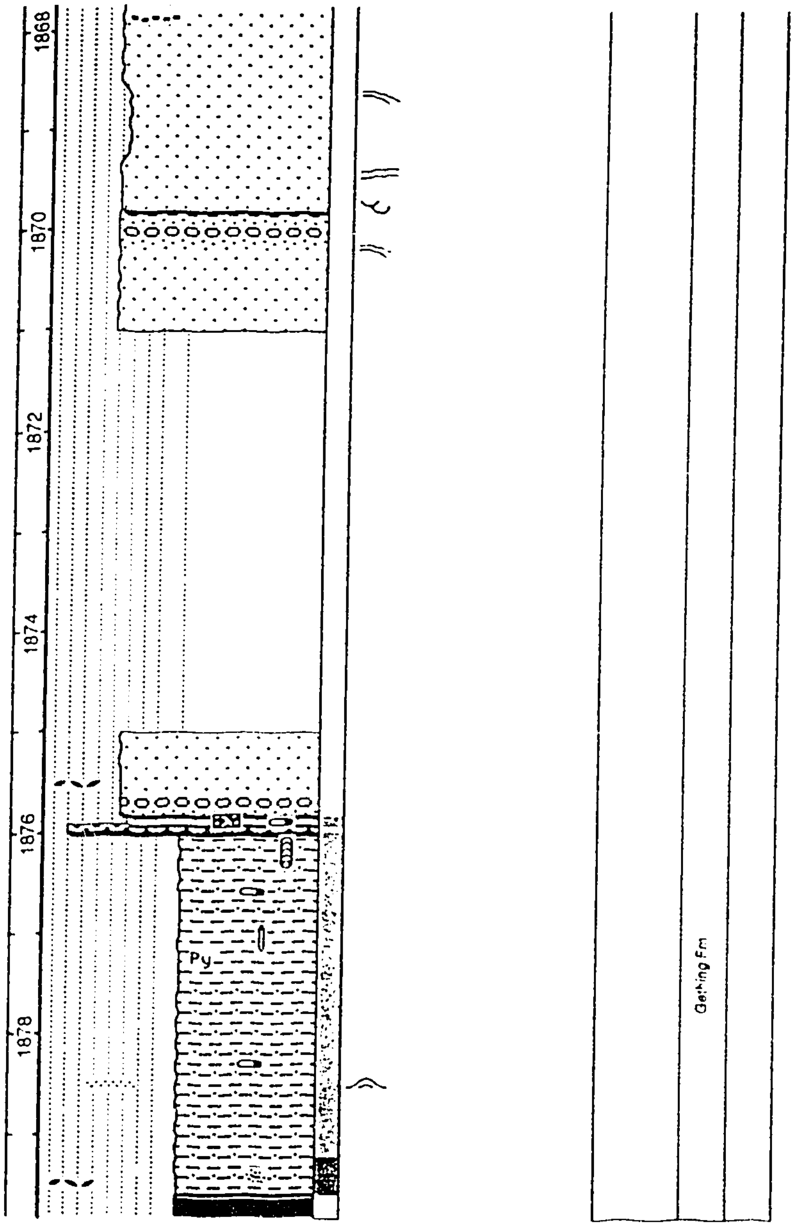

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Dome Total Knopcik

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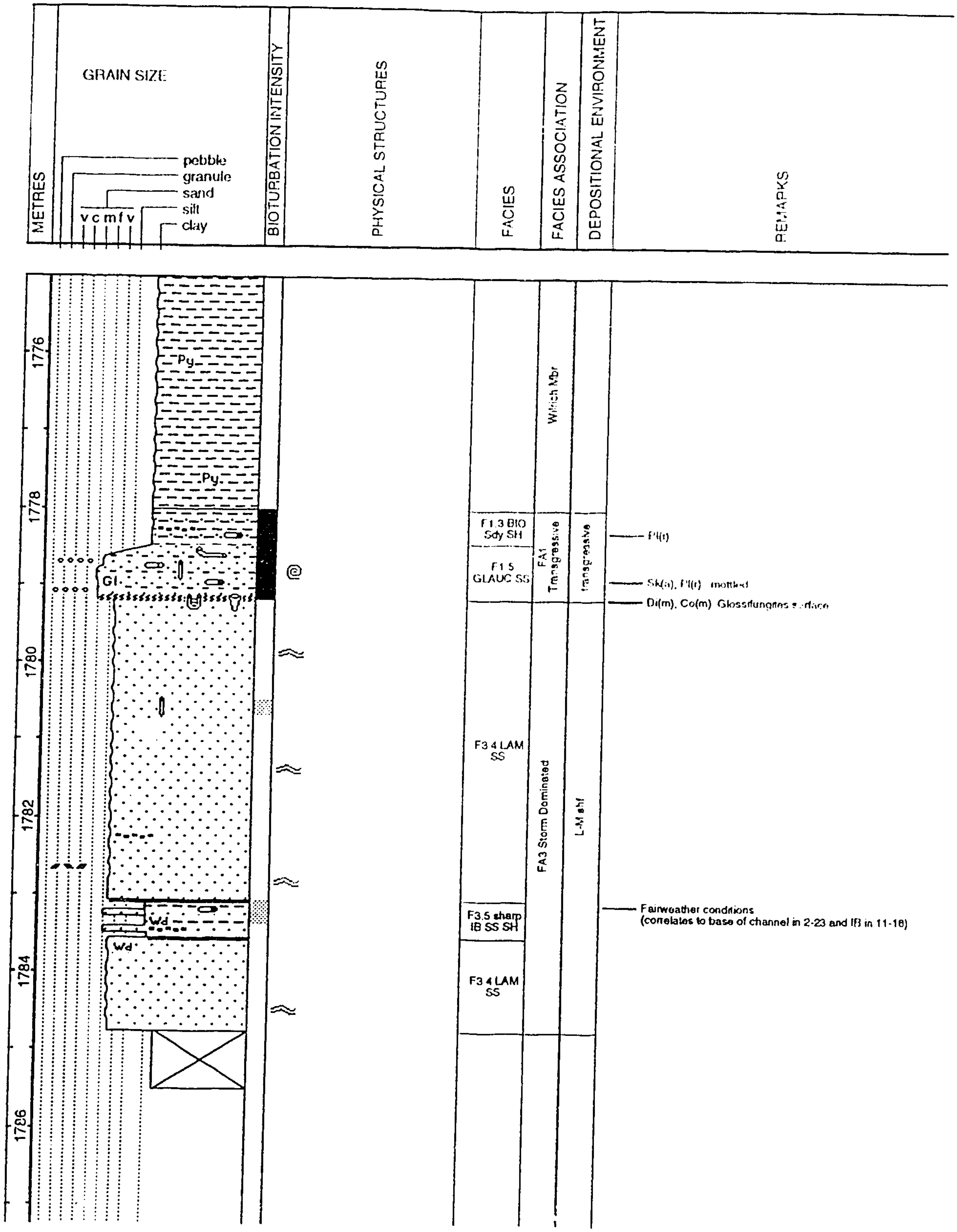

