A PALAEOBIOLOGICAL APPROACH
TO INCISED VALLEY-FILLS, ALBERTA

A PALAEOBIOLOGICAL APPROACH TO TWO CRETACEOUS INCISED VALLEY-FILLS, ALBERTA BASIN
(DUNVEGAN AND VIKING ALLOFORMATIONS)

By

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ABSTRACT

This study was undertaken to further understand the interrelationships between the endobenthos and sedimentation. Quantification of ichnospecies abundance and diversity are used to interpret their significance and the ecological conditions two sedimentologically different incised valley-fills.

This study is based on cores from two incised valley-fills from the Cretaceous Western Interior Seaway (Alberta). The first, the Waskahigan Channel (Shingle D1) in the Dunvegan Alloformation (Cenomanian) interpreted as a migrating delta, contains mud and fine-grained sand. The second, the South Willesden Green Channel (Allomember C) in the Viking Alloformation (Albian) interpreted as a straight incised valley-fill, contains coarser, reworked marine sand and conglomerates. These differences provide a comparative test for the innovative techniques used herein.

This research provided a tool to interpret changes in sea level and the depositional environment by subtle changes observed in the abundance and diversity of ichnofossil communities and ichnofacies. In the Waskahigan Bottleneck Channel (7-13-64-24W5), estuarine sand flats are distinguished by the such changes. The assemblages' abundance and diversity increased, then decreased and increased again as the channel infilled. In the South Willesden Green Channel, core 10-35-40-7W5 is interpreted as estuarine bay fill deposit. Without quantitative ichnology, the five successive fills recognized herein would be considered one deposit. In both channels, shells and shell fragments are absent as a result of physical weathering and chemical dissolution.

This study contributes methods of ichnological quantification and comparison in subsurface core. The subtle details reveal more information about the ecological conditions during the infilling of these Cretaceous depositional environments.

DEDICATION

This thesis is dedicated to my parents, Franklin and Joanne Bishop, and my brother, Leigh Bishop. Your love, support and encouragement were the beacon when the seas were rough and the shore out of sight. Calmer seas and clear sailing always follow the storm. I love you.

ACKNOWLEDGEMENT

This thesis is the result of my "path not taken." As a biologist, this study combines the mystery of estuarine communities in the past, present and possibly the future. This journey began at Acadia University. The encouragement and zest for learning were fostered by professors Drs. Graham Daborn, Sherman Boates, and Gary Yeo.

Financial support was provided by Dr. Roger Walker of McMaster University, who enabled me to choose this research topic. Technical assistance was provided by Dave Bechtel, Indy Raychaudhuri and James MacEachern of the University of Alberta. They taught me almost everything I know about ichnology. The support of Drs. William Morris, William Rink and Michael Risk of McMaster University is also greatly appreciated.

My friends that have "put up with my quest for knowledge" are numerous. However, I would like to extend my thanks and appreciation to Pam Butler and Christine Hatfield who listened even when they did not understand but ask the "right" questions anyway! Thank you.

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CHAPTER 1

BACKGROUND

1.1 INTRODUCTION

The benthic activity of organisms is one of the most fundamental concepts in ichnology. Ichnology relates biological responses of organisms to environmental changes, in particular rates of sedimentation and freshwater influx. This intricate relationship permits trace fossils to be important tools in facies analysis and palaeoenvironmental reconstructions (Frey and Seilacher, 1980). This thesis attempts to quantify some aspects of ichnology and suggests generalizations regarding the evolution of two Western Interior Seaway (Alberta Basin) incised valley-fills.

This research has four objectives. The first objective is to identify trace fossil assemblages within two Cretaceous (Cenomanian and Albian) estuaries. I chose to concentrate my research in estuaries, not because of their economic importance, but rather the interrelationship between sedimentology and benthic communities. Biogenic sedimentary structures are fundamental to understanding these stressful environments because they are controlled by the sedimentologically complex substrate in addition to environmental parameters (Frey and Seilacher, 1980; Pemberton *et al.*, 1992a). Within the rock record, estuaries have been preserved as incised river valleys infilled during rises in relative sea level. Subsurface cores enable a more comprehensive study than modern environments due the accessibility of core and the *in situ* nature of trace fossils. Using the rock record and facies analysis, palaeoenvironmental interpretations can be put forth in terms of benthic community evolution due to increased salinity during a relative rise in sea level.

The second objective is to quantify lateral and vertical variations in trace fossil diversity and abundance. Analysis of the ichnofacies will demonstrate the interrelationships of environmental variations (e.g., relative sea level fluctuations and sedimentation rates) and biogenic communities. The third objective is to compare the evolution of two incised valley-fill systems within the Western Interior Seaway (Viking and Dunvegan Formations). The final objective is to suggest behavioural responses of organisms to environmental changes during the evolution of the incised valley-fills. The overall purpose of this ichnological study is to contribute to the understanding of how ecological conditions influenced benthic communities during the infilling of these incised valleys.

The background information embodied in this chapter is divided into three sections. The first section deals with general estuarine principles and facies models. The second section introduces ichnology principles. The third section gives a brief overview of the previous work completed in the Dunvegan and Viking study areas.

1.2 ESTUARIES

Estuaries are unique spatial and temporal entities subject to marine (wave and tide) and fluvial processes. Estuaries develop within drowned river valleys as a result of eustatic or tectonic processes (Nichols and Biggs, 1985). The longevity of an estuary depends on the balance between the rate of relative sea level rise and the rate of sediment infilling (Nichols and Biggs, 1985; Dalrymple *et al.*, 1992).

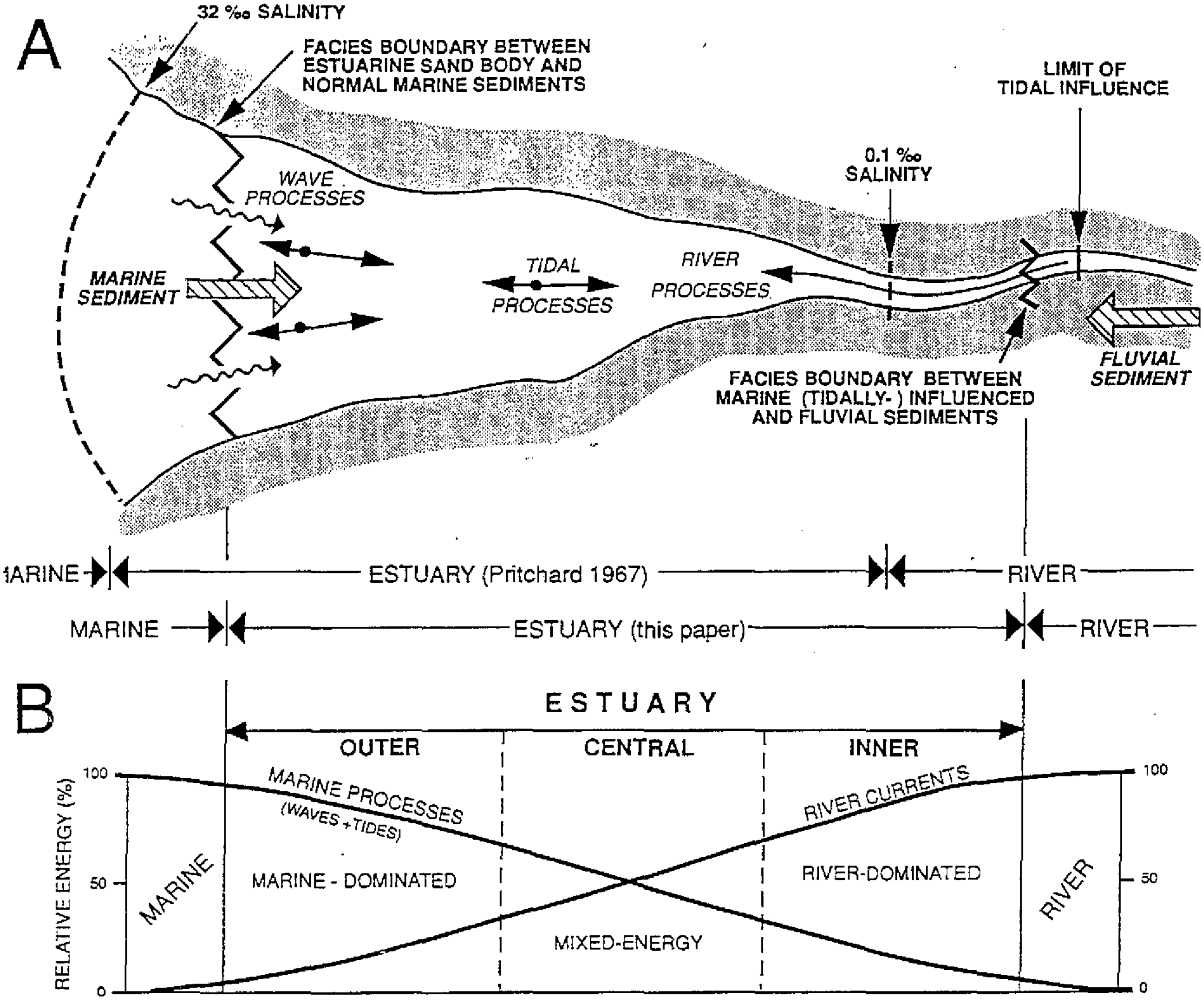
Estuaries have been defined using different criteria. The most widely accepted definitions are proposed by Pritchard (1967) and Fairbridge (1980). These definitions are based on modern estuarine environments and are not as useful when applied to ancient estuarine environments. For this study an estuary is defined as *"the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial* *processes. The estuary is considered to extend from the landward limit of tidal facies at its head to the seaward limit of coastal facies at its mouth"* (Dalrymple *et al.*, 1992, p.1132). This definition recognizes the ephemeral aspect of an estuary during transgression and the relative influence of the marine processes (waves and tides).

Ancient estuarine deposits are characterized by sedimentary and biogenic structures. These structures reflect the physical and biotic stresses of this complex environment. Characteristic trace fossil assemblages develop in these brackish water environments. These biogenic structures assist palaeoenvironmental interpretations regarding the depositional conditions governing the incised valley-fills. Based on Georgia estuaries, Frey and Howard (1986, p.911) defined an estuarine succession as *"a complex of intertidal and shallow subtidal, mostly channel-form intracoastal facies dominated to some extent by tidal processes, exhibiting conspicuous variations in sediment texture, composition, and provenance, and in physical and biogenic sedimentary structures."* The facies analysis and environmental interpretations in this thesis are based on the definitions of Dalrymple *et al.* (1992) and Frey and Howard (1986).

Wave-dominated versus Tide-dominated Estuaries

Ancient and modern estuarine facies models are classified on the basis of the dominant marine process: waves or tides. Each process produces a distinct estuarine geomorphology.

In wave-dominated estuaries, wave processes mask the weaker tidal processes of a micro- or mesotidal system. These open-ended environments are characterized by a tripartite zonation (Figure 1.1) (Allen, 1991; Dalrymple *et al.*, 1992; Reinson, 1992). The estuary mouth contains barrier-related marine deposits. The muddy central basin, within the mixed marine-fluvial zone, consists of mud, silt and very fine sand. The bay-head delta has meandering upper estuary channels composed of river-derived sand and gravel in the channel with sandy and muddy point bars along the channel-margins (Allen, 1991; Dalrymple *et al.*, 1992; Reinson, 1992).



(Taken from Dalrymple *et al.*, 1992, p. 1131)

Figure 1.1. (A) The tripartite zonation of a wave-dominated estuary was first defined by salinity levels (Pritchard, 1967). Dalrymple *et al.*'s (1992) used facies boundaries to determine the tripartite zonation. **(B)** Relative energy levels in an estuary vary depending on the relative dominance of marine processes and river currents. Both zonation models and the relative energy levels are used to interpret the palaeoecology of the incised valley-fills.

The seaward portion of the estuary can be recognized by a fining upwards of the coarse-grained sediments as relative sea level rises. The central basin is characterized by a coarsening upwards succession of interbedded very fine sandstones and mudstones. The upper estuary can be recognized by fining upwards successions of fluvial sands and gravel (Reinson, 1992).

Tide-dominated estuaries do not have this tripartite distribution of sediments (Reinson, 1992). These macrotidal estuaries experience tidal processes which extend farther into the upper estuary than wave processes. The deposited sediments become finer-grained in the landward direction, changing from coarse-grained tidal bars to high-energy sand flats to extensive intertidal and fluvial mud flats (Dalrymple *et al.*, 1992; Reinson, 1992). Channels tend to be straight in the estuary mouth, but meander in the region of the fine-grained deposits. They reestablish a straight morphology in the upper reaches of the estuary (Dalrymple *et al.*, 1992; Reinson, 1992). The lateral distribution of the channel sediments is characterized by low-energy, tidal mud flats and salt marshes bordering the channel margins and the higher-energy sands deposited along the channel axis (Dalrymple *et al.*, 1992). Physical structures such as numerous mud drapes and tidal bundles may be preserved in tide-dominated estuaries.

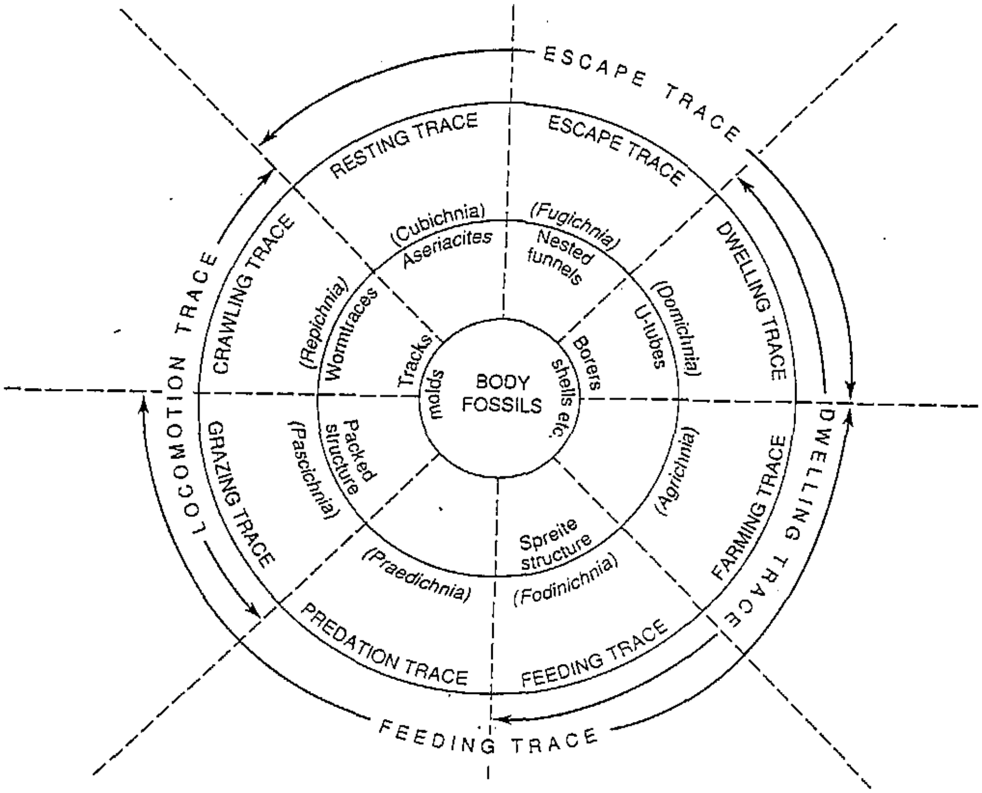
1.3 ICHNOLOGY

Trace fossils are *in situ* evidence of benthic communities in deposits which lack body fossils. In contrast to body fossils, they document the behaviour of organisms and their related ecology. These are important considerations when determining a palaeoenvironment (Seilacher, 1964, 1967; Crimes, 1975; Frey, 1975; Frey and Seilacher, 1980; Ekdale, 1985; Bromley, 1990; Pemberton *et al.*, 1992a, 1992b). Even though trace makers have evolved through geologic history, their lebensspuren (traces) have remained relatively constant (Frey and Seilacher, 1980; Pemberton *et al.*, 1992b). Ekdale (1992, p.334) states *"it is not lists of named trace fossils discovered at various intervals in core that are important, but rather it is the entire sedimentary context of bioturbation patterns and the sediment* *itself which provides the most meaningful information to the geologists."*

Feeding activities are inherent in most bioturbation patterns. An organism's feeding mode is influenced by water turbulence, sedimentation rates, water turbidity, substrate stability, salinity, dissolved oxygen and nutrient availability (Rhoads and Young, 1970; Scott, 1978). Bioturbation within the top 10-30 cm of the benthos is produced by two main trophic groups: deposit-feeders and suspension-feeders (Rhoads and Young, 1970; Scott, 1978; Wolff, 1980; Bromley, 1990). Deposit-feeders tend to occur in organically-rich, mud to fine grain sediments. As bottom currents and sediment grain size increase, the endobenthos adapts in favour of suspension-feeders. A trace fossil fits into at least one of four basic ethological patterns (Figure 1.2): feeding (fodinichnia, pascichnia, praedichnia, agrichnia), dwelling (domichnia, fodinichnia, agrichnia), escaping (fugichnia, cubichnia, domichnia), and locomotion (repichnia, pascichnia) (Pemberton *et al.*, 1992b).

Ichnofacies incorporate ethology, trophic level and depositional environment. An ichnofacies is defined as a *"characteristic association of trace fossils that directly reflects certain environmental conditions, such as bathymetry, salinity, substrate character and so forth"* (Ekdale, 1988, p.464). Ichnofacies classification is an important tool in revealing palaeoenvironments that govern recurring benthic communities. Four marine ichnofacies occur in this study: *Glossifungites, Skolithos, Cruziana,* and *Zoophycos.* *Glossifungites* is a firmground ichnofacies, whereas the others are softground ichnofacies distinguishable by decreasing hydraulic energies (Seilacher, 1967; Marintsch and Finks, 1978; Ekdale, 1985, 1988; Bjerstedt and Erickson, 1989; Frey *et al.*, 1990; Pemberton *et al.*, 1992b).

The *Treatise of Invertebrate Paleontology, Supplemental Part W* (Häntzschel, 1975) is the primary literature source for the systematics of the 28 trace fossils documented in the Waskahigan Bottleneck and South Willesden Green Channels (Table 1.1). Appendix A contains systematic ichnology including my own measurements of preserved burrow intersections.



(From Pemberton *et al.*, 1992b, page 8.)