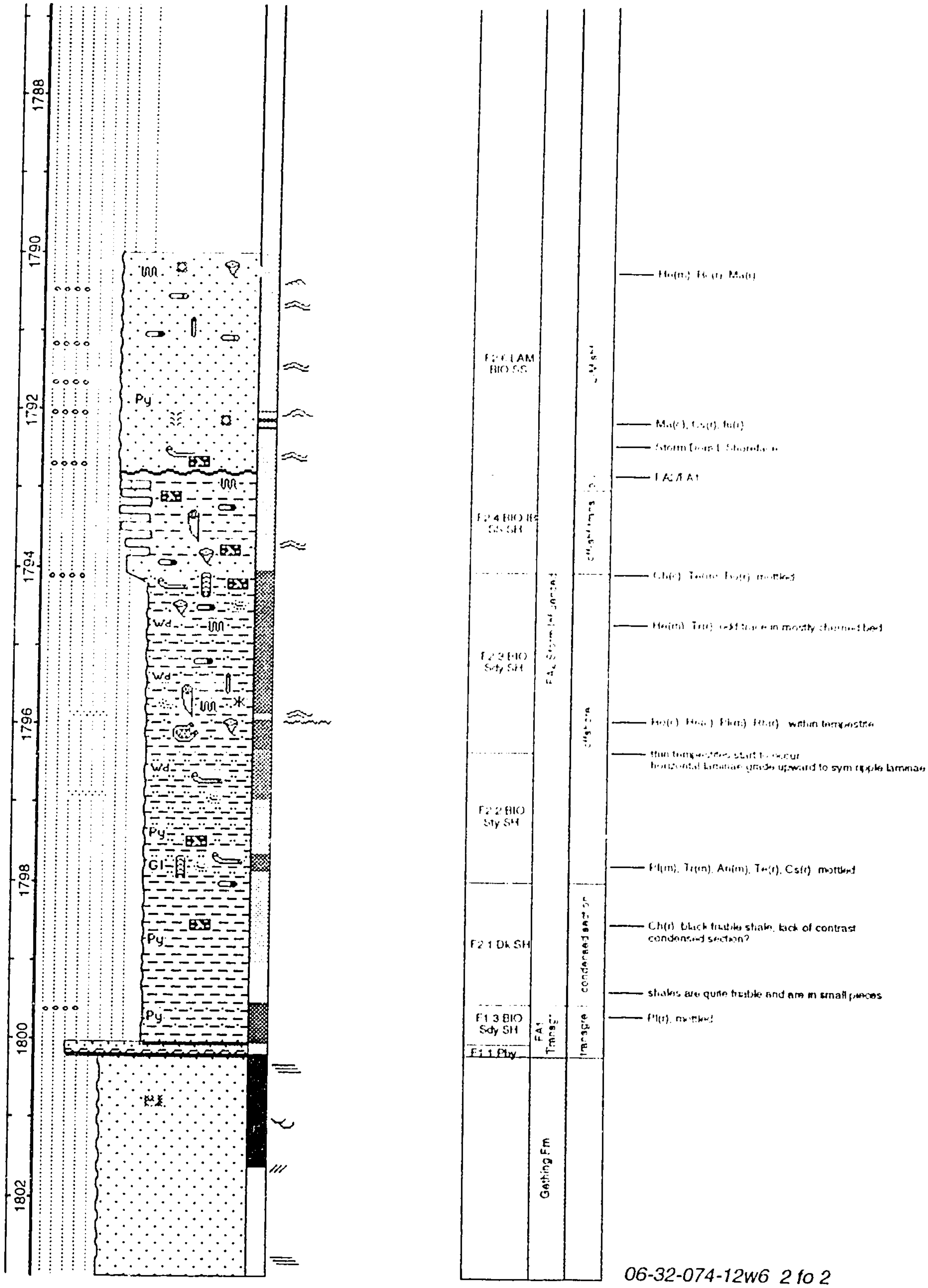

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Cheifco Texaco Jersey

06-05-074-13w6

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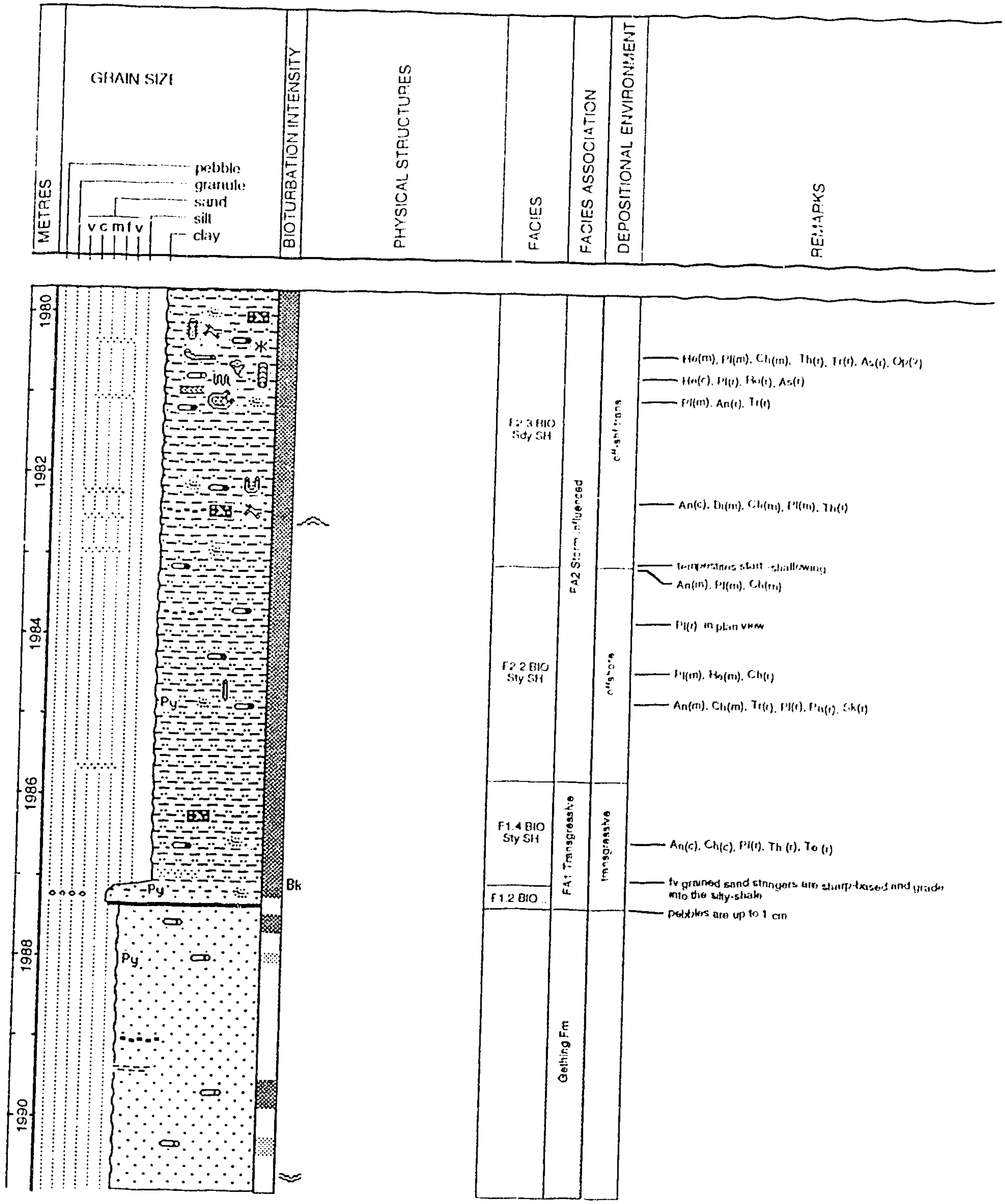

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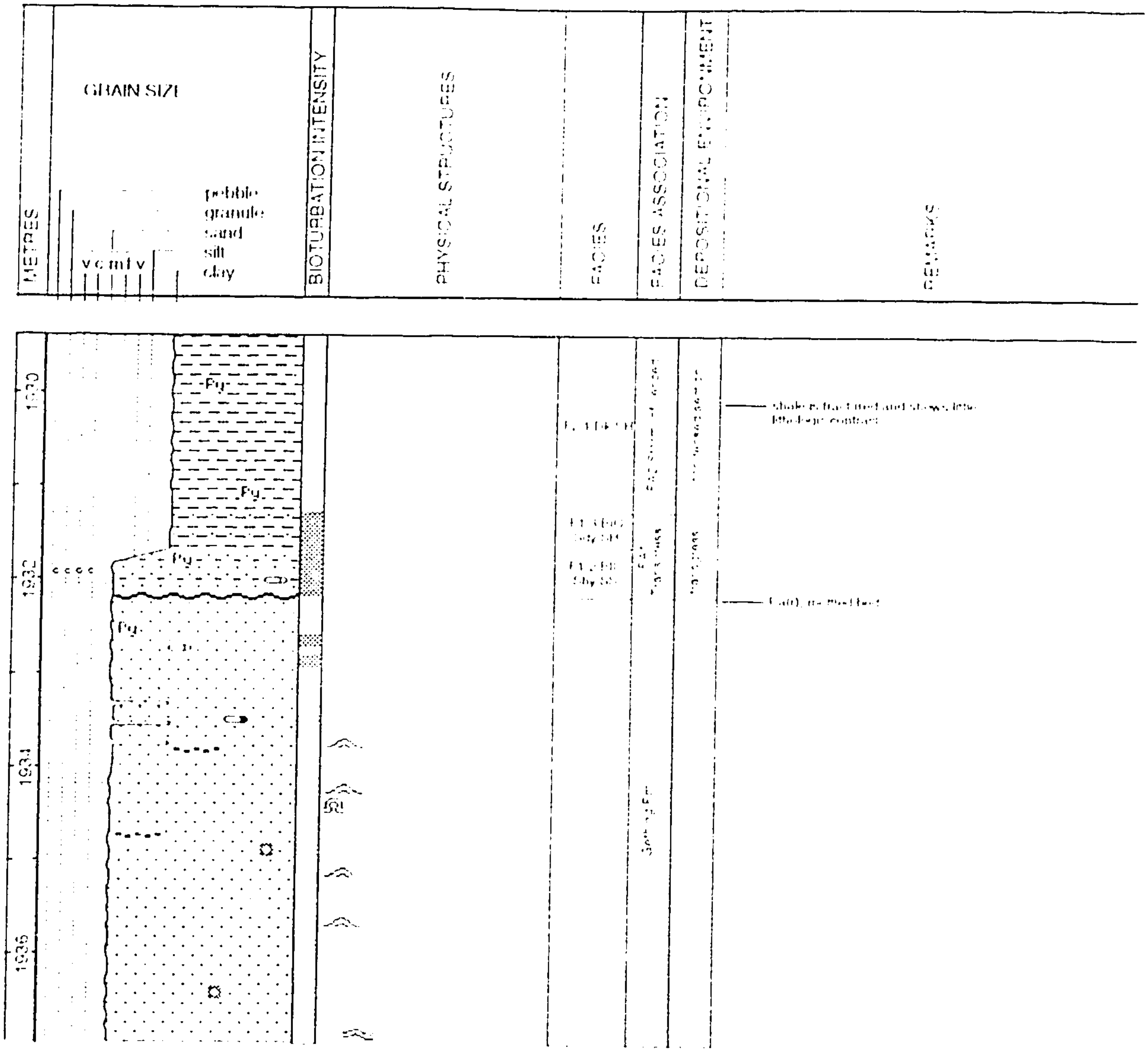

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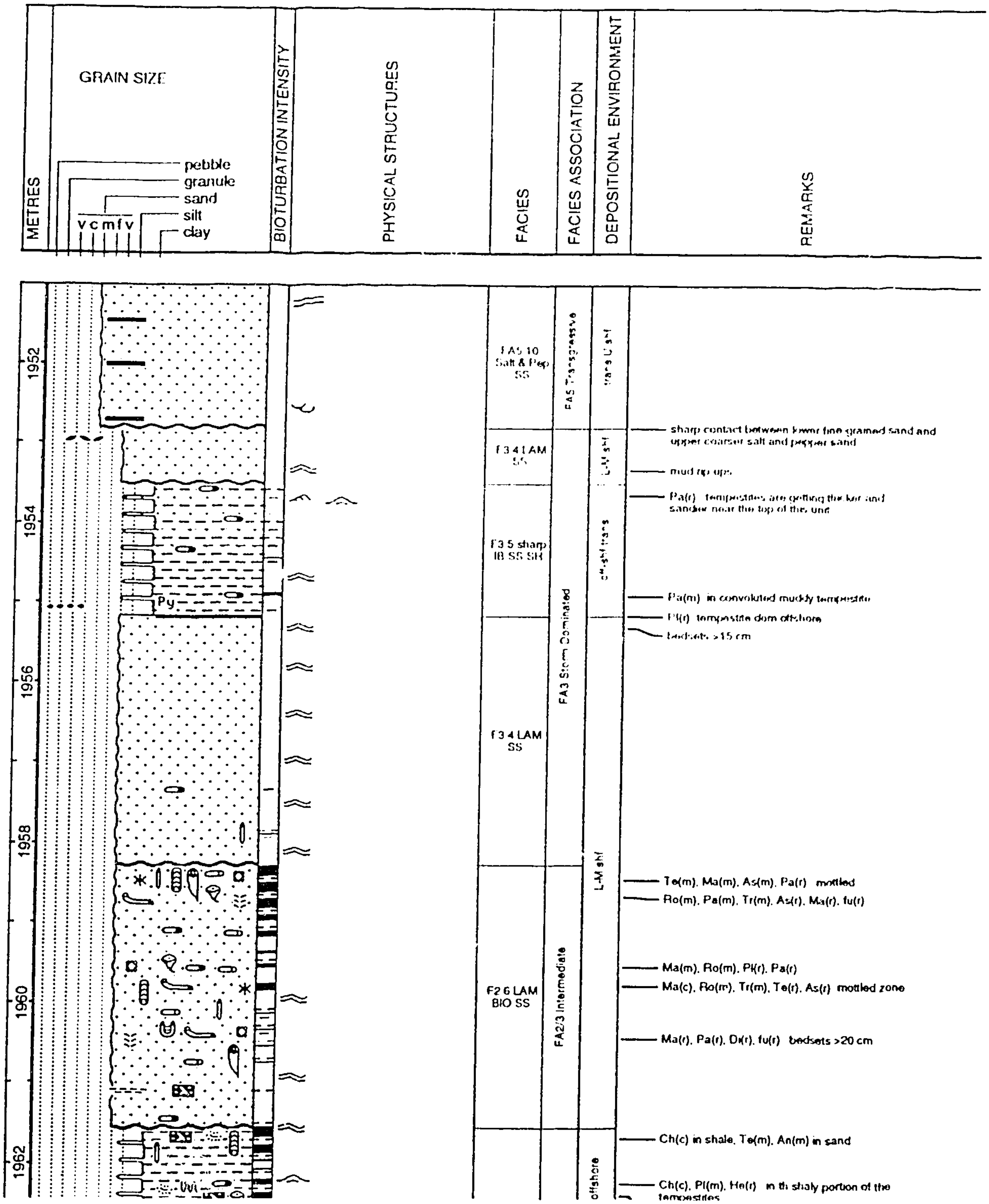

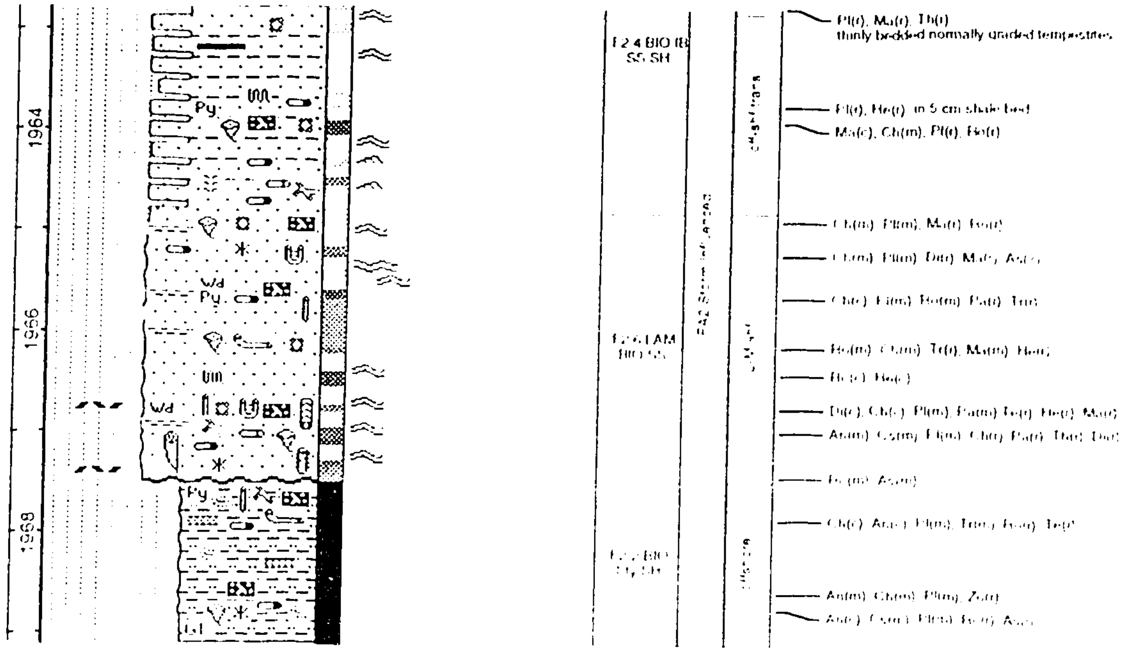

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Chiefco Texaco Sinclair
10-36-074-13w6