Figure 1.2. Benthic organisms produce ethological patterns that fit into one or more of the eight patterns. Many of these ethologies overlap, depending on the organism and the physical environment.

Ichnofossil	Ethological Classification	Trophic Group	Most Probable Organism
Anconichnus horizontalis Kern, 1978	Fodinichnia	Deposit-feeder	annelid or other worm-like phyla
Arenicolites Salter, 1857	Domichnia / Fodinichnia	Suspension-feeder	polychaete or echiuriod
Asterosoma von Otto, 1854	Fodinichnia	Suspension-feeder	anemone
Bergaueria Prantl, 1946	Domichnia / Fodinichnia	Suspension-feeder	anemone
Chondrites von Sternberg, 1833	Domichnia / Fodinichnia	Deposit-feeder	echiuroid, sipunculid, or polychaete
Cylindrichnus concentricus Howard, 1996	Domichnia / Fodinichnia	Deposit-feeder / Suspension feeder	annelid
Diplocraterion parallelum SD Richter, 1926	Domichnia / Equilibrichnia	Suspension-feeder	crustacean (amphipod)
Diplocraterion yoyo Goldring, 1962	Domichnia / Equilibrichnia	Suspension-feeder	crustacean (amphipod)
Escape trace (no official ichnotaxon)	Fugichnia	Deposit-feeder	brachiopod, bivalve, sea star or semi-sessile worm
Helminthopsis Heer, 1877	Pascichnia	Grazer / Deposit-feeder	annelid or other worm-like phyla
Macaronichnus segregatis Clifton and Thompson, 1978	Fodinichnia	Deposit-feeder	polychaete
Monocraterion Torell, 1870	Domichnia	Carnivore	burrowing anemone
Ophiomorpha irregulaire Frey, Howard and Pryor, 1978	Domichnia	Suspension-feeder	crustacean (thalassinid decapod)
Ophiomorpha nodosa Lundgren, 1891	Domichnia	Suspension-feeder	crustacean (thalassinid decapod)
Palaeophycus heberti (Saporta, 1872)	Domichnia	Carnivore	annelid
Palaeophycus tubularis Hall, 1847	Domichnia	Carnivore	annelid
Planolites beverleyensis (Billings, 1862)	Fodinichnia	Deposit-feeder	annelid or other worm-like phyla
Planolites montanus Richter, 1937	Fodinichnia / Pascichnia	Deposit-feeder	annelid or other worm-like phyla
Rhizocorallium Zenker, 1836	Fodinichnia	Deposit-feeder	annelid or crustacean
Rosselia socialis Dahmer, 1937	Domichnia / Fodinichnia	Deposit-feeder	annelid or other worm-like phyla
Schaubcylindrichnus coronus Frey and Howard, 1981	Domichnia	Deposit-feeder	annelid or other worm-like phyla
? *Siphonichnus*/ *Polycylindrichnus*	Fodinichnia	Deposit-feeder	annelid or other worm-like phyla
Skolithos linearis Haldemann, 1846	Domichnia	Suspension / deposit -feeder, carnivore	polychaete
Subphyllochorda	Repichnia / Pascichnia	Deposit-feeder	annelid, echnoid or other worm-like phyla
Teichichnus rectus Seilacher, 1955	Fodinichnia	Deposit-feeder	annelid, phoronid or other worm-like phyla
Terebellina Ulrich, 1910	Domichnia	Suspension-feeder, passive carnivore	annelid, phoronid or other worm-like phyla
Thalassinoides suevicus (Rieth, 1932)	Fodinichnia / Domichnia	Deposit-feeder	crustacean (thalassinid decapod or callianassid)
Zoophycos Massalongo, 1855	Fodinichnia	Deposit-feeder / systematic grazer	unknown, possibly an echiuroid

1.4 STUDY AREAS

The Dunvegan and Viking Alloformations were chosen for study from previous McMaster subsurface work in Alberta by Bhattacharya (1989) and Boreen (1989), respectively (Figure 1.3). Regional allostratigraphy was the principal objective in each study. Bhattacharya (1989) used trace fossils as qualitative descriptors in the distributary channels of the Dunvegan Alloformation, whereas Boreen examined in detail the trace fossils located in Viking Alloformation sedimentary facies.

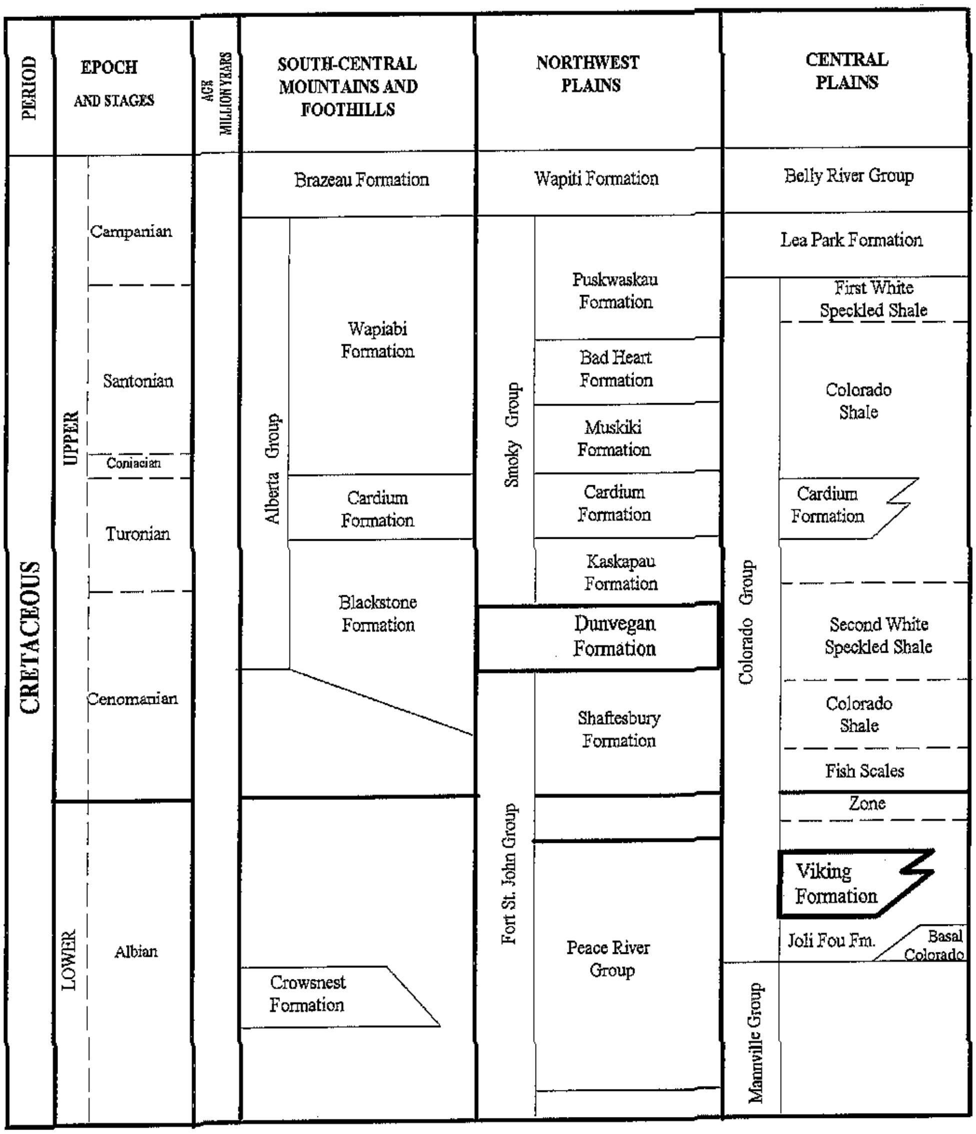
The intent of the following subsections is to briefly summarize the research initiated by Bhattacharya (1989) and Boreen (1989).

The Waskahigan Bottleneck Channel, Dunvegan Alloformation

Bhattacharya's (1989) study focused on the regional allostratigraphy and depositional systems associated with a clastic wedge (Dunvegan Alloformation) that prograded into the northwest region of the Western Interior Seaway (Alberta) during a global lowstand of sea level (94 Ma, Middle Cenomanian). His study encompassed Townships 50-67 and Ranges 15W5-10W6, and examined 134 cores and more than one thousand well logs.

The Dunvegan Alloformation (Middle Cenomanian) is up to 350 m thick, and situated between the Shaftesbury and Kaskapau Shales (Figure 1.3). Rice and Gautier (1983) named this southeastward prograding clastic wedge the "Dunvegan Delta." This wedge, consisting of interbedded marine to nonmarine sandstones and mudstones, was deposited in the actively subsiding Alberta foreland basin during the waning stages of Columbian Orogeny (Bhattacharya, 1989; Bhattacharya and Walker, 1991a; 1991b). The succession of depositional environments displays an overall upwards decline of fluvial processes and an increase of marine influences, such as waves and tides (Bhattacharya and Walker, 1991a; 1991b).

The Dunvegan sediments are divisible into seven subsurface allomembers (A-G). Each composed of several autocyclic shingles of deltaic to shoreline-related sediments (Bhattacharya and



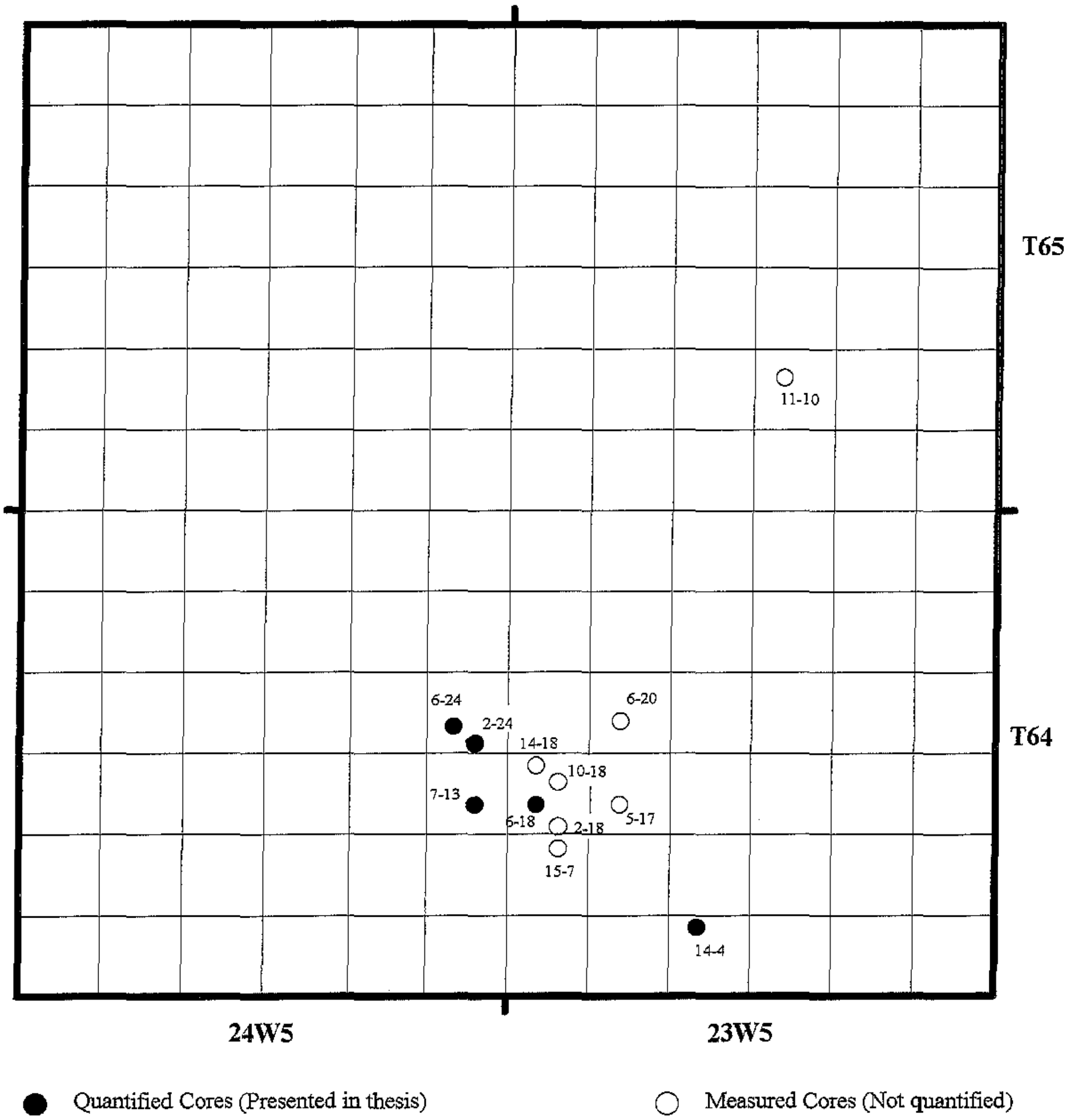
(modified from AGAT Laboratories, 1988)

Figure 1.3 Stratigraphy of the formations located in west-central and northern Alberta. The Viking and Dunvegan Formations are highlighted yellow.

Walker, 1992). Allocyclic processes such as a rise in relative sea level induced by transgressions and/or regional tectonics control the accommodation space for sediment deposition of each allomember. Each allomember consists of packages of sediments that are governed by autocyclic processes (river avulsion and lobe switching). Ravinement surfaces indicate the maximum flooding events that terminate the deposition of individual allomembers. Only the ravinement surface between allomember D and C was observed in the cores of my study. The autocyclic shingles are terminated by regressive surfaces of erosion mantled by shale and sideritized mud rip-up clasts.

The Dunvegan is primarily composed of wave-influenced depositional systems, including deltas and barrier islands. The sediments deposited in the distributary channels during rises of relative sea level were also influenced by tidal processes and salinity fluctuations. Evidence of these processes is preserved in physical sedimentary structures such as parallel and wave laminations, mud couplets and synaeresis cracks. Bhattacharya (1989) assigned these marine-influenced deposits to Facies Association 5 (FA5) which is commonly located in the upper portions of most allomembers (A-D) and underlying ravinement surfaces (Bhattacharya, 1989; Bhattacharya and Walker, 1991a).

The Waskahigan Bottleneck region is my chosen study area as a result of comments made by Bhattacharya (1989) regarding the location of the incised valley. The channel in this region is a major distributary channel of Shingle D1 (Allomember D). My study encompasses Townships 63-64 and Ranges 23-24W5 (Figure 1.4). The measured cores are located along the deeper portions of the channel, with one core in the northeastern margin in the Ante Creek field (Township 65 and Range 23W5). Unlike the South Willesden Green Channel, the Waskahigan Channel has preserved fluvial sediments and a regressive surface of erosion marks the base of this distributary channel in Shingle D1. This shingle erosively truncates a prograding barrier complex, including a tidal inlet capped by lagoonal facies associated with Shingle D2. The 10 cm ravinement surface separating Allomembers D and C contains bioturbated sandy mudstone. Allomember C is represented by black, rarely bioturbated shales.



Core Locations in the Waskahigan Bottleneck Channel, (Shingle D1), Dunvegan Alloformation

Figure 1.4 Location map of the Waskahigan Bottleneck, Dunvegan Alloformation study area.

Detailed discussions of the subsurface sedimentology of the Dunvegan Formation have been presented Burke (1963) and Bhattacharya (1989, Chapter 1).

South Willesden Green Channel, Viking Alloformation

Previous Viking research at McMaster University focused on the regional stratigraphy of the shallow marine to shoreline deposits within the late Albian Alberta Basin. The Viking Alloformation overlies the Joli Fou shales and is overlain by the marine shales of the Colorado Group (Figure 1.2).

Boreen (1989) studied the sedimentology and stratigraphy of the Willesden Green, Ferrier and Gilby B oil and gas fields in west central Alberta in the area of Township 39-43 and Ranges 4-8W5. He measured 127 cores and used 514 well logs to establish the Viking stratigraphy for this region. Within the Willesden Green area, he mapped two channels, one trending NNW-SSE (North Channel) and the other trending ENE-WSW (South Channel). The sediments of the estuary mouth display evidence that channel infilling apparently occurred in two stages, with the second stage being coarser than the first as a result of marine winnowing of finer-grained sediments.

Boreen (1989) divided the Viking deposits at Wiliesden Green into five allomembers (A-E). As relative sea level fluctuated, the deposits of each allomember were separated by pebble-mantled discontinuities, identified as Viking Erosion surfaces 1-4 (VE1-VE4). The deposits of allomembers A and B were interpreted as upper offshore and lower shoreface, respectively. A major fall of relative sea level caused the erosive truncation of these sediments and produced the pebble-mantled VE2 erosion surface. This regression was followed by a slow, continuous, basinwide transgression and deposition of the incised valley sediments. The VE2 surface marks the incision of the Willesden Green valley that was subsequently backfilled with wave-dominated estuarine sediments (allomember C). The VE3 erosion surface that blankets the incised valley-fill is overlain by the storm-dominated marine sediments of allomember D which are stratigraphically equivalent to the "Viking regressive facies" of Leckie (1986). The presence of HCS sandstone intervals suggests that deposition occurred above storm wave base. Allomember E consists of black shales and interbedded granular sandstones and lenticular siltstones. Discernable burrows are rare but fish scales are abundant, suggesting a quiet, deep marine environment. Stratigraphically above the transgressive mudstones is the Westgate Formation of the Colorado Group (formerly the unnamed shales of the Colorado Group) (Bloch *et al.*, 1993).

Boreen's (1989) work is incorporated into my smaller, localized study of the South Willesden Green Channel in Allomember C (Figure 1.5). My study encompasses Townships 40-42 and Ranges 6-7W5. Allomember C is interpreted as a channel backfilled with interbedded estuarine mudstones and sandstones, cross-bedded sandstones and clast supported conglomerates (Boreen, 1989). The fluvial deposits were reworked into transgressive lags directly overlain by marginal marine deposits that overlie the VE2 discontinuity. This modified regressive/transgressive surface of erosion is marked deposited in two stages in the Willesden Green area. The interbedded mudstones and sandstones (Facies Association 3) deposited in the first stage are finer-grained than the overlying cross-bedded sandstones by a regionally extensive *Glossifungites* Ichnofacies. This firmground is burrowed by *Skolithos*, *Thalassinoides* and *Arenicolites* tracemakers. The marine-derived sediments of the channel fill are interpreted to have been (Facies Association 2) associated with the second stage (Boreen, 1989; Boreen and Walker, 1991). Biogenically, Facies Association 3 is more interesting than Facies Association 2 due to the preservation of more diverse and abundant trace fossil assemblages due to the nature of the sedimentary deposits and other physical conditions affecting bioturbation. The likelihood of similar diversities and densities of ichnofossils being preserved is unlikely in the high-energy environment of the estuary mouth where Boreen's (1989) Stage 2 deposits are located. Further interpretations and details can be found in Boreen (1989).