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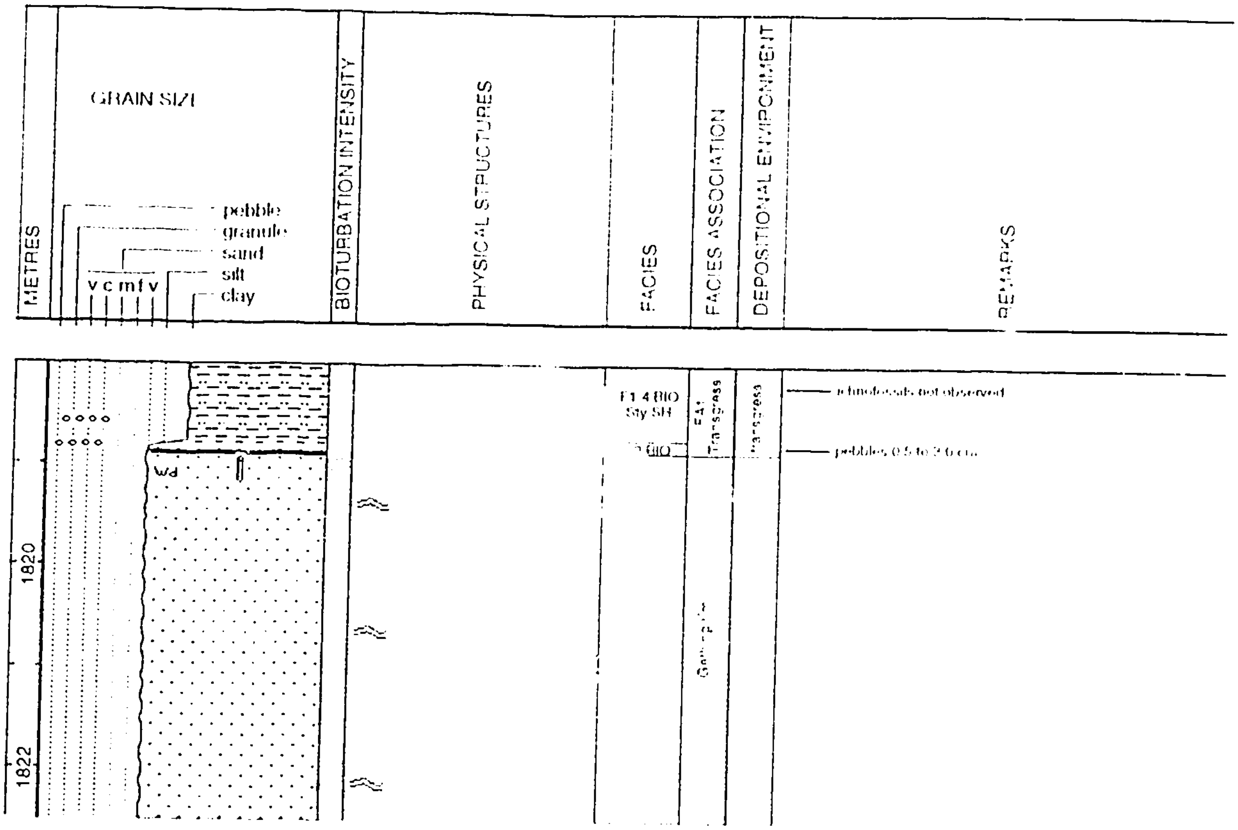

Sulpetero et al LaGlace

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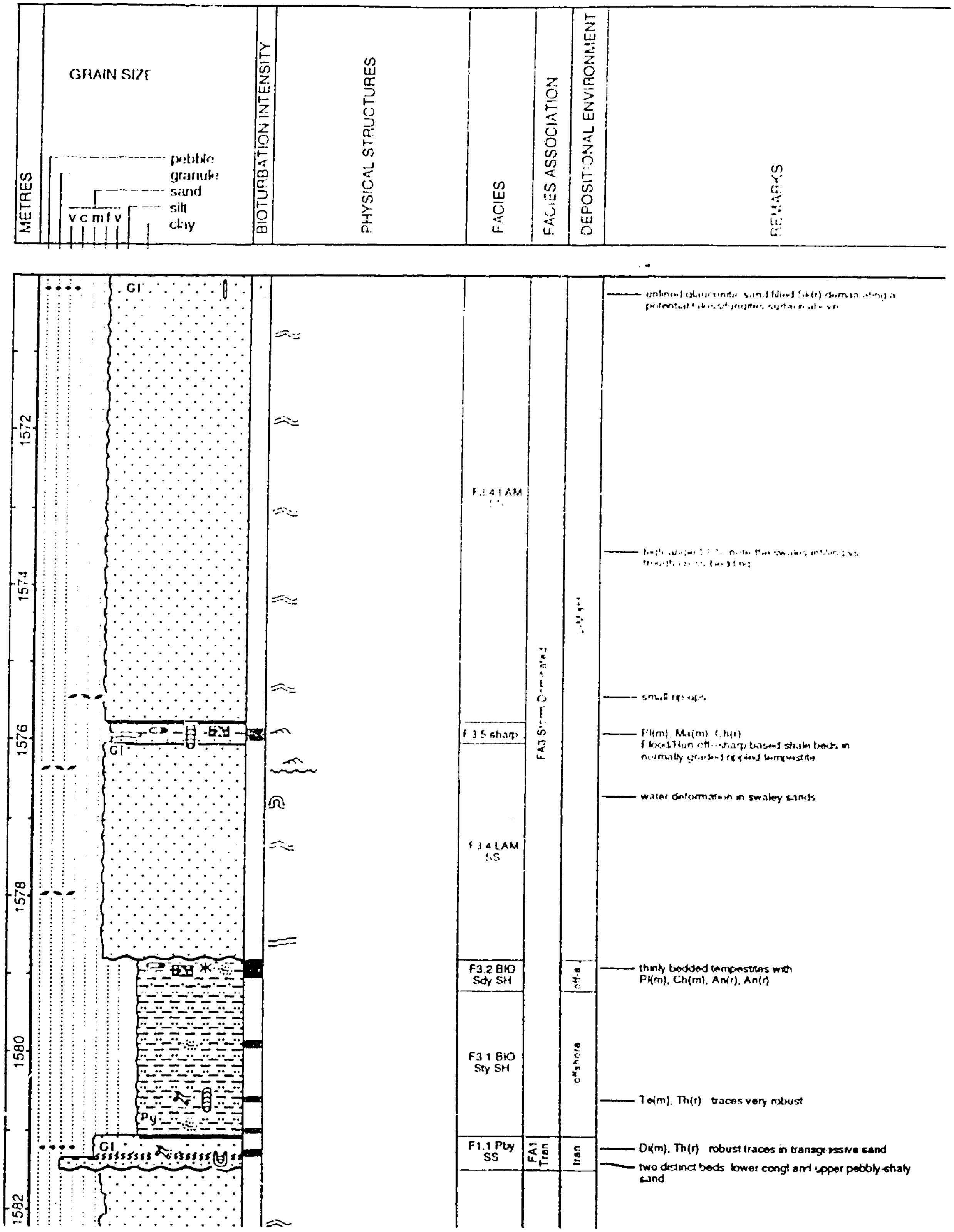

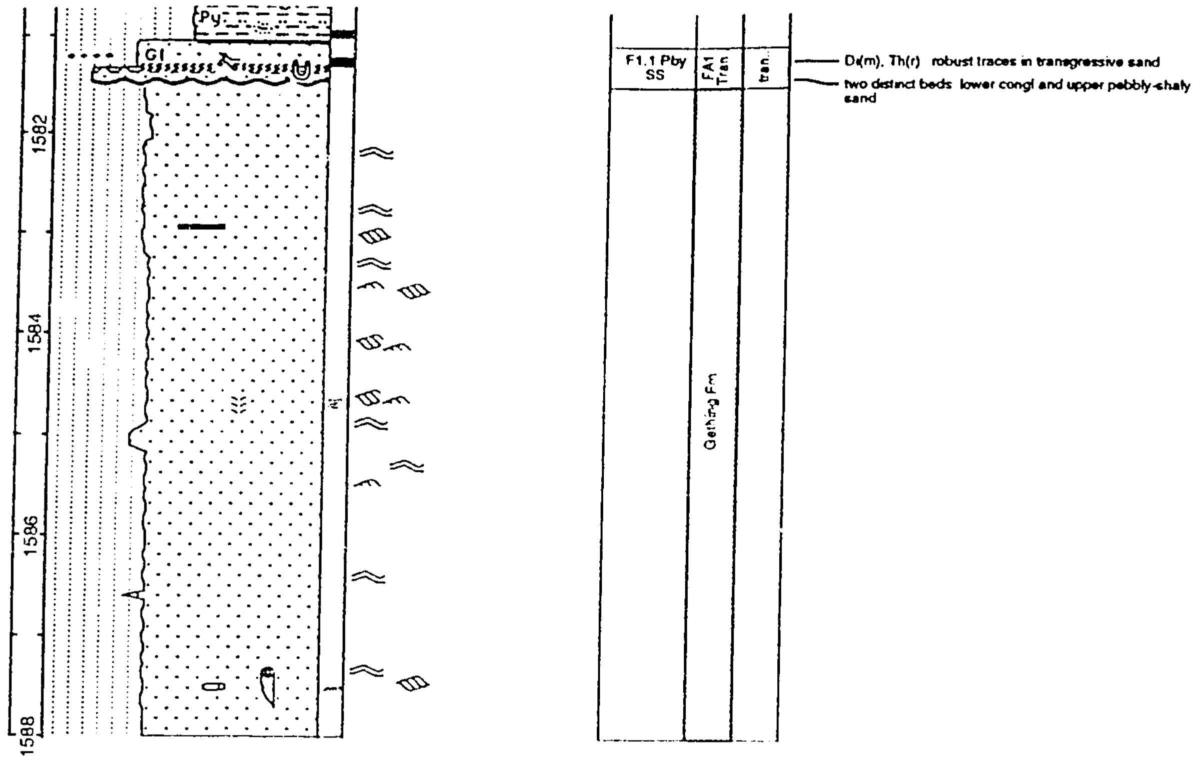

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Dome et al Laglace

06-10-075-08w6

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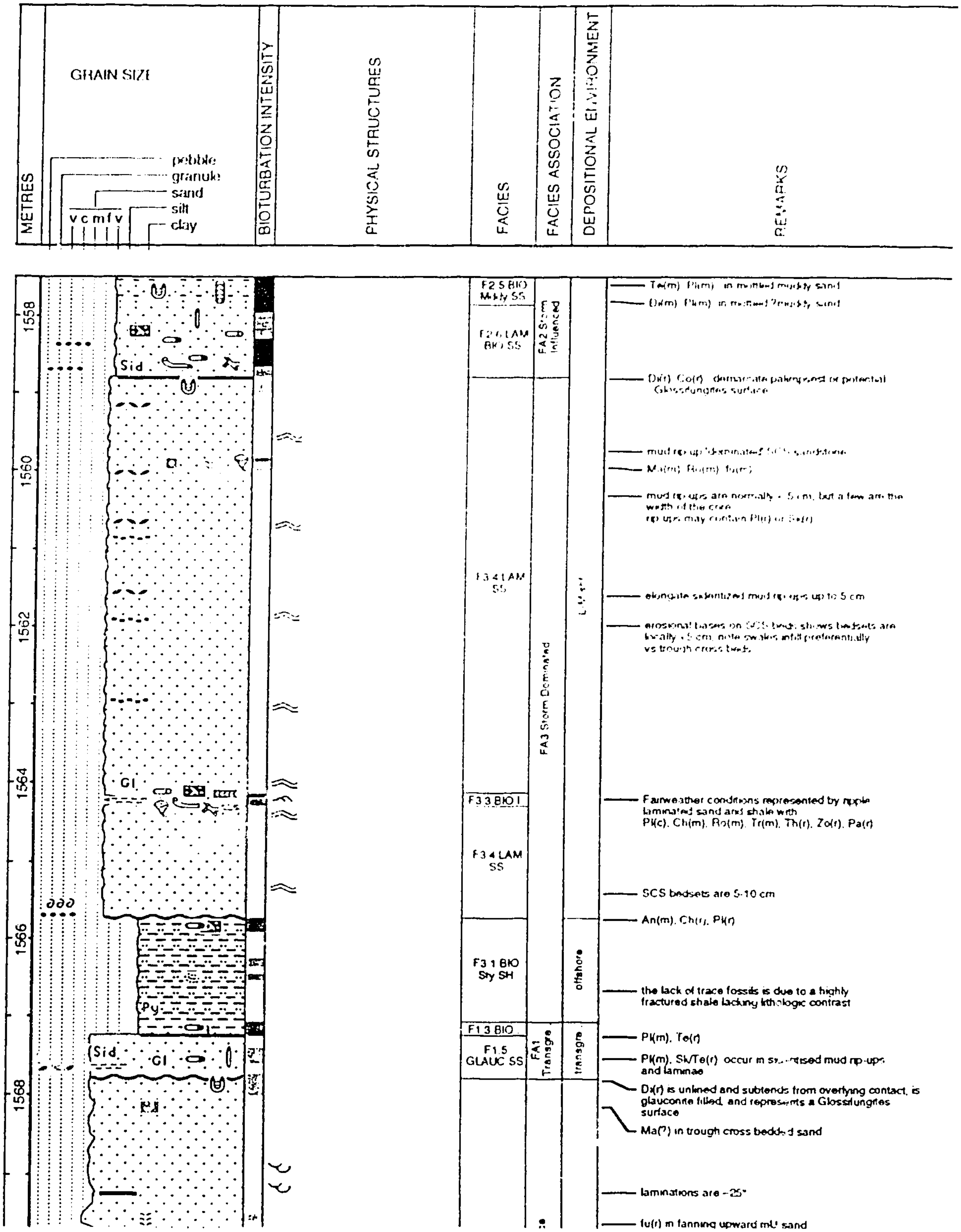
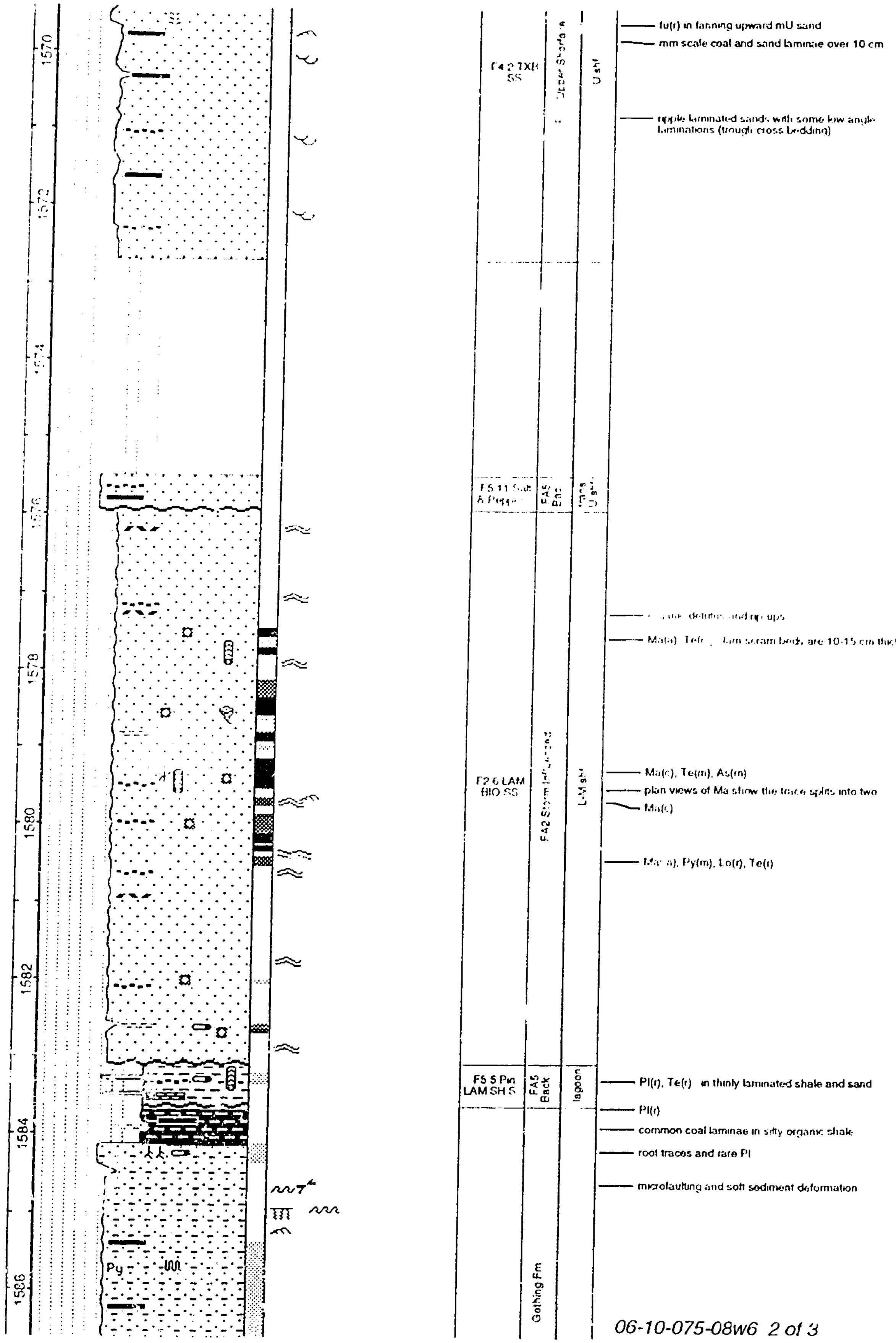
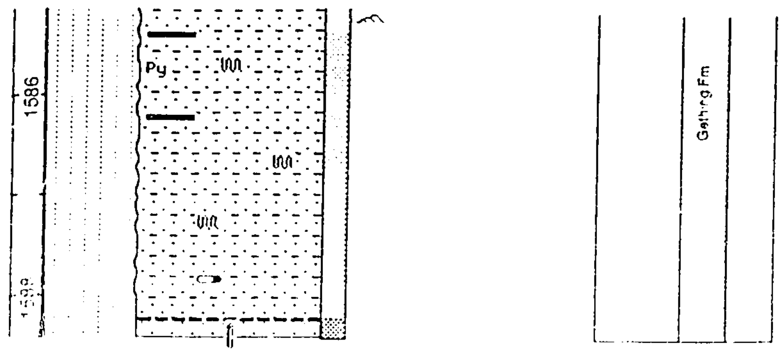