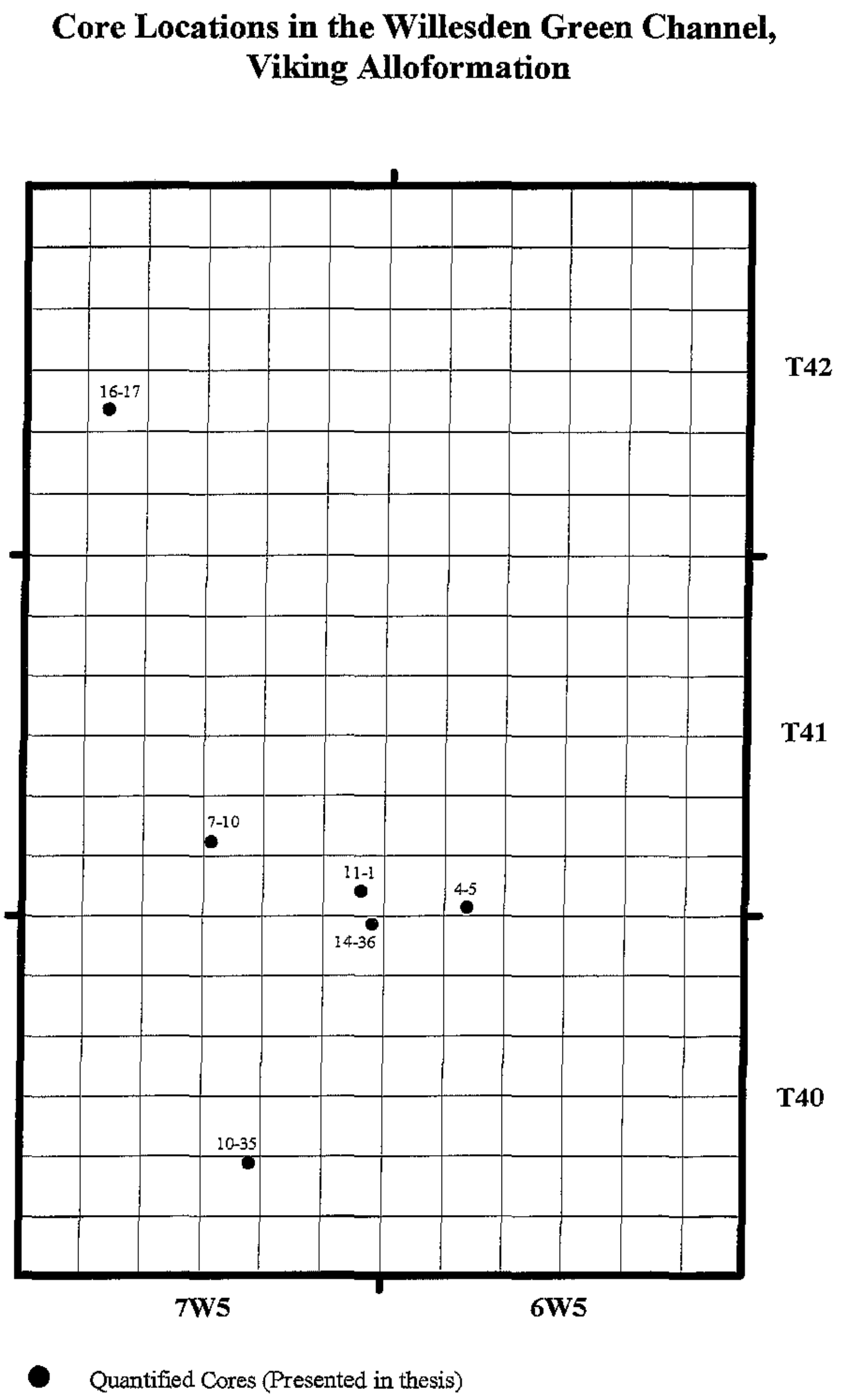


Figure 1.5 Location map of the Willesden Green, Viking Alloformation study area.

This thesis focuses on the results and generalizations regarding the palaeoecology and palaeogeography of Waskahigan Bottleneck and the South Willesden Green Channels. The devised methods were tested using twelve Waskahigan and six Willesden Green cores. The reexamination of these cores provided more biological data for these incised valley-fills in order to further existing palaeoenvironmental generalizations.

CHAPTER 2

METHODS OF DATA ACQUISITION

2.1 QUANTITATIVE PALAEOECOLOGY

A reconstruction of the palaeoecology of a marine environment depends on the information at the sediment-water interface. Sedimentary facies and biogenic structures are essential components for reconstructing an estuarine environment (Fürsich, 1978; Frey and Seilacher, 1980; Birks, 1985). Environmental parameters such as salinity, temperature, water depth and/or chemistry can be measured or suggested by the lithology, grain size and physical sedimentary structures. Biogenic sedimentary structures document morphological changes in population size and composition in response to physical variations (water chemistry, turbidity and sedimentation rates) and/or ecological parameters such as nutrient availability and substrate consistency (Seilacher, 1967; Ekdale, 1985). The size and shape of individual burrows can reflect changes in the physical environment such as salinity and oxygen levels (Savrda and Bottjer, 1986, 1989; Pemberton and Wightman, 1992).

Quantitative palaeoecology encompasses numerical techniques used to reconstruct the ecological conditions of ancient depositional environments. Birks (1985) outlined eight commonly used statistical methods, depending on the size and type of data being manipulated to effectively reconstruct the palaeoenvironment. Clark and Evans (1954) and Pemberton and Frey (1984) measured the distances between ethological patterns in outcrop quadrants to determine spatial relationships in ancient populations by using "nearest neighbour" and "dispersion coefficient" methods. Clark and Evans (1954) suggested that these methods could be modified to estimate dispersal distances throughout a volume of rock. However, my data sets are inappropriate for these statistical methods because I concentrated on counting and measuring discrete burrow intersections on the core surface rather than measuring the distance between burrows. The burrow dimensions in the Cretaceous incised valleys reveal critical information regarding the response of benthic invertebrates to resources and/or niche competition (Pemberton and Frey, 1984; Savrda and Bottjer, 1986, 1989; Pemberton and Wightman, 1992).

I quantified ichnofossil assemblages in order to investigate subtle environmental variations in the conditions that may have existed during the infilling of the incised valleys of the Western Interior Seaway, Alberta. The following methods were designed to initiate palaeoecological investigations of these complex depositional environments and suggest generalizations, testable in other incised valley-fills.

2.2 DATA ACQUISITION

During the summer of 1992, at the E.R.C.B. Core Laboratory in Calgary, I had two objectives: 1) assemble a data base by logging cores with emphasis on the biogenic structures in the Waskahigan Bottleneck and the South Willesden Green incised valley-fills and 2) document these trace fossils and associated facies by photographing the cores. Data quality was the main criterion in determining the number of cores I was able to log during three months. Fewer cores with accurate data are more beneficial to my ichnological study than many cores with poorer-quality data.

Logging Core

I used the core listings and interpretations of Bhattacharya (1989) and Boreen (1989) to choose the cores located in the incised valley-fills consisting of estuarine sediments. In total I logged 18 cores: 12 from the Waskahigan Bottleneck Channel (Dunvegan Alloformation) and six from the South Willesden Green Channel (Viking Alloformation) (See Appendix B for locations and depths). However, only 11 cores (5 Dunvegan and 6 Viking) are used to develop the palaeoenvironmental generalizations.

The Dunvegan cores are presented in the thesis because ichnological interpretations are not presented by Bhattacharya (1989). Each core took 1-2 weeks to log depending on facies variations and thickness, in addition to the diversity and abundance of ichnofossils preserved in the 3" (7.5 cm) or 4" (10.0 cm) diameter cores (9-18 m long). In my centimeter-scale investigation, every discernable trace fossil intersection on the vertical core surface and accessible bedding planes are described, counted and measured (width and height, mm-scale). In pervasively bioturbated sediments, most traces are not well defined, and therefore only discrete trace fossils are included in the quantitative analyses. This exclusion of undiscernable traces is to preserve to the accuracy of the ichnofossil data base. Two Dunvegan wells consist of sandstones which lack trace fossils and are not included in this ichnological study but were interpreted as channel deposits.

Photographing Core

I photographed the cores for two reasons: 1) to establish a permanent record of the sediments and trace fossils for reference at McMaster University and 2) record the reflectivity of the sediment surface as an approximation of the proportion of sand. I hypothesize that the proportion of sand might be related to biogenic structures.

All cores were photographed in their boxes, to show their overall stratigraphic position, and selected portions were also photographed close up, with or without an extension tube on the camera. These photographs are helpful in identifying those biogenic structures of initially unknown ichnogenera (e.g., *?Siphonichnus* and *Subphyllochorda*).

The second reason for photographing the cores was to measure the reflectivity of the core surface under standard lighting conditions. This approach semi-quantitatively estimated the proportion of sand (pale grains), and mud and silt (dark grains). The data are used to determine the relationships, if any, between substrates and ethological patterns of benthic animals. Due to financial and time constraints, thin sections are not available for calibration with the photographed sections.

The equipment used for measuring the surface reflectivity consisted of a camera with an extension tube, set to a f-stop of twenty-two. The camera was focussed on the core surface (10-30 cm long) until only the surface was visible. Maximizing the core surface allowed for an accurate record of the proportion of pale and dark grains in the examined lithologies. The lights were adjusted to the same height as the camera to standardize the illumination of the core. At the table edges, the light stands were placed diagonally from the core cradle which was located in the center of the table. The distance of the camera varied slightly depending on the length of the core section. For relatively long core sections (>15 cm) the height of the camera was higher than with the shorter sections because filling the viewfinder did not need major reductions in the distance between the core and camera. Figure 2.1 illustrates the basic arrangement of equipment.

Once the photographic equipment was adjusted and the camera focussed, the shutter speed estimated by the camera was recorded for five randomly selected locations on the core surface. Of these locations at least one was from the top, middle and bottom of the core segment. The interval depths and corresponding paleness as estimated by the shutter speed were recorded for all selected core sections. In general, non-interbedded facies gave five identical shutter speed measurements. However, interbedded facies usually registered two distinct measurements. Sand-dominated intervals registered higher shutter speeds because of thicker and cleaner, sand (paler) interbeds as opposed to lower shutter speeds associated with thicker and mud (darker) intervals. These recorded shutter speeds are related to substrate types in an attempt to suggest possible animal-sediment associations. Photographs were taken of the sediments registering these shutter speeds so that they could be quantified in terms of pale (sand) and dark (mud, silt) grains.

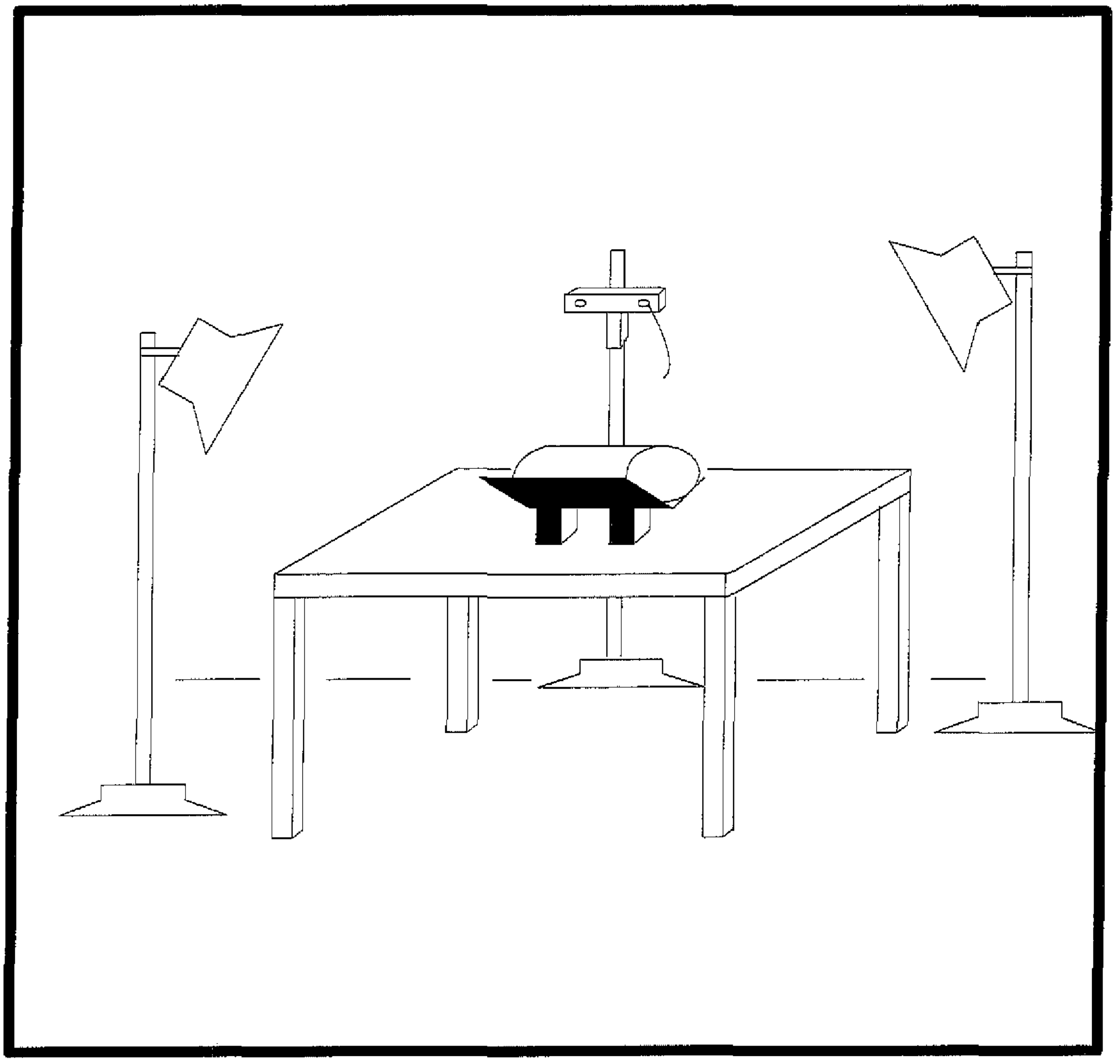


Figure 2.1 A schematic diagram of the photographic equipment arrangement used to measure the reflectivity of core sections.

2.3 DATA MANIPULATION

Upon returning to McMaster in the Fall of 1992, the data were manipulated in an attempt to suggest palaeoecological conditions that may have existed during the deposition of the Waskahigan Bottleneck Channel and South Willesden Green sediments. This data manipulation occurred in three stages: 1) computer drafting and data entry, 2) statistical analyses and 3) substrate quantification. The quantitative methods were chosen to show how trace fossil assemblages within brackish-water environments were affected by subtle environmental variations.

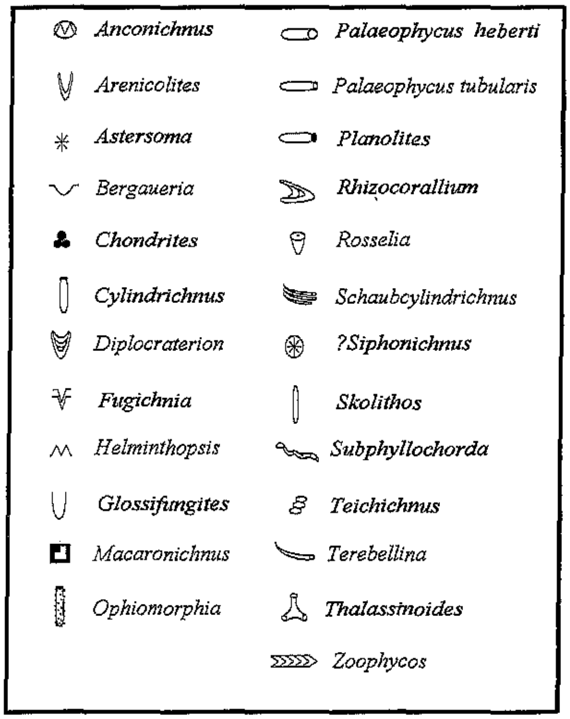
2.3.1 COMPUTER DRAFTING AND DATA ENTRY

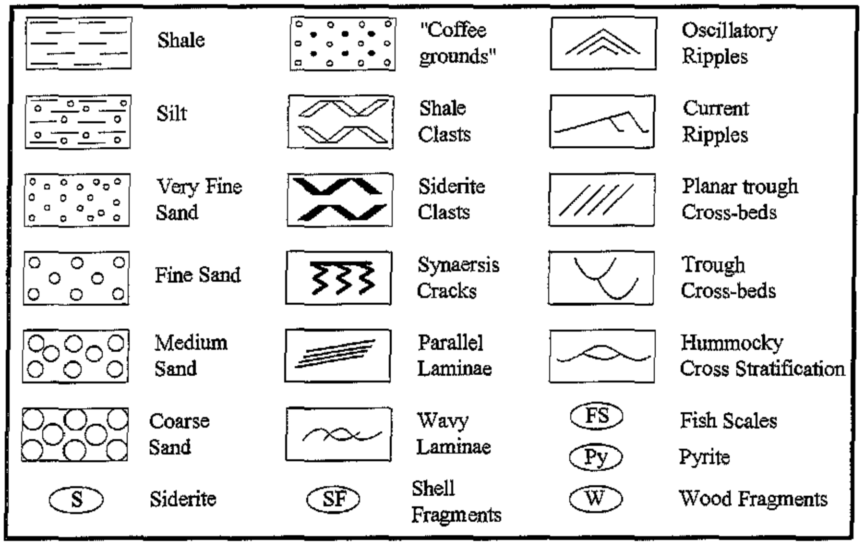
The hand-drawn core lithologies were drafted on the computer using Designer, a Micrografx software program. My template is based on accepted symbols for physical structures and most of my ichnofossil symbols are based on the legends published by Pemberton (1992) (Figure 2.2 and Pocket 1). These trace fossils symbols were designed by Mike Ranger (University of Alberta) for his core logging software program. The final drafts of these core sections are presented throughout the body of this work. Associated with these sections are the summarized quantitative data and depositional environments interpreted based on changes in ichnofossil assemblages and lithologies.