1570
1572
1574
1576
1578
1580
1582
1584
1586
F4.2 TXB SS
U shf
fu(r) in fanning upward mU sand
mm scale coal and sand laminae over 10 cm
ripple laminated sands with some low angle laminations (trough cross bedding)
F2.6 LAM BIO SS
L-M shf
Ma(r), Te(m), As(m)
plan views of Ma show the trace splits into two
Ma(c)
Py(m), Lo(r), Te(r)
F5.5 Pin LAM SH S
FA5 Back
lagoon
Pl(r), Te(r) in thinly laminated shale and sand
Pl(r)
common coal laminae in silty organic shale
root traces and rare Pl
microfaulting and soft sediment deformation
Py
Gothing Fm
06-10-075-08w6 2 of 3



06-10-075-08w6 3 of 3

Dome Union Knopcik

07-03-075-12w6

Date logged: May 28, 1995

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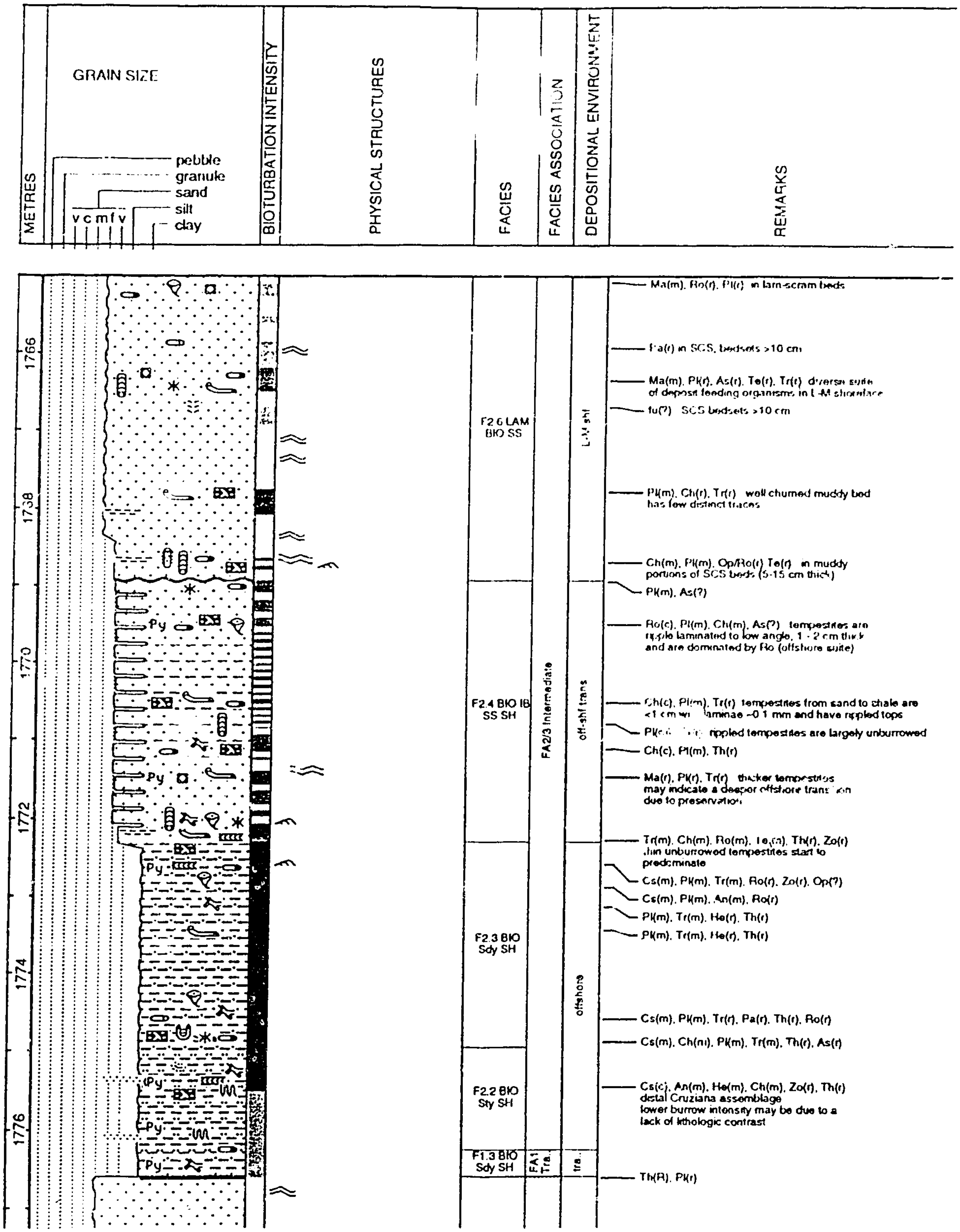

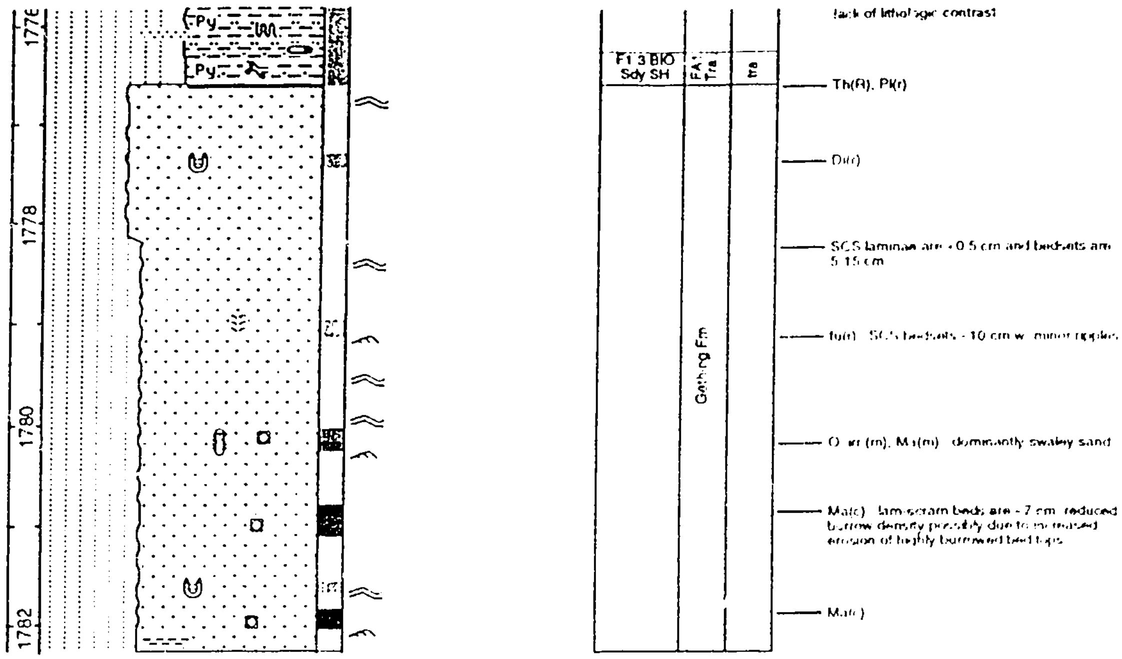
1778
1780
1782
Py
Sdy SH
Gething Fm
lack of lithologic contrast
Th(R), Pl(r)
SCS laminae are
Ma(c)