Quattro Pro 4.0 was used to analyze the total numbers, vertical extension and width measurements of ichnospecies, and corresponding measured core intervals collected in Calgary. The primary analysis involved standardizing the abundance of burrow intersections to a standardized area so that ichnofossil assemblages could be compared. Standardizing the core intervals is useful because the raw data intervals varied depending on the facies changes and breaks in the core.

Number of Burrow Intersections per Standard Area

This quantitative analysis is based on the number of burrow intersections within a given core area and not the number of organisms inhabiting the sediment. The observed burrow intersections may


Anconichnus
Arenicolites
Astersoma
Bergaueria
Chondrites
Cylindrichnus
Diplocraterion
Fugichnia
Helminthopsis
Glossifungites
Macaronichnus
Ophiomorphia
Palaeophycus heberti
Palaeophycus tubularis
Planolites
Rhizocorallium
Rosselia
Schaubcylindrichnus
?Siphonichnus
Skolithos
Subphyllochorda
Teichichnus
Terebellina
Thalassinoides
Zoophycos


Shale
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
S
Siderite
"Coffee grounds"
Shale Clasts
Siderite Clasts
Synaersis Cracks
Parallel Laminae
Wavy Laminae
SF
Shell Fragments
Oscillatory Ripples
Current Ripples
Planar trough Cross-beds
Trough Cross-beds
Hummocky Cross Stratification
FS
Fish Scales
Py
Pyrite
W
Wood Fragments

represent either one or several organisms. One organism can make several ethological patterns, depending on substrate consistency and its life cycle stage or several animals can produce morphologically-similar behavioural responses to environmental conditions (Frey, 1975; Frey and Seilacher, 1980; Pemberton and Frey, 1984; Bromley, 1990). Another reason for using burrow intersections is the potential for incomplete views of a trace in core sections (Bromley, 1990).

Diversity and abundance variations of ichnofossil assemblages are used to suggest potential palaeoenvironmental parameters based on the lithology, physical and biogenic sedimentary structures (Frey and Seilacher, 1980; Birks, 1985).

Based on the above considerations, "Number of Burrow Intersections per Standard Area" (i.p.s.a.) were calculated using the data base and the following equation:

$$x=\frac{a}{(b\cdot c)}\cdot 100$$

where the number of burrow intersections per standard area (**x**) is based on the total number of burrow intersections for a specific ichnospecies per core interval (**a**) divided by interval area. This area is calculated by multiplying the core circumference (**b**) by the interval thickness (**c**). The core circumference is based on a 3" (7.50 cm) or 4" (10.00 cm) diameter and average interval thickness of 20 cm, but as thin as 5 cm. To compare burrows, the number of intersections per area is standardized by multiplying (**a/(b•c)**) by 100.

The resultant burrow i.p.s.a. ranged from 0.01 to >30.00. They are related to a colour-symbol scheme (Figure 2.3 and Pocket 1) to help identify vertical variations concerning diversity and abundance of particular ichnofossil assemblages. The colour/symbol scheme is based on colours becoming warmer as the burrow intersections of a particular ichnospecies becomes more abundant. The symbol qualifies the abundance. Five of the six colours are repeated as the three symbols change, in order to keep the

Colour Scheme for the Number of Burrow Intersections per Standard Area (i.p.s.a.)

▲	30.01	–	>40.00
◬	20.01	–	30.00
■	18.01	–	20.00
▨	16.01	–	18.00
□	14.01	–	16.00
■	12.01	–	14.00
■	10.01	–	12.00
●	8.01	–	10.00
◍	6.01	–	8.00
○	4.01	–	6.00
●	2.01	–	4.00
●	1.01	–	2.00
●	0	–	1.00

colour/symbol scheme simple. Circles represent the lowest densities in this study (0-10.00 i.p.s.a.). Squares are associated with intermediate burrow abundances of 10.01-20.00 burrow i.p.s.a. and triangles designate those traces that occurred in densities greater than 20.01 burrow i.p.s.a., especially *Helminthopsis* and *Anconichnus*. For example, if a green circle (2.01-4.00 i.p.s.a.) is overlain by a green square (12.01-14.00 i.p.s.a.), the abundance of that trace could have increased by 8.01-11.99 i.p.s.a.

Overall, most ichnospecies occurred in densities fewer than 1.00 burrow i.p.s.a. (indigo blue circles), but even these traces are significant to the overall trace fossil assemblage. The diversity of a trace fossil assemblage was determined by the abundance of individual ichnospecies and breaks in the depositional units. Variations in these assemblages suggest subtle changes in the ecological parameters near the sediment-water interface at the time of deposition. These changes and the intensity of bioturbation, besides preserved physical sedimentary structures, help in the development of ecological generalizations and enhance facies analyses.

2.3.2 STATISTICAL ANALYSIS

The data were analyzed by two methods: 1) graphs and 2) correlations. The results of these tests were used to construct the palaeoecological generalizations of the Cretaceous incised valley-fills.

Graphs

Abundances of each trace fossil were plotted against abundances of another trace to detect subtle patterns. These patterns represent potential affinities between animal burrowing and substrates or other physical parameters. Patterns recognized include 1) i.p.s.a. for both traces increased or decreased together and 2) the i.p.s.a. for one trace decreased as the i.p.s.a. for the other trace increased. The best five trace fossil pairs were chosen for statistical analysis from these graphs.

Burrow abundances of *Planolites* were also plotted against abundance of shrinkage cracks to assess subtle changes occurring at sediment-water interfaces. The abundance of burrow i.p.s.a. generally increased above intervals containing shrinkage cracks, but did decrease above some intervals.

Correlations

Correlation, one method outlined by Birks (1985), is the numerical technique best suited for my small data sets. This method tests the statistical significance of two associated ichnofossils without quantifying many integrated factors, unlike multivariate tests that require large data sets ($n \geq 150$) (Birks, 1985).

The five best trace fossil pairs, as determined by graphs, were analyzed for potential potential trends in the paired occurrences within the channel fills. The correlations suggest dependent trace fossils ($R^2 \geq 0.60$) or result from substrate texture and unknown quantitative parameters. Some assemblages are preserved completely while others are partially destroyed by biogenic reworking or erosion, potentially reducing the statistical significance (Frey and Seilacher, 1980; Pierce, 1989). Although not statistically significant, these correlations provided useful information on the complex interactions between sedimentation and the presence or absence of ichnofossils. In controlled biological studies, parameters are established and tested. However, in geological studies all factors cannot be quantified, thus many dependent factors can influence the depositional interface (Birks, 1985).

2.3.3 SUBSTRATE QUANTIFICATION

The systematic, qualitative substrate method (see page 19) is based on the assumption that specific trace makers only colonize suitable depositional interfaces (i.e., appropriate consistencies and sand/mud ratios) (Rhoads and Young, 1970; Bromley, 1990; Pemberton *et al.*, 1992b). In unsuitable substrates, these trace makers should be rare or absent. Physical processes, sedimentation rates and food supply will also influence the benthic colonization of particular substrates.

Substrate compositions were quantified by visual point counts of the pale (sand) and dark (mud and silt) grains. These proportions represent the documented qualitative measurements. Paper copies of the original slides, reproduced by a laser photocopier, were used to quantify the ratio of pale versus dark sediment grains for each substrate type. These photographs depict the core surface that registered the shutter speed range, and the functional grain size (agglutinated grains larger than the individual sediment grains) as observed by the organism. This method reduced possible sediment discrepancies of a thin section cut from a core sample that may not be the actual surface that registered a particular shutter speed. However, if time and funding permitted, thin sections could have been used to calibrate the sediment proportions. Disaggregation, another possible method, was not used because the functional grain size and the organic content might be destroyed and potentially change the substrate proportions. With these limitations and the burrowing position of an organism in mind, I chose to do point counts of the pale versus dark grains using the photographs.

These photographs represent close-ups of the core surface, commonly taken using an extension tube mounted on the camera. However, some close-up photographs used in this analysis were taken without the extension tube, so they were classified as either extension tube or non-extension tube photographs. This distinction qualified the results in terms of sediment percentages, especially the averaged percentages. For example, inaccurate pale versus dark grain percentages may have resulted from non-extension tube photographs due to the inability to distinguish discrete dark grains and a reduction of the sample size for calculating the average percentages.

To calculate the percentage of pale and dark grains, the paper copies of the slides were divided into 16 cm^2 areas. Extension tube photographs were divided into fifteen or twenty squares, depending on the photograph, whereas non-extension tube photographs were only divided into three or four squares. To simplify counting and reduce personal error, each square was subdivided into eight sections. All discernable pale grains, defined as light grey and bright white grains, were counted. Similarly, the dull medium to dark grey and black grains were counted. The percentages of the two groups were tabulated and averaged over the number of squares (3-10) examined, depending on the photograph.

A limitation to this method occurs in the Viking sediments. The Viking sediments contain black chert grains. These sand grains likely affect the overall reflectivity of the core surface, however, the trace fossil assemblages associated with these sediments should be similar to those in non-black sand deposits.

The information provided by these point count averages is valuable in generalizations regarding the type of sediment and preservation potential of trace fossils (Rhoads and Young, 1970). This information provides insights to why certain facies are characteristic of some substrate types and not others.

CHAPTER 3

WASKAHIGAN BOTTLENECK INCISED VALLEY-FILL, DUNVEGAN ALLOFORMATION

3.1 INTRODUCTION

This ichnological investigation of the brackish-water sediments in the Dunvegan Alloformation was based on data and interpretations published by Bhattacharya (1989). The study area, known as the Waskahigan Bottleneck, encompasses Townships 63-65 and Ranges 23-24W5 (Figure 3.1). This incised channel is preserved in Shingle D1 of Allomember D, a wave- and storm-dominated deltaic system (Bhattacharya, 1989). The meandering distributary channels in this shingle were backfilled with estuarine sediments during the initial stages of transgression. The thickest deposits of estuarine sediments are preserved in the cut bank portions of these channels.

Various shales, mudstones, sandstones and erosional lags were described by Bhattacharya (1989). My independent observations agree with those published. Of his ten facies only seven are observed in my study because it is smaller and contains fewer cores. The facies descriptions are located in Appendix C. Bhattacharya (1989) grouped these facies into seven facies associations, which ranged from channel sandstones to interdistributary bay/lagoonal mudstones-fills (Appendix D.1).

The facies associations were divided into eight depositional environments to enhance Bhattacharya's (1989) work (Appendix E.1). These depositional environments are identified on the vertical core sections presented in this chapter. Facies changes reflect changes in the physical energies and ethological patterns of benthic communities. Depositional boundaries are determined by facies

Core Locations in the Waskahigan Bottleneck Channel (Shingle D1), Dunvegan Alloformation

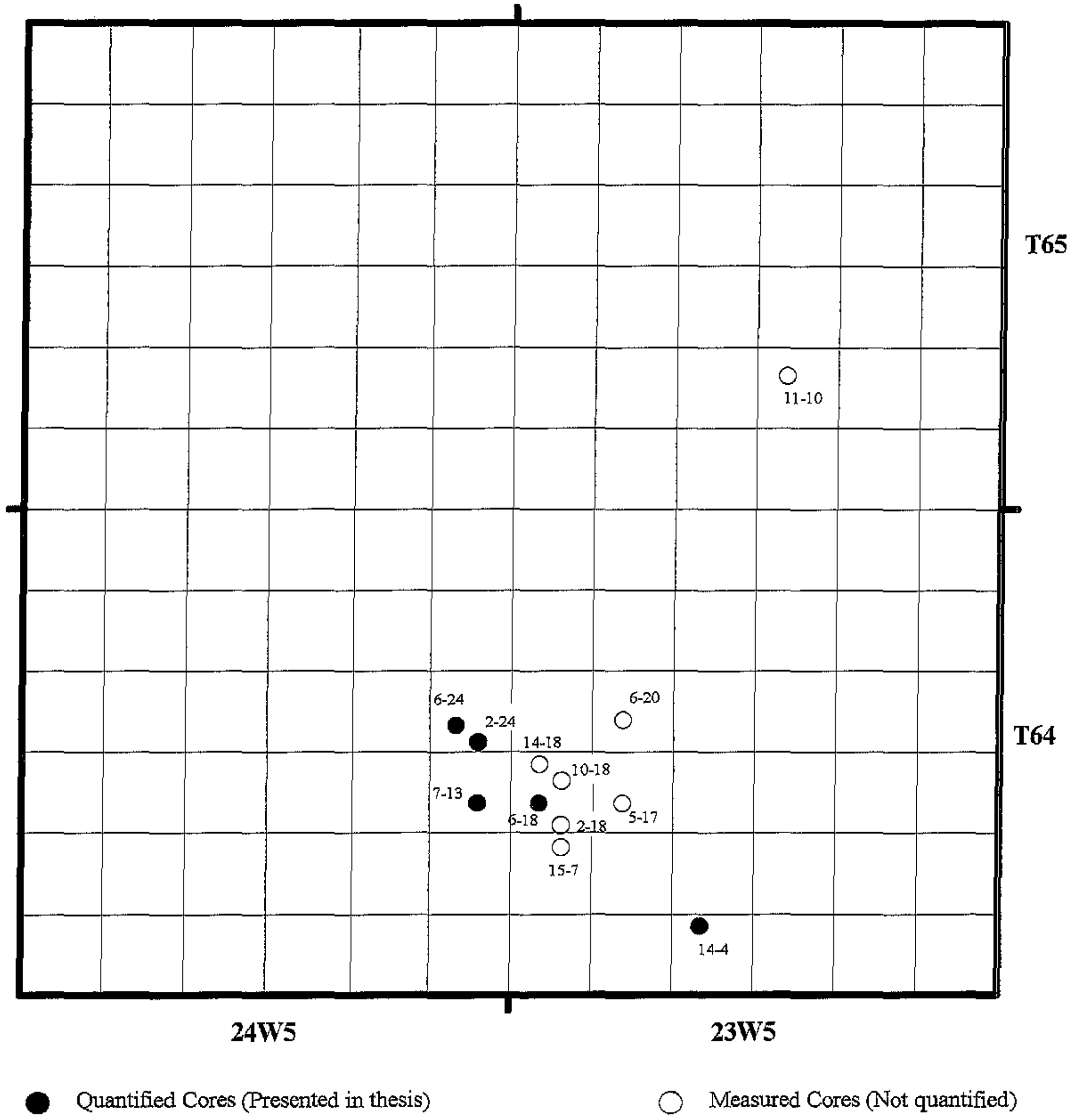


Figure 3.1 The Waskahigan Bottleneck study area cores in Townships 63-65 and Ranges 23-24W5. The solid circles show the cores presented in this chapter.

successions and abrupt diversity and/or abundance variations in ichnofossil assemblages.

The Waskahigan Bottleneck Channel, unlike the South Willesden Green Channel, is a distributary channel that has not been interpreted with respect to ichnological variations along the channel axis. The following ichnological approach attempts to provide further insight into the environmental parameters governing the development of biological communities in a wave-dominated deltaic system.

3.2 VERTICAL VARIATIONS IN ICHNOFOSSIL ASSEMBLAGES

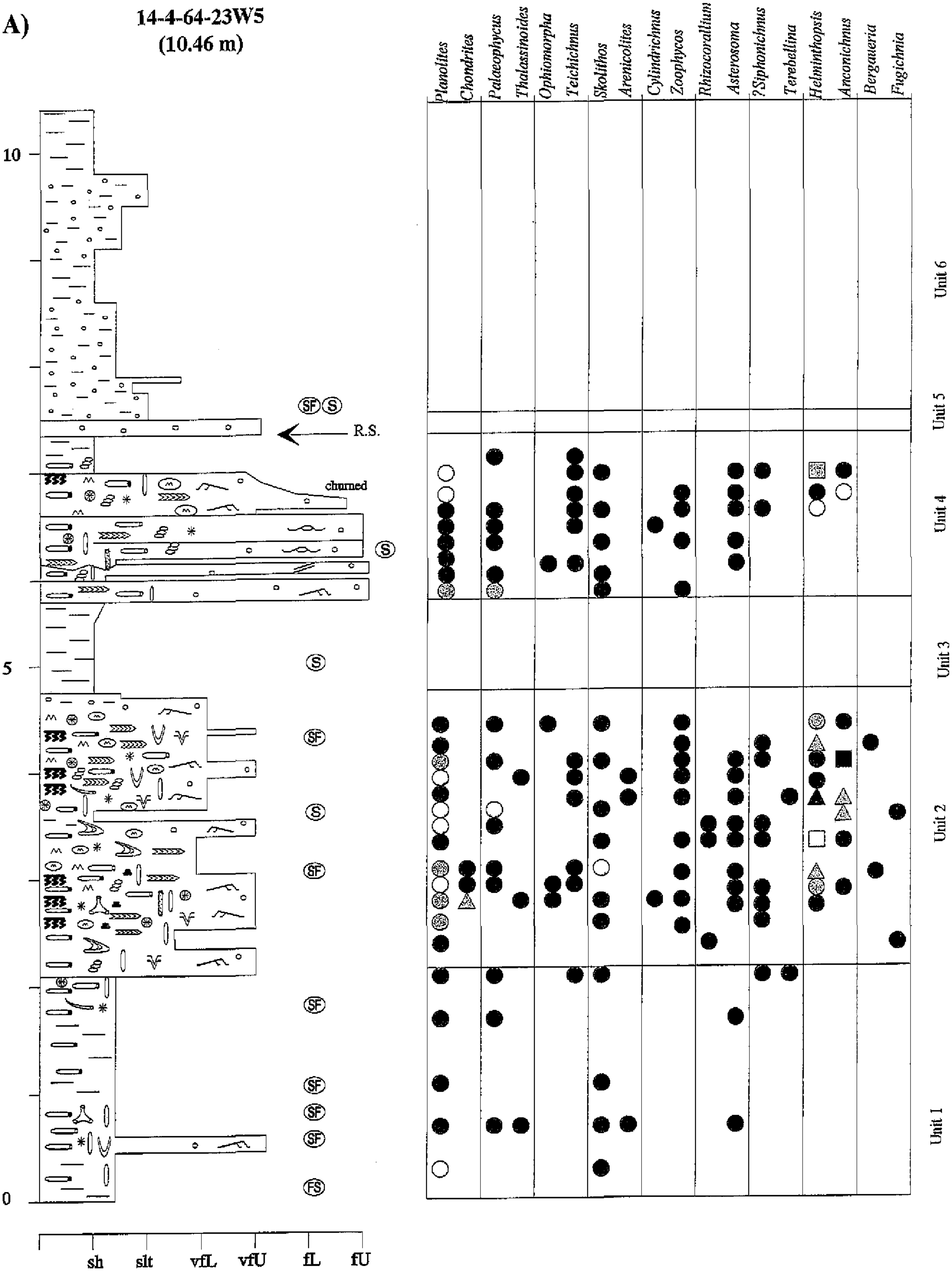
This section contains detailed descriptions of five Dunvegan cores, organized from the most seaward (14-4-64-23W5) to the most landward (6-24-64-24W5) location. Physical structures allowed subdivision of the cores into many measurement units. Ichnospecies were measured and grouped into trace fossil assemblages based on abundances and diversities.

14-4-64-23W5 Core Description

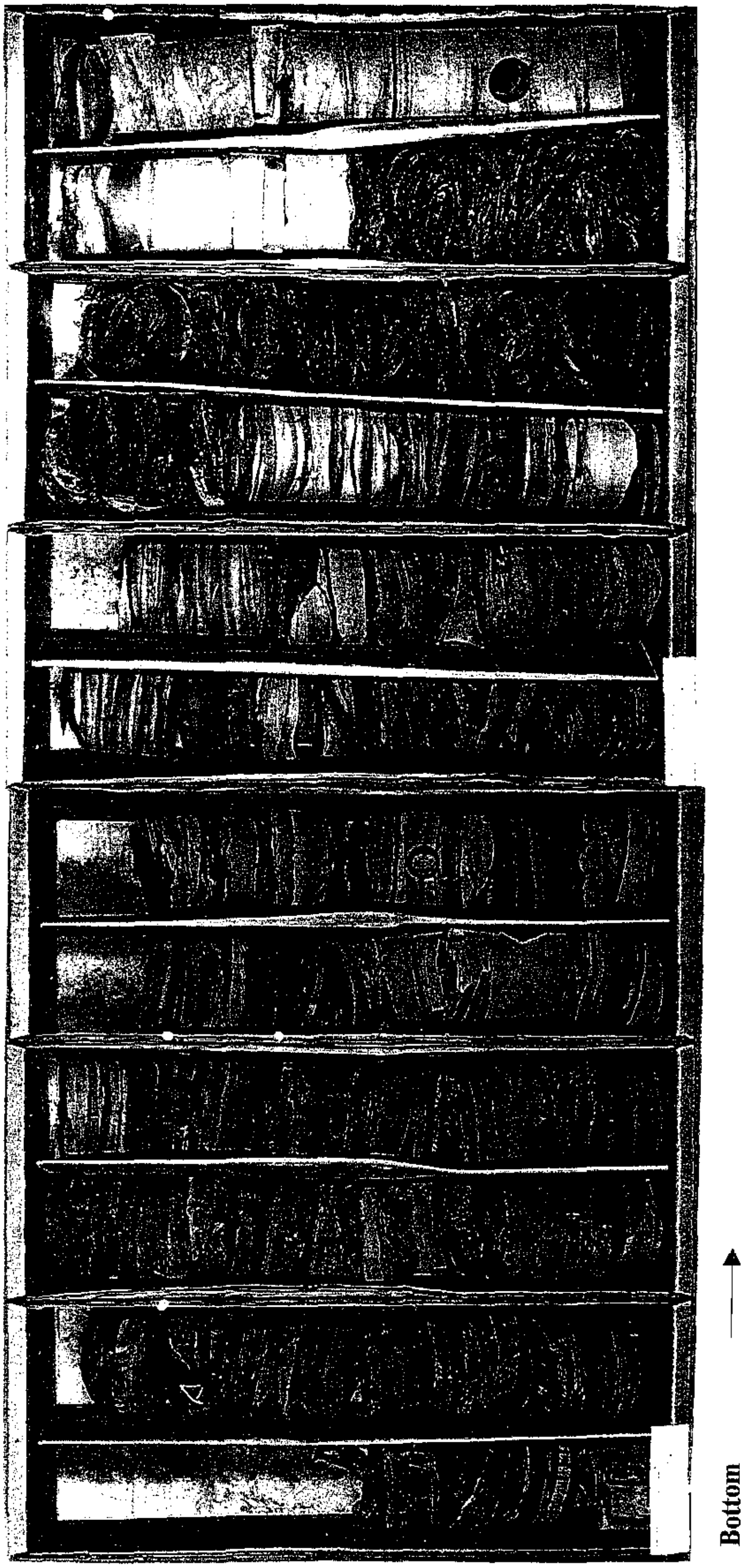
This 10.46 m core contains shales and mudstones interbedded with very-fine to fine-grained sandstones (Figure 3.2). Six depositional units are defined by facies breaks and abrupt changes in trace fossil assemblages.

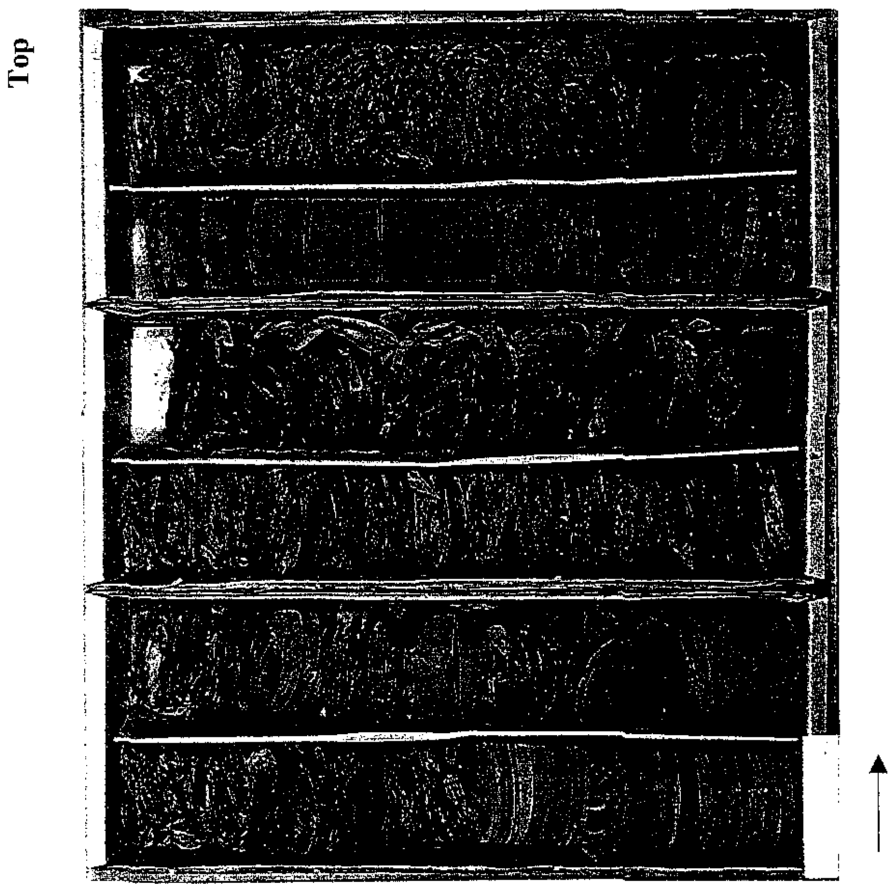
Unit 1 (0-2.15 m) consists of banded mudstones (Facies 5). Ethological patterns other than *Planolites* and *Skolithos* are relatively rare. However, six ichnospecies are present near very-fine-grained, current-rippled sandstones (Facies 8F, 2.00-2.15 m). Most trace abundances are 0-1.00 i.p.s.a. but some intervals contain greater abundances of *Planolites* (1.07-4.92 i.p.s.a.), *Palaeophycus* (2.17 i.p.s.a.) and *Skolithos* (9.40 i.p.s.a.).

Unit 2 (2.15-4.73 m) comprises very-fine-grained, current-rippled sandstones interbedded with bioturbated mudstones (Facies 3B). Sand-filled synaeresis cracks are present throughout this unit at


A)
14-4-64-23W5
(10.46 m)
0
5
10
sh
slt
vfL
vfU
fL
fU
FS
SF
S
churned
R.S.
Planolites
Chondrites
Palaeophycus
Thalassinoides
Ophiomorpha
Teichichnus
Skolithos
Arenicolites
Cylindrichnus
Zoophycos
Rhizocorallium
Asterosoma
?Siphonichnus
Terebellina
Helminthopsis
Anconichnus
Bergaueria
Fugichnia
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6

B)




Top

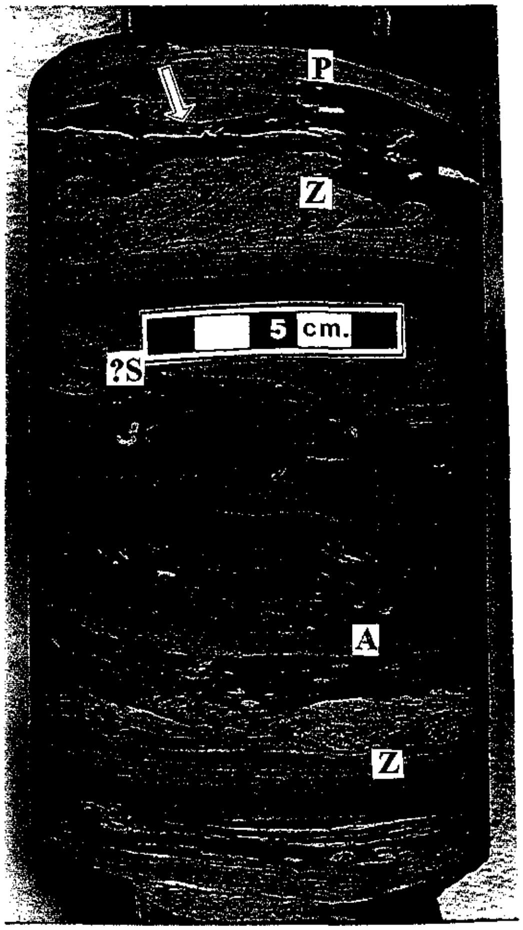
with bioturbated mudstones (Facies 3B). Sand-filled synaeresis cracks are present throughout this unit at mudstone-sandstone contacts. The number of *Planolites* burrows decreased across these crack intervals in the lower portion (average 7.22 i.p.s.a. below and 5.07 i.p.s.a. above). They increased in the upper portion (average 9.36 i.p.s.a. below and 10.54 i.p.s.a. above). The overall averages show a decrease in *Planolites* burrows near shrinkage cracks from 8.29 i.p.s.a. to 7.81 i.p.s.a.. Eighteen ichnogenera are identified in this unit with *Chondrites*, *Helminthopsis* and *Anconichnus* (squares and triangles) being the most abundant. The remaining traces are fewer than 10.00 i.p.s.a. (all circles). Other than *Planolites*, intervals containing *Zoophycos* intersections are more common in this unit than overlying units. This is the only unit in 14-4-64-23W5 that does not contain *Bergaueria* and *fugichnia* intersections (Figure 3.3).

Unit 3 separates Units 2 and 4. It consists of fissile, blockstones (Facies 2, 4.73-5.81 m) and contains no discernable trace fossils.

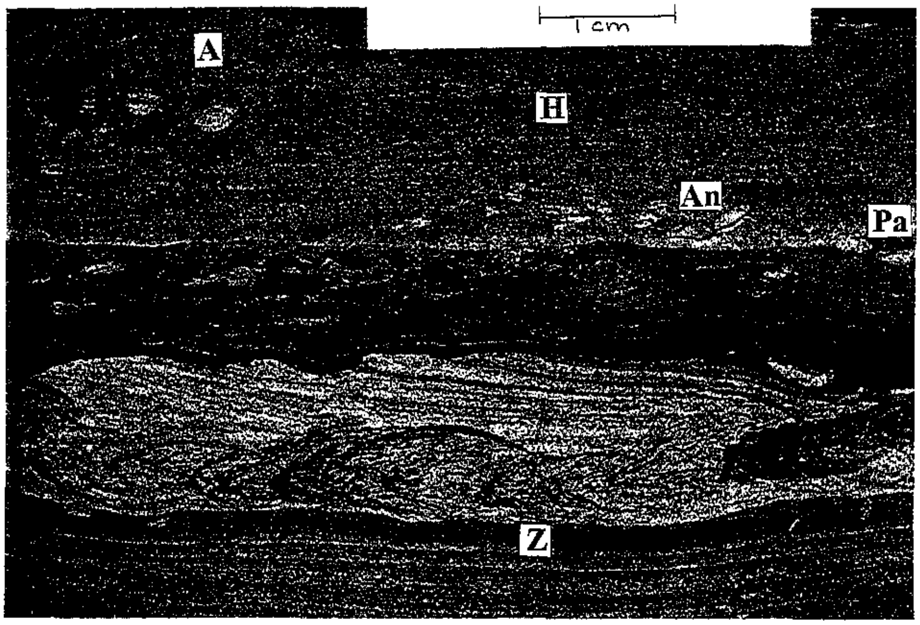
Unit 4 (5.81-7.36 m) is sandier than unit 2 and consists of current-and wave-rippled sandstones (Facies 8E, 8F), HCS sandstones (Facies 8C) and pervasively bioturbated sandstones (Facies 8I). The biogenic structures are similar to those preserved in Unit 2 but seven of the Unit 2 traces are absent in Unit 4 (*Chondrites*, *Thalassinoides*, *Arenicolites*, *Rhizocorallium*, *Terebellina*, *Bergaueria* and *fugichnia*). *Planolites* are the most common trace with abundances increasing from 0.17 i.p.s.a. to 6.04 i.p.s.a. across the shrinkage crack interval. Within the muddier layers, *Helminthopsis* and *Anconichnus* are the most abundant traces, but are present in fewer intervals than in Unit 2. *Zoophycos* burrows are rare. Above the pervasively bioturbated sandstones (6.68-7.01 m) an abrupt decrease from eleven to two ichnospecies (*Palaeophycus* and *Teichichnus*) occurs across the contact between the sandstones and overlying banded mudstones.

Unit 5 (7.36-7.46 m) consists of nonburrowed, very-fine-grained siltstones and represents a lag on a ravinement surface (Bhattacharya, 1989).

A)



B)



Unit 6 (7.46-10.46 m) consists of muddy, very-fine-grained siltstones and shales and was deposited after the lag. Both Units 5 and 6 lacked discernable biogenic structures.

In this core, horizontally-oriented trace fossils are preserved more frequently and in greater abundances than vertically-oriented trace fossils. This suggests horizontal burrows are favoured for preservation in fine-grained silty substrates.

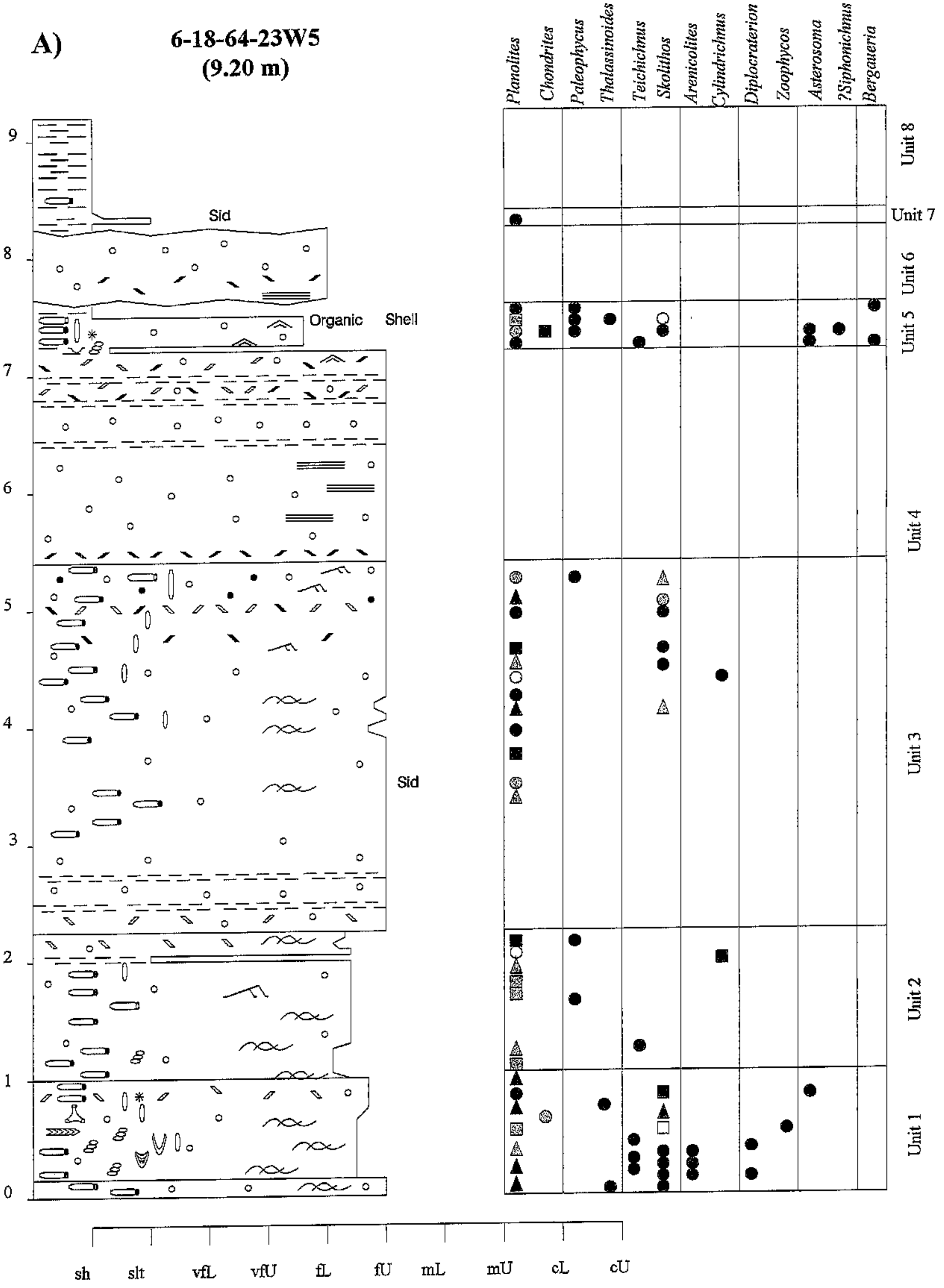
6-18-64-23W5 Core Description

This well (9.20 m) contains six units defined by facies breaks and abrupt changes in the diversity of ichnofossil assemblages (Figure 3.4).