Chiefco Texaco Sinclair

02-23-075-13w6

Date logged: May 28, 1995

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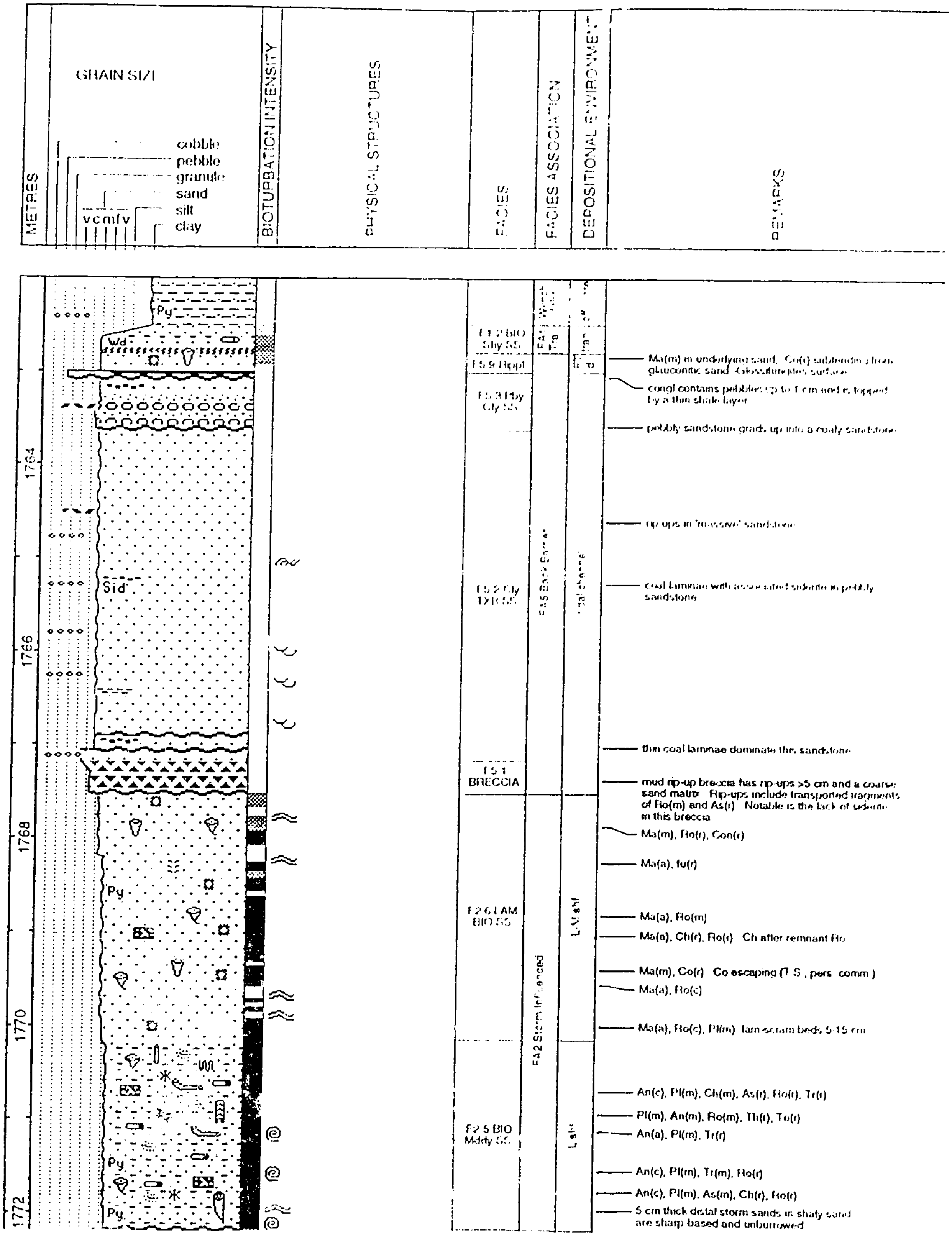

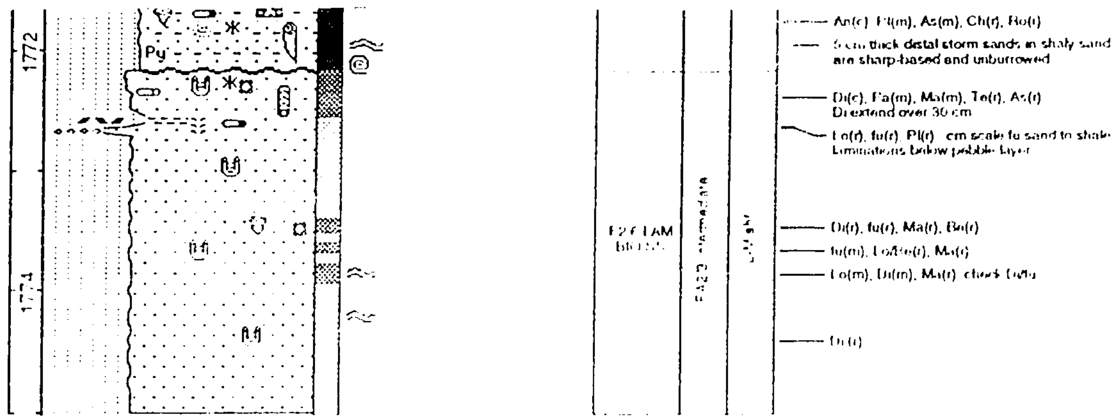

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APPENDIX B

Systematic Ichnology

Anconichnus Kern, 1976

Diagnosis: Vermicularly tangled, predominantly horizontal, silt haloed and unlined, fecal cored trace. *Anconichnus* is commonly the dominant trace yielding a mottled fabric, obscuring other traces. The only species is *A. horizontalus*.

Discussion: The trace is interpreted to be a deposit-feeding structure, likely of a vermiform (worm-like) animal.

Arenicolites Salter, 1857

Diagnosis: Simple, vertical, U-shaped tubes, lacking spreite, rarely branched, and possibly flared at either or both ends. Burrow walls may be lined or unlined, uncemented, and are commonly smooth. Paired tubes normally seen in plan view may not be present in core. *Arenicolites* commonly appears as vertical tubes curving downward into a J-shape.

Discussion: These are considered to be the dwelling structures of a suspension- or filter-feeding organisms, probably annelids and crustaceans.

Asterosoma von Otto, 1854

Diagnosis: Burrow system composed of radiating arms, circular to elliptical in cross section and tapering inward towards an elevated centre. Cross sections of arms reveal concentric laminations of sand and clay (spreite) around a central sand core. The exterior is normally smooth, but may be longitudinally wrinkled or striated.

Discussion: *Asterosoma* is interpreted to be the selective deposit-feeding structure of a vermiform organism.

Bergaueria Prantl, 1946

Diagnosis: Cylindrical to hemispherical, smooth walled, lined or unlined depressions with essentially structureless infill. Structures are approximately equal in length and diameter, and may have a shallow depression at the base, as well as 6 to 8 short radiating tubercles (small knoblike structures).

Discussion: Two ethological interpretations have been hypothesized for *Bergaueria*. Lined traces are likely dwelling burrows while unlined depressions are thought to be resting traces. *Bergaueria* are created by the actions of actinian anenomes.

Chondrites von Sternberg, 1833

Diagnosis: Dendritic, smooth walled, regularly but asymmetrically branched (ramifying) small burrow systems that do not interpenetrate. Diameter of components within a given system remains more or less constant. Fill is of contrasting lithology to surrounding material and typically of lighter colour.

Discussion: Traces are interpreted as the feeding structures of sipunculids or annelids.

Conichnus Myannil, 1966

Diagnosis: Conical, weakly lined structures perpendicular to bedding with a circular cross section and patterned fill. The base may rounded or may display an apical protuberance. Patterned fill is normally present as chevron like laminae. Shell hash may be present at the base of the burrow.

Discussion: There are two species, *C. conicus* and *C. papillatus*, discerned by burrow outline and the presence of the apical protuberance. Both species are considered to be dwelling structures of anenomes.