Unit 1 (0-1.06 m) consists of fine-grained pervasively bioturbated mudstones (Facies 3A) interbedded with wavy laminated-to-burrowed mudstones (Facies 3B). The lower/upper fine-grained sandstones contain more ichnospecies (9) than the upper fine-grained sandstones (3). *Planolites*, *Chondrites* and *Skolithos* are the most abundant burrow intersections in this unit. *Arenicolites*, *Diplocraterion* and *Zoophycos* burrows are present only in this unit.

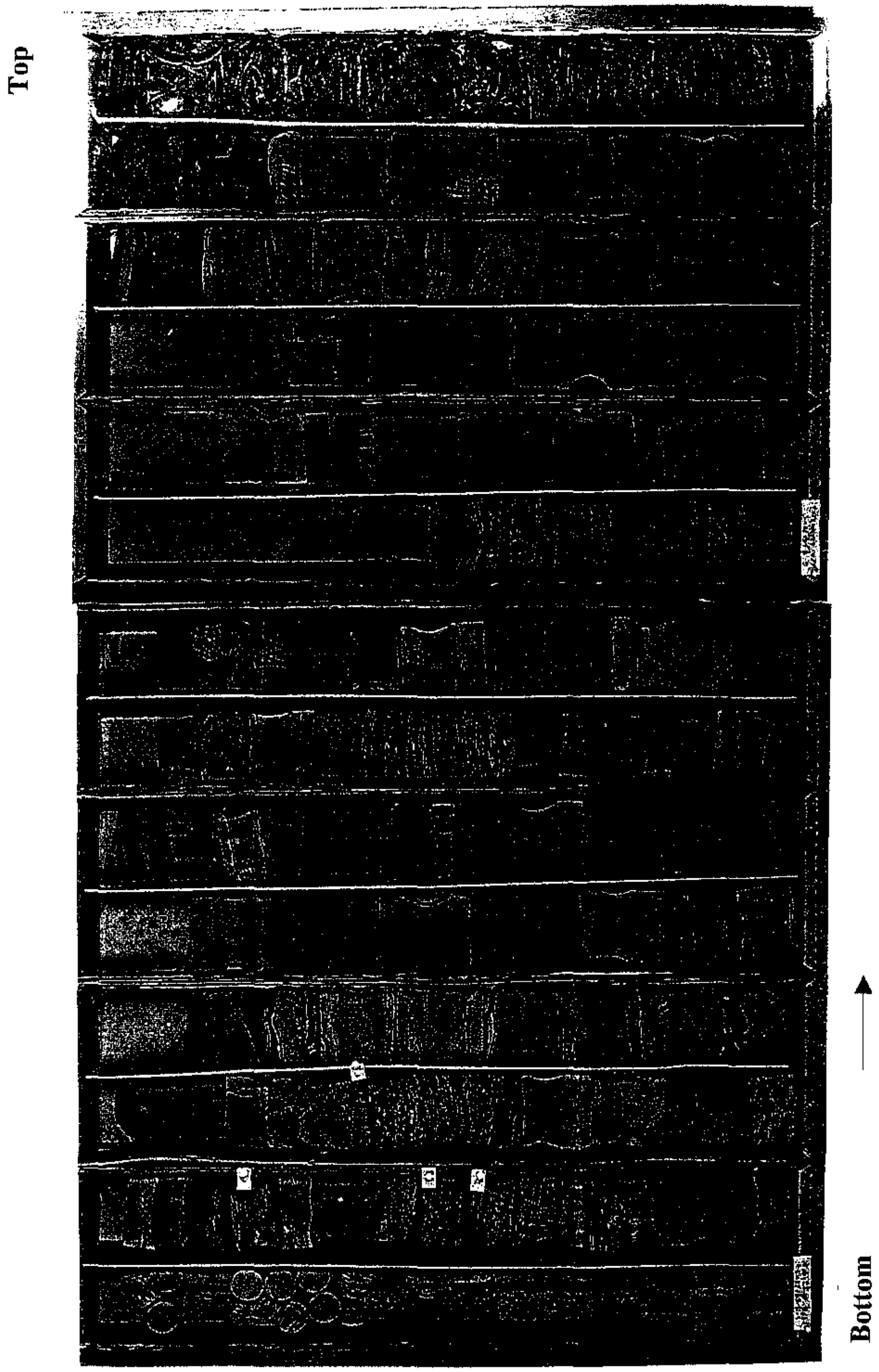
Unit 2 (1.06-2.22 m) consists of fine-grained, cross-bedded sandstones (Facies 8G) interbedded with current-rippled sandstones (Facies 8F). Each interval contains only one or two of the four ichnospecies present in this unit. Mud drapes are dominated by *Planolites* burrows (4.70-27.03 i.p.s.a.) and the current-rippled sandstone (1.87-1.93 m) contains a moderate abundance of *Cylindrichnus* shafts (13.23 i.p.s.a.). *Palaeophycus* and *Teichichnus* are sparse with abundances of 0.42-0.84 i.p.s.a. and 4.18 i.p.s.a., respectively.

Unit 3 (2.22-5.39 m) consists of structureless sandstones containing rip-up clasts, mud partings (Facies 8I, 10A) and cross-bedded sandstones (Facies 8G, Figure 3.5) and is capped by current-rippled sandstones (Facies 8F). The biogenic structures are in the mud drapes and tops of current-rippled sand-

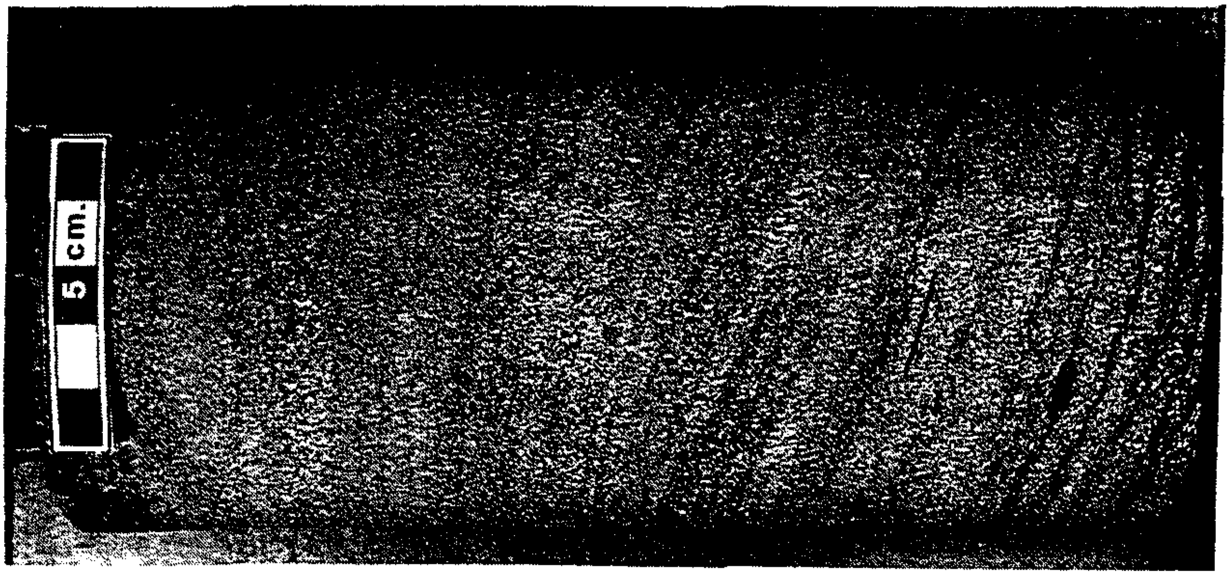


A) 6-18-64-23W5 (9.20 m)

B)




5 cm.


5 cm.

stones. The trace fossil assemblage is similar to unit 2 but *Skolithos* shafts are present and *Teichichnus* burrows are absent. This exclusion reflects the coarser substrate (upper-fine-grained) of this unit. *Planolites* and *Skolithos* burrows are the most abundant trace fossils.

Unit 4 (5.39-8.24 m) consists of flat-laminated sandstones (Facies 8D), massive to wave-rippled sandstones (Facies 8E, 8I) and pervasively bioturbated sandstones (Facies 8J). Nine trace fossils occur in the pervasively bioturbated sandstones (7.24-7.52 m). Of these traces, *?Siphonichnus* and *Bergaueria* occur only in this unit. The relative abundances are fewer than 10 i.p.s.a. for all traces except *Chondrites* (18.80 i.p.s.a.). The top of Unit 4 (7.63-8.28 m) consists of flat-laminated to massive sandstones containing scattered shale and sideritized mud rip-up clasts (Facies 10A) and a 4-cm shale drape.

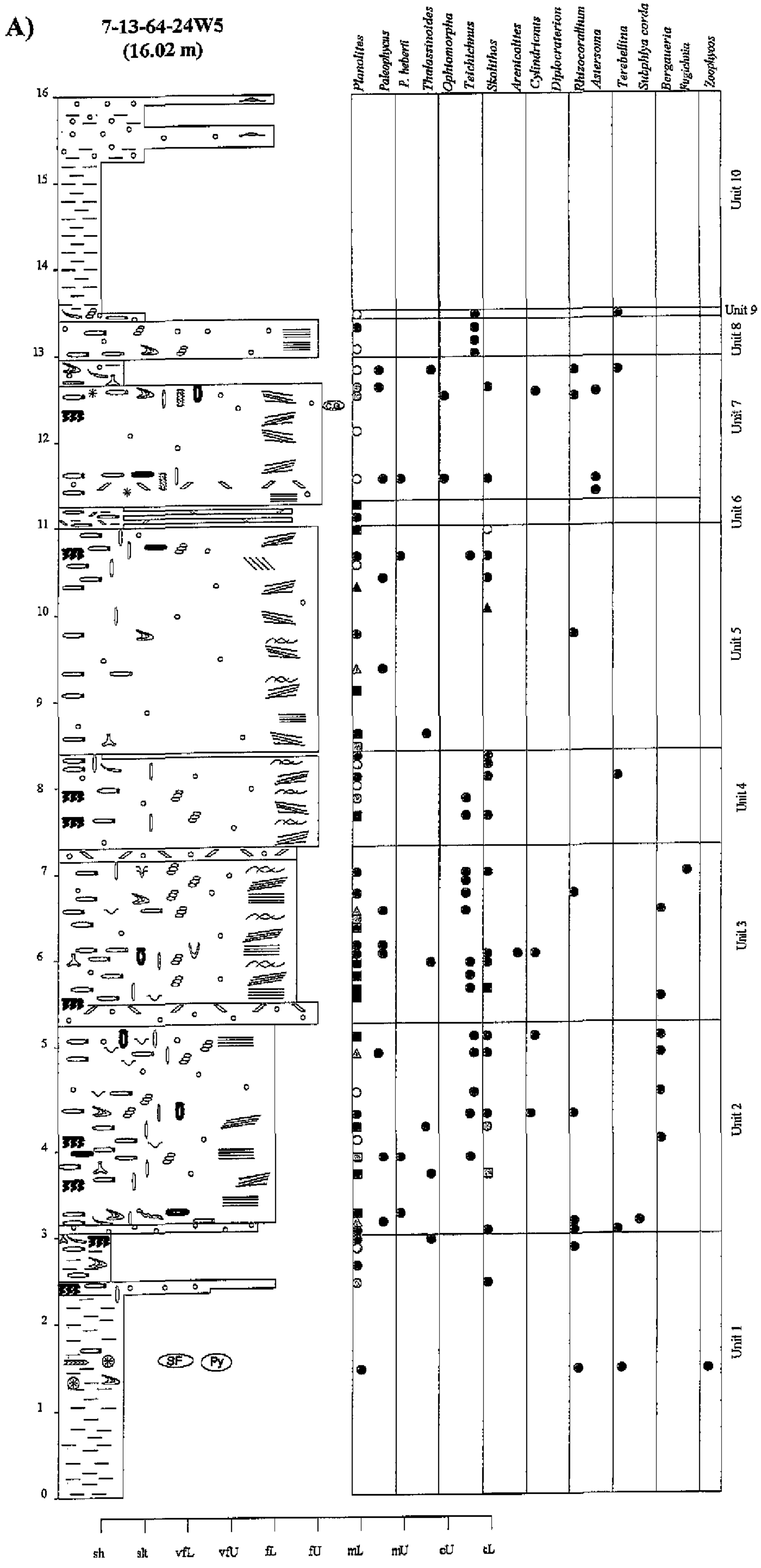
Unit 5 (8.28-8.35 m) consists of a ravinement surface and a 7-cm siltstone lag burrowed by *Planolites*-trace makers (9.55 i.p.s.a.) (Bhattacharya, 1989).

Unit 6 (8.35-9.20 m) consists of nonburrowed, black shales (Facies 1A). These shales are associated with Allomember C (Bhattacharya, 1989).

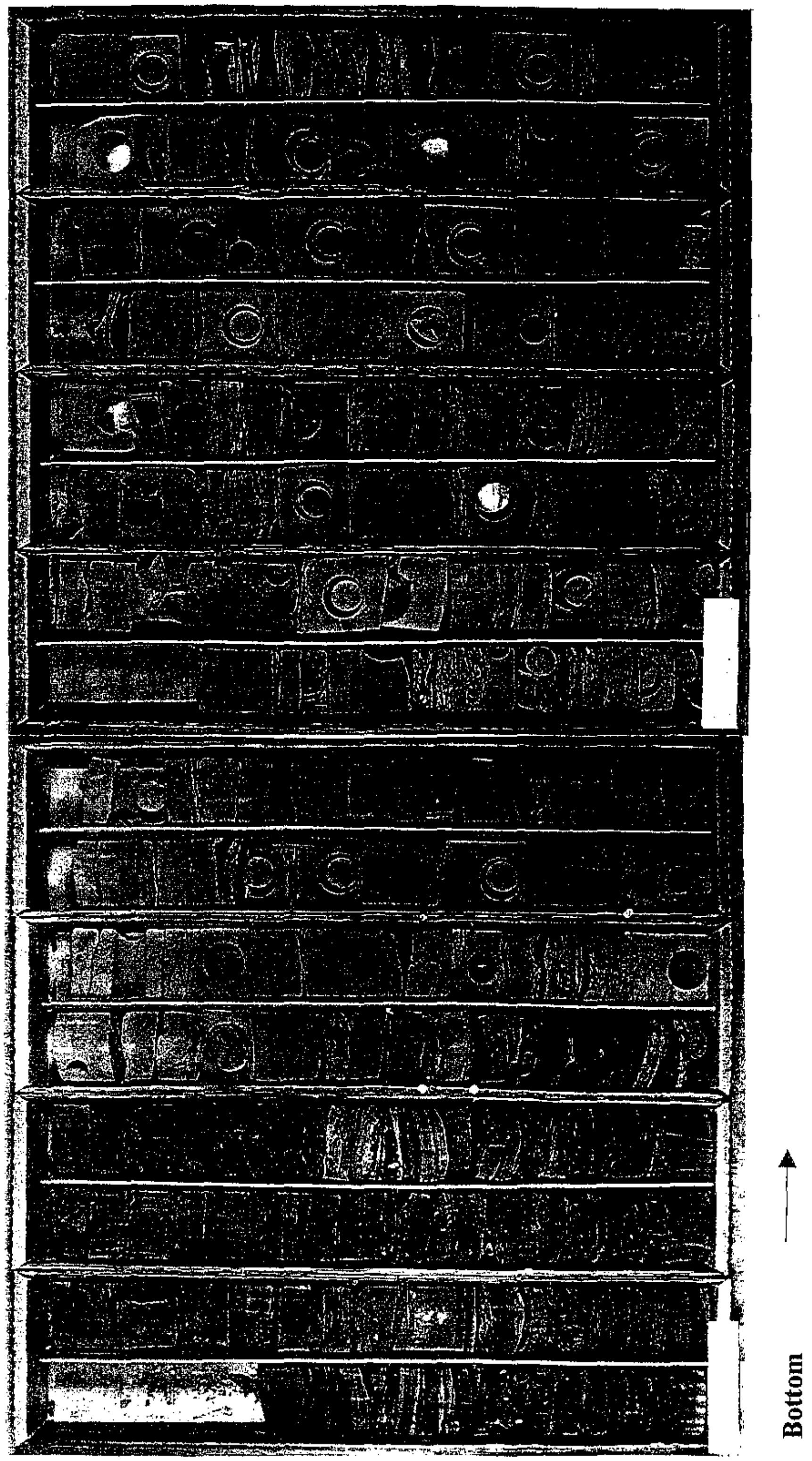
7-13-64-24W5 Core Description

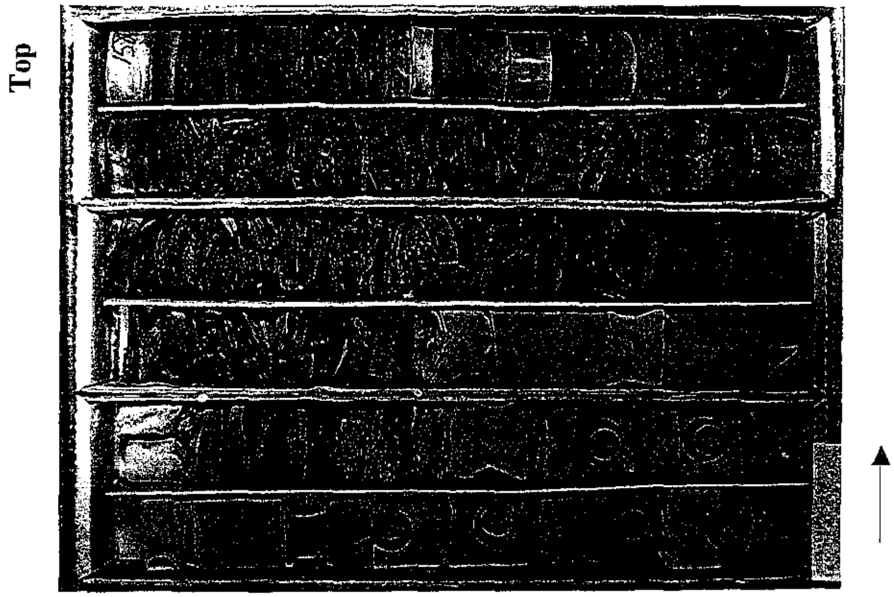
Ten depositional units were recognized in this core (16.02 m) as defined by erosion surfaces, facies changes and ichnofossil assemblage diversities and abundances (Figure 3.6). Each unit has similar facies and trace fossil assemblages but abrupt changes in ichnofossil diversity occur near the erosion surfaces that separate these units (Figure 3.6).

Unit 1 (0-3.04 m) consists of blockstones (Facies 2). Discernable trace fossils are absent in the first 1.35 m. However they are found in siltstones containing shell fragments and pyrite, fine-grained event beds (2.35-2.49 m) containing sand-filled shrinkage cracks, and blockstones (2.49-3.04m).


A)
7-13-64-24W5
(16.02 m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
SF
Py
sh
slt
vfL
vfU
fL
fU
mL
mU
cU
cL
Planolites
Paleophycus
P. heberti
Thalassinoides
Ophiomorpha
Teichichnus
Skolithos
Arenicolites
Cylindricnus
Diplocraterion
Rhizocorallium
Astersoma
Terebellina
Subphlya corda
Bergaueria
Fugichnia
Zoophycos
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6
Unit 7
Unit 8
Unit 9
Unit 10

B)




Top

As the substrate changed, the diversity of trace fossils changed upward from five ichnospecies (*Planolites*, *Rhizocorallium*, *?Siphonichnus*, *Terebellina* and *Zoophycos*) to two ichnospecies (*Planolites* and *Skolithos*) then to four with *Thalassinoides* and *Rhizocorallium* burrows present in the muddier blockstones.

Unit 2 through Unit 5 have similar facies and ichnofossil assemblages. However, assemblages in Units 2-3 are more diverse and more abundant than Units 4-5. The facies present in these units include: structureless sandstones with scattered mud rip-up clasts (Facies 8I, 10A), flat-to-gently dipping parallel-laminated sandstones (0-10°, Facies 8D), current-rippled sandstones (Facies 8F) and pervasively bioturbated sandstones (Facies 8J). In a few intervals sand-filled shrinkage cracks are found in each unit. Most trace fossils are preserved at the top of parallel-laminated and current-rippled beds, particularly in thick (mm-scale) mud drapes. The most abundant burrow intersections are *Planolites* and *Skolithos* but the horizontal burrows are more common.

Unit 2 (3.04-5.26 m) contains eleven horizontally- and vertically-oriented traces in very-fine-(upper)-grained sandstones (Facies 8D, 8F, 8J). These traces are concentrated in the pervasively bioturbated sandstones (10 cm beds). This assemblage is dominated by *Planolites* (4.18-22.97 i.p.s.a.) and *Skolithos* (0.26-16.51 i.p.s.a.) burrows. The remaining ichnospecies have abundances fewer than 2.09 i.p.s.a. In two shrinkage crack intervals (3.03-3.12 m and 4.03-4.16 m), *Planolites* burrows increased from 12.33 i.p.s.a. below to 16.39 i.p.s.a. above and from 5.78 i.p.s.a. to 14.62 i.p.s.a., respectively.

Unit 3 (5.26-7.19 m) facies are similar to those in Unit 2 but a differnt assemblage of traces exists in the fine-grained sand. This assemblage of ten ichnospecies is dominated by *Planolites* burrows but horizontal deposit-feeding traces are more common than vertical traces (e.g., *Skolithos* and *Cylindrichnus*). The vertical traces of *Diplocraterion parallelum / D. yoyo* and *fugichnia* are found in parallel-laminated sandstones. The absence of *Palaeophycus heberti*, *Terebellina* and

Subphyllochorda burrows suggest that Unit 3 is ecological different from Unit 2.

Unit 4 (7.32-8.41 m) is dominated by *Skolithos* and *Teichichnus* burrows found in the sandstones (Facies 8D and 8F) and *Planolites* and *Terebellina* burrows in the thick mud drapes near the top of this unit. This unit is capped by a mudstone (5 cm). *Planolites* abundances changed across the two intervals containing shrinkage cracks. Burrows increased across the first interval (7.62-7.72 m) from 0.28 i.p.s.a. below to 18.80 i.p.s.a. above and decreased above the second interval (7.92-8.04 m) from 6.50 i.p.s.a. to 4.18 i.p.s.a. above.

Unit 5 (8.41-11.04 m), the thickest depositional unit, contains fine-grained current-rippled sandstones, parallel-laminated sandstones and cross-bedded sandstones (Facies 8G). The latter were deposited before the only interval of shrinkage cracks (10.44-10.62 m). Of the seven trace fossils in this assemblage, *Palaeophycus tubularis*, *Palaeophycus heberti*, *Thalassinoides* and *Rhizocorallium* occur in this unit but not in the previous unit. The most abundant *Skolithos* shafts (71.01 i.p.s.a.) and *Planolites* burrows (33.42 i.p.s.a.) recorded in this core occur in the unit, the former in sandstone (10.05-10.06 m) and the latter in mudstone (10.33-10.36 m).

Unit 6 (11.04-11.30 m) consists of banded mudstones (Facies 5) exclusively burrowed by *Planolites*-trace makers. These burrows increased upward from 2.28 i.p.s.a. to 11.14 i.p.s.a. (a green circle to blue square).

Unit 7 (11.30-12.92 m), consists of parallel-laminated, ripple cross-laminated and structureless fine-grained sandstones. It is similar to Unit 2 but it is capped by bioturbated shale (Facies 1B, 12.66-12.92 m). The trace fossil assemblage resembles Unit 2 but *Teichichnus*, *Subphyllochorda*, and *Bergaueria* are absent; *Ophiomorpha irregulaire* and *Asterosoma* are present. The horizontally-oriented *Ophiomorpha* burrows (0.28-0.70 i.p.s.a.) are preserved only in this unit. The bioturbated shales contain only horizontal trace fossils whereas the sandstones contain both horizontally- and vertically-oriented traces.

Unit 8 (12.92-13.40 m) consists of parallel-laminated sandstones. This unit contains low abundances of *Planolites* (2.51-4.56 i.p.s.a.) and *Teichichnus* (0.84-2.51 i.p.s.a.) burrows present in the thicker mud drapes. Vertical burrows or escape structures are absent in this unit.

Unit 9 (13.40-13.50 m) has a sharp-based erosion surface that truncates Unit 8. Bhattacharya (1989) interpreted this erosion surface as a ravinement surface overlain by a 10-cm muddy siltstone lag. This lag contains a similar trace fossil assemblage to Unit 8 but *Terebellina* burrows (2.51 i.p.s.a.) are present with *Planolites* (4.18 i.p.s.a.) and *Teichichnus* (0.84 i.p.s.a.) burrows.

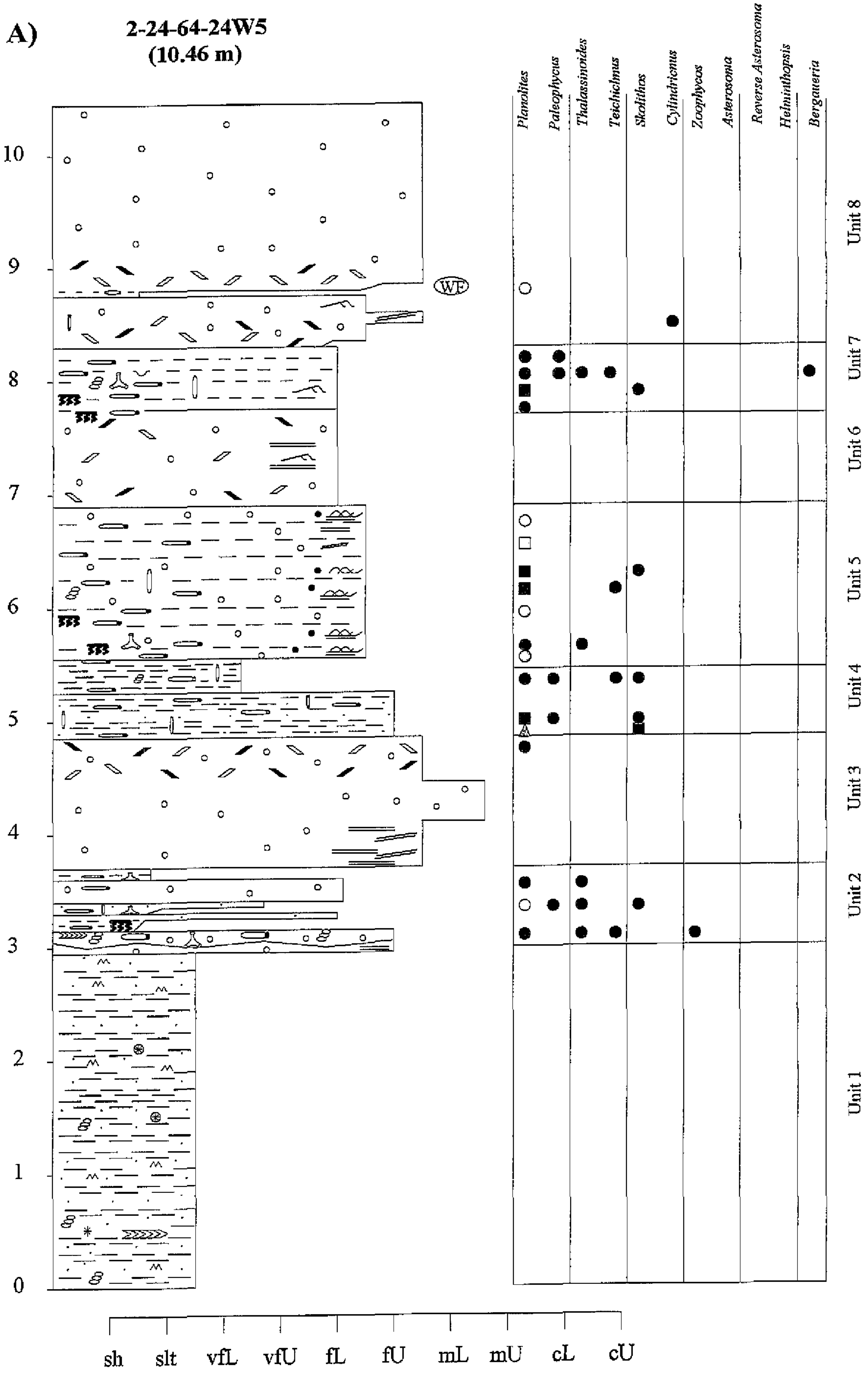
Unit 10 (13.50-16.02 m) consists of mudstones interbedded with hummocky-cross-stratified sandstones (Facies 8C). Discernable trace fossils are not present in this unit associated with Allomember C (Bhattacharya, 1989).

2-24-64-24W5 Core Description

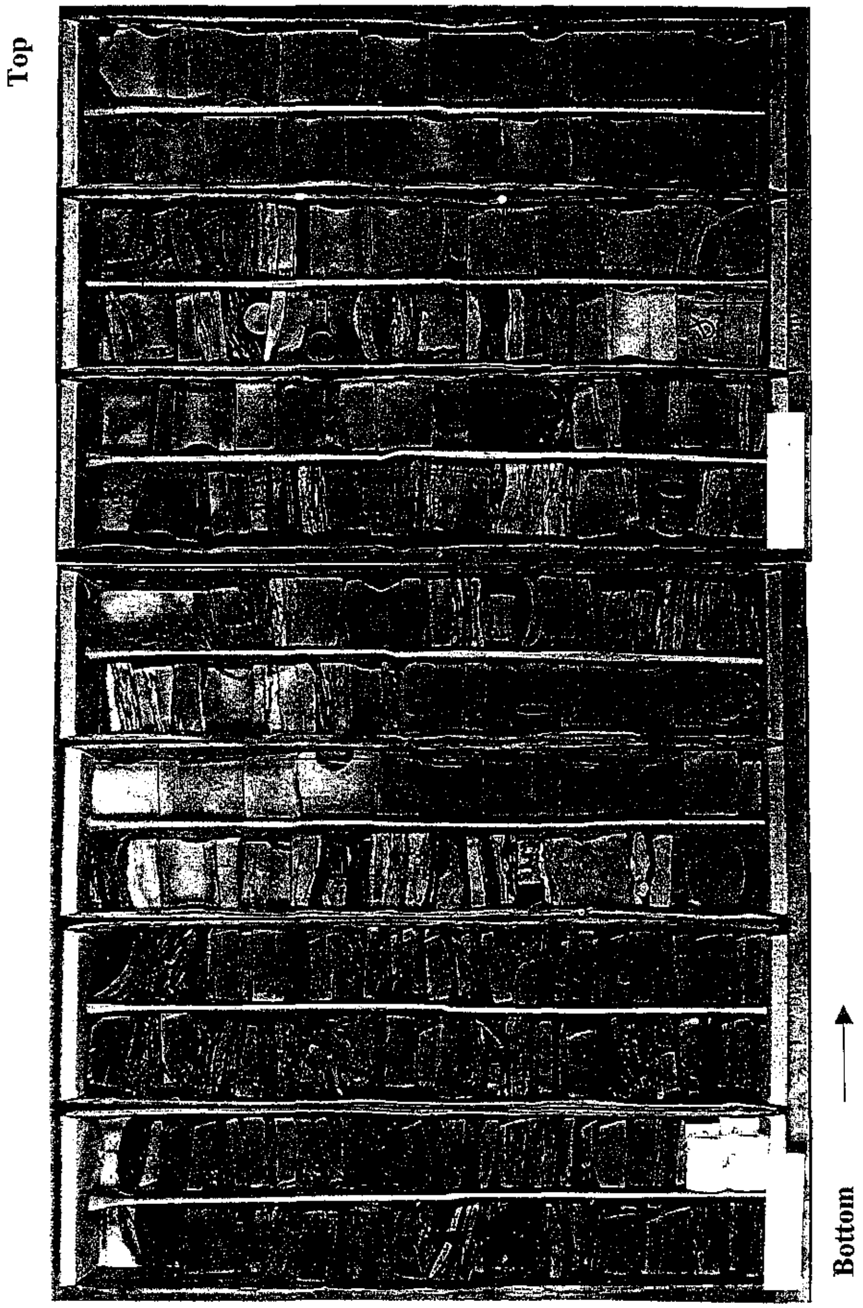
In this 10.46 m section (Figure 3.7), eight depositional units were identified based on erosion surfaces, facies changes and diversity variations in trace fossil assemblages.

Unit 1 (0-2.93 m) consists of silt and very-fine-grained laminated mudstones (Facies 1B). Traces are rare in these black mudstones but *Zoophycos*, *?Siphonichnus*, *Helminthopsis* and *Anconichnus* occur in the some mud-dominated layers, whereas *Teichichnus* and *Asterosoma* occur near thicker silt/sand laminae in the basal 1.50 m. The upper portion of this unit contains only *Helminthopsis*, a fecal trace. This unit was interpreted as an interdistributary bay and part of Shingle D2 (Bhattacharya, 1989).

Unit 2 (2.93-3.72 m) consists of banded mudstones (Facies 5) and an ichnofossil assemblage dominated by *Planolites* (2.78-5.48 i.p.s.a.) with common to rare occurrences of *Teichichnus*, *Palaeo-*


A)
2-24-64-24W5
(10.46 m)
0
1
2
3
4
5
6
7
8
9
10
WE
sh
slt
vfL
vfU
fL
fU
mL
mU
cL
cU
Planolites
Paleophycus
Thalassinoides
Teichichnus
Skolithos
Cylindricnus
Zoophycos
Asterosoma
Reverse Asterosoma
Helminthopsis
Bergaueria
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6
Unit 7
Unit 8

B)



-*phycus*, *Thalassinoides*, *Skolithos* and *Zoophycos* (0.23 i.p.s.a.). Shrinkage cracks are present close to the maximum burrow abundances in the middle of this unit (3.05-3.32 m). More *Planolites* and *Thalassinoides* burrow i.p.s.a. occur above the shrinkage crack interval (3.05-3.23 m) than below: 2.78 to 5.48 i.p.s.a. and 0.23 to 0.52 i.p.s.a., respectively.

Unit 3 (3.72-4.82 m) consists of fine-grained, gently dipping, parallel-laminated sandstones (Facies 8D, 8F) that coarsen upward to medium-grained, structureless sandstones containing scattered shale and sideritized rip-up clasts (Facies 8F, 10A). Discernable trace fossils are absent in this unit.

Unit 4 (4.82-5.52 m) consists of a fining upward succession of very low-angle laminations of interbedded mudstones and very-fine-grained sandstones (Facies 4). Siltstones occur in the upper 25 cm of this unit. The trace fossil diversity changed from *Planolites* and *Skolithos* to include *Palaeophycus* and *Teichichnus*. The greatest abundance of *Planolites* and *Skolithos* i.p.s.a. of this core are 8.35-20.89 i.p.s.a. and 18.10 i.p.s.a., respectively.

Unit 5 (5.52-6.92 m) consists of some fine-grained, laminated-to-burrowed sandy mudstones (Facies 3B). The fine-grained sandy layers contain sideritized mud clasts that are absent in other units. The trace fossil assemblage contains *Thalassinoides*, *Teichichnus*, *Skolithos* and *Planolites*. In the basal 23 cm *Planolites* and *Thalassinoides* burrows occur with sand-filled shrinkage cracks. *Teichichnus* and *Skolithos* intersections are present above the shrinkage cracks where the abundance of *Planolites* burrows decreased from 11.89 to 4.75 i.p.s.a.

Unit 6 (6.92-7.72 m), like Unit 3, lacks discernable trace fossils in the structureless and parallel-laminated to current-rippled sandstones. Shale and sideritized mud rip-up clasts are scattered throughout this unit.

Unit 7 (7.72-8.32 m) is similar to Unit 5 but is finer-grained and contains a more diverse trace fossil assemblage (similar to Unit 4). The dominant trace fossils in the assemblage are *Planolites* and

Palaeophycus. *Planolites* burrows increased from 2.98 to 12.53 i.p.s.a. near shrinkage cracks then decreased to 2.78 i.p.s.a. The trace assemblage includes relatively low abundances of *Planolites*, *Palaeophycus tubularis*, *Thalassinoides*, *Teichichnus*, *Skolithos* and *Bergaueria*.

Unit 8 (8.32-10.46 m) is similar to Units 3 and 6 but wood fragments and rip-up clasts are present in the basal 50 cm of this medium-grained structureless sandstone. *Arenicolites* (5.22 i.p.s.a.) and *Planolites* (4.18 i.p.s.a.) are preserved in this basal sandstone. The remainder of this unit lacks discernable biogenic structures.

The 10-cm muddy siltstone lag and associated ravinement surface that truncates the sediments of Shingle D1 and the shales of Allomember C are not cored in this well (Bhattacharya, 1989).