Cylindrichnus Howard, 1966

Diagnosis: Long, subcylindrical burrows, straight to slightly curved, vertical to horizontal, having concentrically layered walls. The overall shape is subconical, and tapering is slight; branches are rare. Concentric layers are of alternating light and dark sediment, including probable organic detritus. Cores are typically well centred although some are eccentric.

Discussion: The trace is interpreted as the dwelling structure of a suspension-feeding animal.

Diplocraterion Torell, 1870

Diagnosis: Vertical, U-shaped burrows having spreite. The spreiten may be retrusive, protrusive, or a combination of the two. Aperatures may be cylindrical or funnel-shaped; limbs of the U-tube may be parallel or divergent. One species, *D. habichi* is a U-tube where both tubes are in contact with each other.

Discussion: Fürsich (1974) interpreted *Diplocraterion* as the dwelling burrow of a suspension-feeding organism. Probable originators include polychaetes, echiuroids and crusteaceans.

Helminthopsis Heer, 1877

Diagnosis: Simple, irregularly meandering, dominantly horizontal, unbranched and not interpenetrating, smooth-walled traces, circular in cross section. *Helminthopsis* is a fecal string and in cross and longitudinal sections appears as irregular wisps and dots. These are normally darker than the surrounding matrix.

Discussion: *Helminthopsis* and *Helminthoida* are considered to represent the grazing traces of annelids.

Lockeia James, 1879

Diagnosis: Small, vertical, oblong, almond-shaped, symmetrical, normally smooth walled depressions in hyporelief. Individual traces normally occur as part of a crowded community.

Discussion: These are observed to be the resting traces of burrowing pelecypods. Seilacher (1953) observed that present day bivalves make similar impressions.

Macaronichnus Clifton and Thompson, 1978

Diagnosis: An unlined but distinct smooth walled, cylindrical, predominantly horizontal burrow with clean sand infill. The fill may be structureless or faintly meniscate, shown by the arrangement of mica flakes. The wall of the burrow is made up of heavy minerals and mica, with preferential accumulation along the bottom of the trace. These burrows do not branch, but they may interpenetrate where there are dense populations or abundant food. There are three species of *Macaronichnus*: *M. segregatis* (irregular traces), *M. simplicatus* (sparsely populated, irregular traces), and *M. spiralis* (closely packed, spiral shaped traces similar to systematic grazers).

Discussion: *Macaronichnus* represents the deposit-feeding trace of an opheliid polychaete. The actual traces are a function of the ingestion and cleaning of sand grains. *Macaronichnus* is not created while the organism is only moving through the substrate. These traces are normally found in high energy environments with shifting substrates. Conditions in these environments are too high in energy to support dwelling structures, and have not previously been thought capable of hosting deposit feeders.

Ophiomorpha Lundgren, 1891

Diagnosis: Simple to complex burrow systems which are distinctly lined with agglutinated pelletoidal sediment. The burrow lining is more or less smooth interiorly and densely to strongly mammilated exteriorly. Individual pellets or pellet masses may be discoid, ovoid, conical, mastoid, bilobate, or irregular in shape. Characteristics of the lining may vary within a single specimen.

Discussion: It is generally concluded that *Ophiomorpha* mostly represents the dwelling and feeding burrows of decapod crustaceans, especially numerous species of thalassinidean shrimp. The ichnogenus is somewhat intergradational with *Thalassinoides*. Physical collaspse or sediment-deformation structures may also be associated with *Ophiomorpha*. Vertical components tend to predominate in high energy environments whereas horizontal components predominate in low-energy settings.

Palaeophycus Hall, 1847

Diagnosis: Predominantly unbranched, distinctly lined, essentially cylindrical, horizontal to inclined burrows. Sediment fill is typically of the same lithology and texture as the host stratum. Wall linings may be smooth or have external stria. *P. herberti* : Burrow walls are smooth, unornamented, thickly lined and cylindrical in shape. Wall lining is of particulate material (sand or silt) and lighter in colour as well as better sorted than the surrounding stratum. *P. tubularis* : Burrow walls are smooth, unornamented, predominantly horizontal, staight to sinuous and cylindrical in shape. Linings are thin but distinct and tend to weather easily and where preserved are dark grey to black.

Discussion: Traces are interpreted as the passively infilled dwelling structures of predaceous annelids (passive carnivores).

Planolites Nicholson, 1873

Diagnosis: Unlined, rarely branched, straight to contorted, smooth to irregularly walled or annulated traces. Sediment fill is essentially structureless but lithologically different from the host stratum.

Discussion: The traces are interpreted as the feeding structures of annelids.

Rhizocorallium Zenker, 1836

Diagnosis: Horizontal, shallow, U-shaped burrow with spreite between the arms. Fill within the arms is normally identical to the surrounding matrix. Oblique sections may reveal chevron-shaped spreite similar to *Zoophycos*.

Discussion: *Rhizocorallium* is considered to be the dwelling/feeding structure of a crustacean or a vermiform organism.

Rosselia Dahmer, 1937

Diagnosis: Small central tubes surrounded by concentric, funnel-like laminae, nested convex downward, terminating in a subcylindrical, concentrically layered stem. Concentric fill is of alternating light and dark layers of sandy and muddy sediment (spreite). Orientations may be horizontal to vertical; branching is rare.

Discussion: The trace is interpreted as feeding and sediment-waste-stowage burrows of vermiform organisms.

Skolithos Haldeman, 1840

Diagnosis: Cylindrical, straight to curved, distinctly walled, rarely branched, vertical to steeply inclined burrows. Shafts are simple, unornamented, and passively filled.

Discussion: The traces are interpreted as the dwelling structures of suspension-feeding annelids.

Teichichnus Seilacher, 1955

Diagnosis: Vertical blade-like spreiten consisting of several closely concentric, horizontal or inclined, longitudinally nested individual burrows (retrusive). Long axes of spreiten are straight to sinuous, oriented at various angles with respect to bedding. Some spreiten may interprenetrate but true branching is not observed.

Discussion: The traces are interpreted as the feeding-dwelling structures of annelids.

Terebellina Ulrich, 1910

Diagnosis: Subcylindrical, straight ot gently curved, vertical to inclined burrows having thick, distinct wall linings of agglutinated sediment. The whitish wall lining closely resembles that in *Palaeophycus herberti*, although *Terebellina* is distinguished by its size and configuration.

Discussion: The trace is interpreted as the dwelling tubes of suspension-feeding or passively carnivorous polychaetes.

Thalassinoides Ehrenberg, 1944

Diagnosis: Predominantly horizontal, essentially cylindrical burrows in ramifying systems, typically enlarged at points of bifurcation; Y-branches are more common than T-junctions. Burrow walls are distinct but wall linings are rare; such linings may also include small, vague knobs, suggesting a rudimentary interrelationship with *Ophiomorpha nodosa*.

Discussion: The trace is interpreted as the feeding-dwelling burrows of crusteaceans (thalassinidean shrimp).

Zoophycos Massalongo, 1855

Diagnosis: Circular to lobate sheet-like spreite either horizontal, inclined or curved, and wound in a screw shape. A central shaft or curved marginal tube may be present.

Discussion: Most investigators regard it as the feeding burrow of a worm-like organism.

fugichnia (escape traces)

Diagnosis: Disrupted sedimentary structures and vertically repetiti· · burrows. The perturbed texture is vertical to near vertical, may spiral upwards, and normally appears as a sag trail. Some organisms may cause complete bed destruction.

Discussion: Episodic and rapid sedimentation causes benthic organisms, endobionts and epibionts to be co:ered by sediment. Buried organisms must escape up to the sediment-water interface to survive.

rhizoliths (root traces)

Diagnosis: Tapering downward, vertical, carbonaceous, branching traces. Branches are distinct; daughter roots and root hairs are smaller than the primary root, which tapers downward. Textures from the original root may also be present in the rhizolith. If filled, the trace will have an unstructured fill. This represents passive infilling after the decay of the root. Where plant density was not high, undisturbed bedding features may be common.

Discussion: Rhizoliths can occur in sandstone, mudstone, and carbonate. In carbonates, rhizoliths indicate a disconformity where plants have chemically bored into rock. Rooted sandstone may indicate submarine colonisation by plants, although a vegetated beach or barrier sand is also possible. Muds are the most commonly rooted substrate and these may be alluvial plain to coastal marsh deposits. Rooted horizons normally represent terrestrial sediments. The recognition of coastal sediments within a marine sequence may depend on the presence of root traces. Plant colonisation of land started in the Upper Cretaceous with the evolution of angiosperms (seed bearing plants).