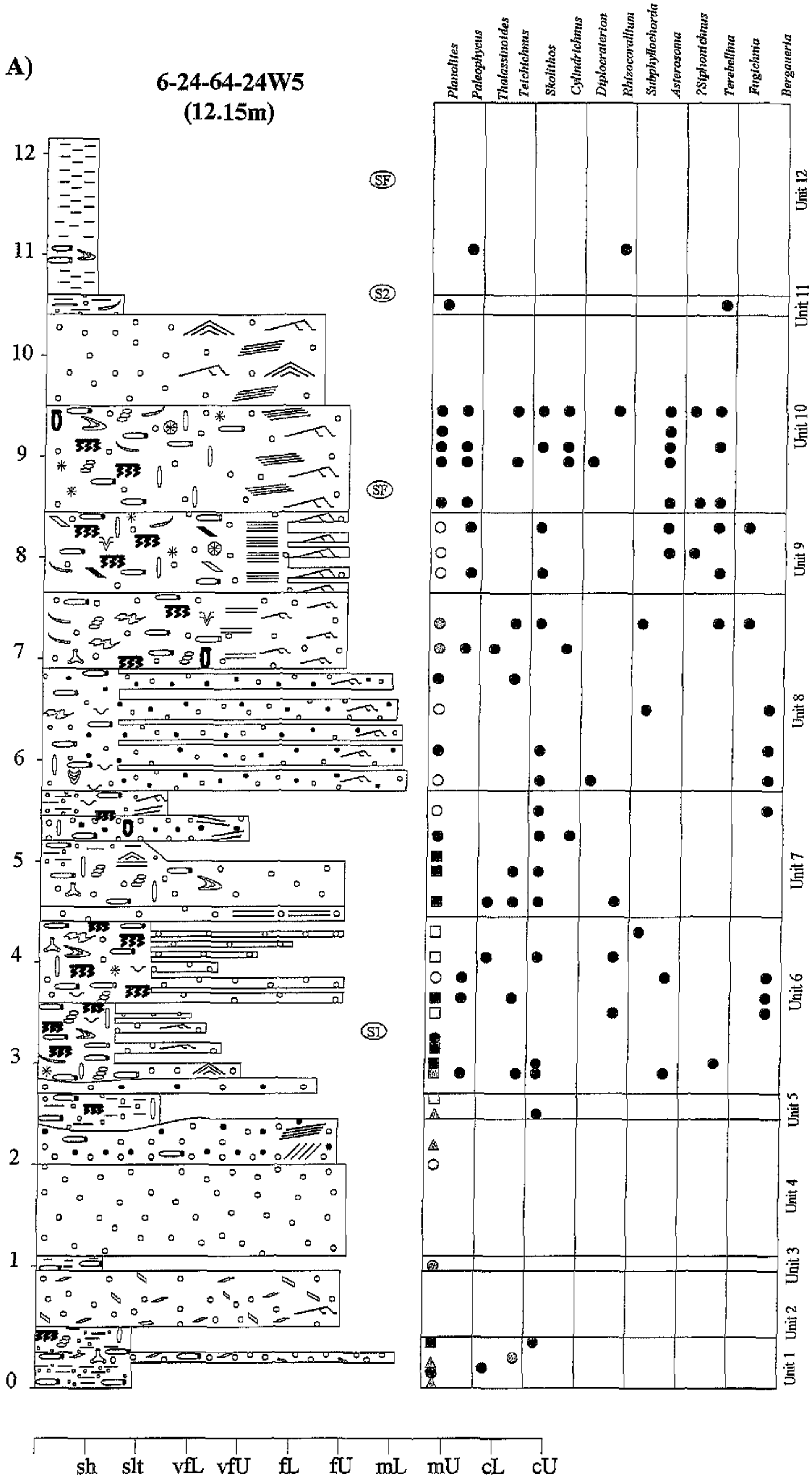
6-24-64-24W5 Core Description

The eight units described in the most landward well are defined by sedimentary facies and preserved biogenic structures (Figure 3.8). Abrupt variations in the trace fossil assemblages, and associated facies changes and erosion surfaces define the boundaries of these depositional units.

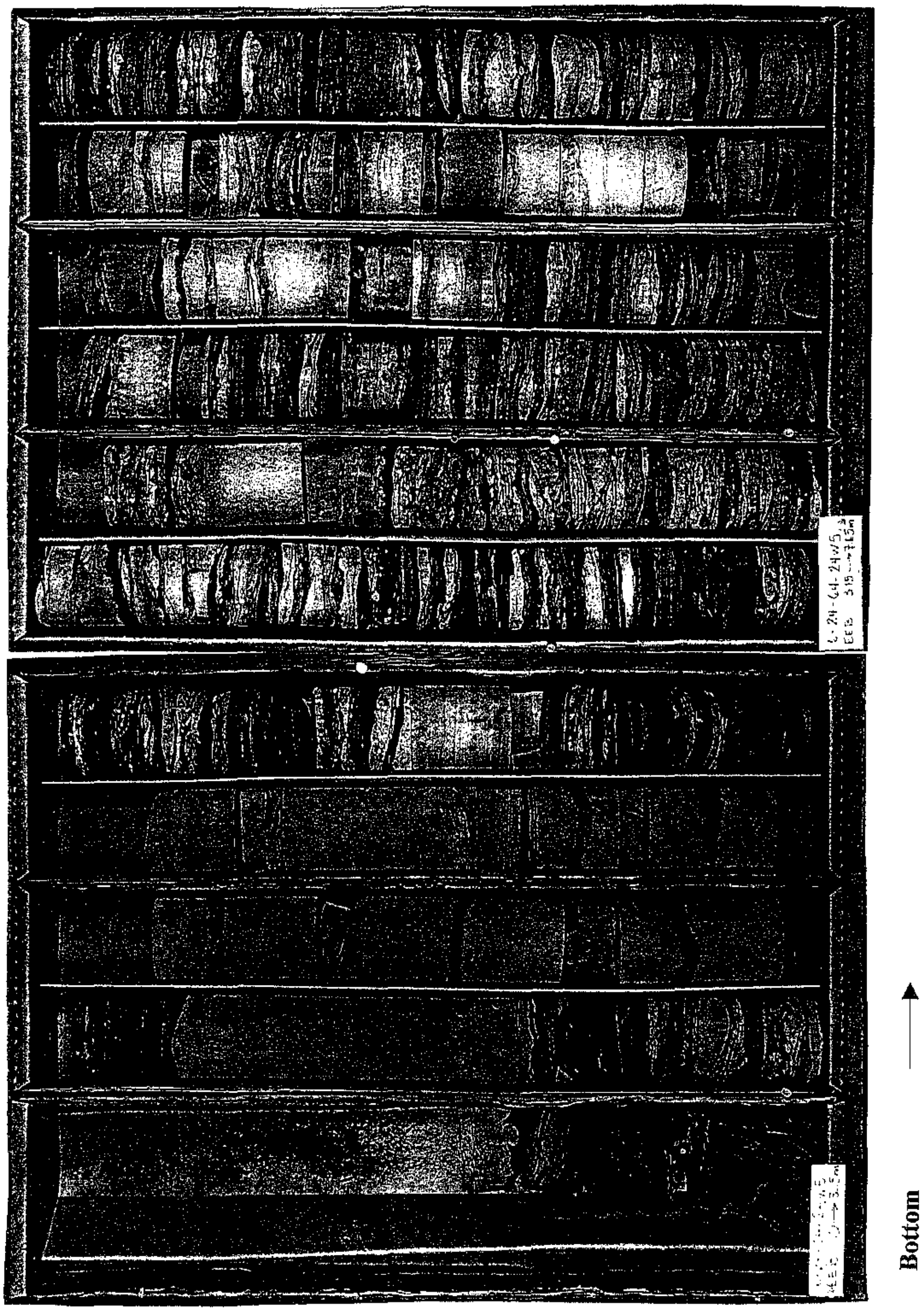
Unit 1 (0-2.67 m) consists of three mudstone and two sandstone deposits. The basal and upper mudstones (0-0.58 m and 2.37-2.67 m) are pervasively bioturbated (Facies 3A). The basal mudstones contain four ichnospecies (*Planolites*, *Teichichnus*, *Thalassinoides* and *Skolithos*) as compared with two found in the upper mudstones (*Planolites* and *Skolithos*). In contrast, the bioturbated shales (Facies 1B, 0.94-1.08 m) are exclusively burrowed by *Planolites*-trace makers (6.27 i.p.s.a.).

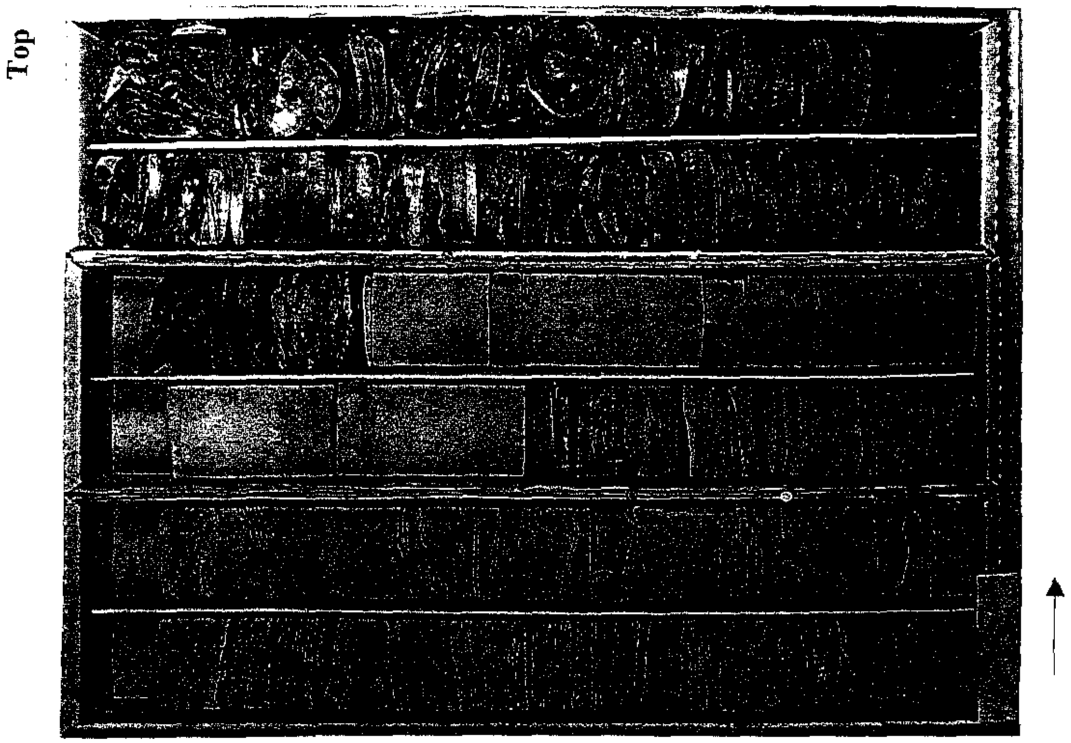
The sandstones in Unit 1 display a variety of physical structures. The basal upper-fine-grained sandstones contain wave-ripples (Facies 8E) and grade into structureless sandstones with scattered shale rip-up clasts (Facies 8I, 10A). The upper structureless sandstone is truncated by cross-bedded (Facies 8G) and parallel-laminated (Facies 8D) sandstones that contain *Planolites* burrows.

A)


6-24-64-24W5
(12.15m)
12
11
10
9
8
7
6
5
4
3
2
1
0
SF
S2
SF
S1
sh
slt
vfL
vfU
fL
fU
mL
mU
cL
cU
Planolites
Paleophycus
Thalassinoides
Teichichnus
Skolithos
Cylindrichnus
Diplocraterion
Rhizocorallium
Subphyllochorda
Asterosoma
?Siphonichnus
Terebellina
Fugichnia
Bergaueria
Unit 12
Unit 11
Unit 10
Unit 9
Unit 8
Unit 7
Unit 6
Unit 5
Unit 4
Unit 3
Unit 2
Unit 1

B)




Top

Unit 2 (2.67-4.39 m) consists of fining upward banded mudstones (Facies 5) and laminated-to-burrowed mudstones (Facies 3B). These mudstones have many shrinkage cracks present at mudstone-sandstone contacts. The assemblage of ten ichnogenera consists of *Planolites* (the most abundant), *Palaeophycus*, *Thalassinoides*, *Teichichnus*, *Skolithos*, *Rhizocorallium*, *Subphyllochorda*, *Asterosoma*, *Terebellina* and *Bergaueria*. *Planolites* intersections increased above the shrinkage crack interval (3.01-3.15 m) from 11.94 to 19.03 i.p.s.a.

Unit 3 (4.39-5.69 m) consists of laminated-to-burrowed, fine-grained sandstones (Facies 8B) and very-fine-grained, cross-laminated sandstones (Facies 8F). The trace fossil assemblage includes horizontal burrows and vertical shafts (e.g., *Bergaueria, Cylindrichnus, Planolites* [3.81-19.54 i.p.s.a.], *Rhizocorallium*, *Skolithos*, *Teichichnus* and *Thalassinoides*). Animal locomotion traces (e.g., *Subphyllochorda*) are absent, but resting traces (e.g., *Bergaueria*) occur at mud drape-sandstone contacts. The abundance of *Planolites* burrows increased from 3.81 to 4.18 i.p.s.a. above a shrinkage crack interval (5.39-5.50 m). Only two vertically-oriented ichnospecies (*Skolithos* and *Cylindrichnus*) occur in this unit with abundances fewer than 1.00 i.p.s.a.

Unit 4 (5.69-7.65 m) consists of sharp-based, fine-grained, current-rippled, "coffee ground" sandstones (1-15 cm thick, Figure 3.9). Sparsely bioturbated mudstones (1-20 mm thick) draped these sandstones. Some basal mudstones were sideritized after *Planolites*-trace makers abandoned their burrows. The upper portion of this unit contains thinner sandstones and mudstones: 1-5 cm and 1-5 mm, respectively.

The trace fossil assemblage of this depositional unit varies with the thickness to the sandstone intervals. The basal section (5.69-7.01 m) contains six ichnogenera (*Planolites*, *Bergaueria*, *Skolithos*, *Diplocraterion*, *Subphyllochorda* and *Teichichnus*). Rare intersections of *Diplocraterion* burrows (vertical U-tubes and dumbbell-shaped bedding plane views) occur only in Unit 4.

The diversity of the upper section (7.01-7.65 m) increased to eight ichnogenera. *Bergaueria*

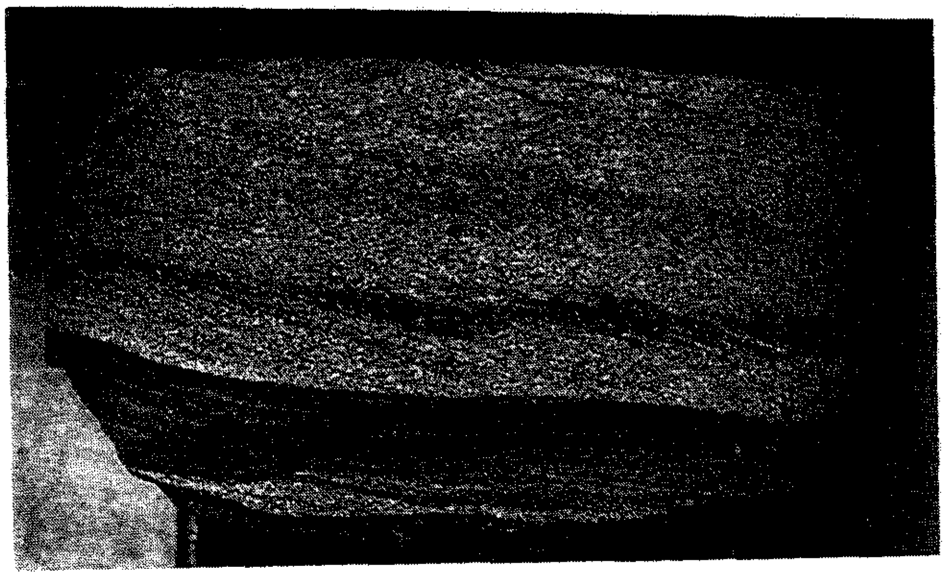


Figure 3.9 Some current-rippled sandstones have siderite and mud chips lining the reactivation surfaces (Unit 4, 6-24-64-24W5). These particles resemble "coffee grounds." The diameter of the core is 3 inches.

and *Diplocraterion* are absent from this assemblage, but *Terebellina* and *fugichnia* are present. This is the first occurrence *fugichnia* in the core. *Planolites* burrows are the most abundant (3.48-7.31 i.p.s.a.). The remaining ichnospecies have fewer than 1.00 burrow i.p.s.a. (*Palaeophycus*, *Subphyllochorda*, *Teichichnus*, *Thalassinoides*, *Cylindrichnus* and *Skolithos*).

Unit 5 (7.65-10.39 m) is finer-grained and consists of parallel-laminated and current-rippled sandstones (1-4 cm) which are draped by mudstones (1-5 mm). The upper sandstone interbeds (5-15 cm) contained low-angle, parallel-laminations and current-rippled internal structures. Of the eleven ichnospecies present, *?Siphonichnus* occurs for the first time in this core, and *Bergaueria*, *Subphyllochorda* and *Thalassinoides* burrow intersections are absent.

Unit 6 (9.48-10.39 m) consists of fine-grained, low-angle, ripple-cross laminations, current- and wave-rippled sandstones (Facies 8E, 8F). These sandstones lacked discernable burrow intersections. The upper contact of this unit is knife-sharp. This erosion surface represents a ravinement surface (Bhattacharya, 1989).

Unit 7 (10.39-10.59 m) is a 20-cm lag consisting of silty mudstones. This lag contains *Planolites* and *Terebellina* burrows equal to 1.46 and 1.67 i.p.s.a. The silty mudstone marks the allocyclic boundary between Allomember D and C (Bhattacharya, 1989).

Unit 8 (10.59-12.15 m) consists of black shales containing few event beds. Discernable traces were absent, except in an interval of blockstones (11.02-11.06 m) that contain *Palaeophycus* (2.09 i.p.s.a.) and *Rhizocorallium* (1.04 i.p.s.a.) burrows. These sediments are associated with Allomember C (Bhattacharya, 1989).

3.3 SUBSTRATE CHARACTERISTICS AND ASSOCIATED ICHNOFOSSILS

3.3.1 SUBSTRATE CHARACTERISTICS AND ASSOCIATED ICHNOFOSSILS: RESULTS

In the Waskahigan Bottleneck, sediments were qualitatively classified into ten substrate groups based on how much light was reflected off the core surface (see Section 2.3.3). This section deals with the reflectivity as measured by shutter speeds for sediments in five wells, four of which are the focus of this chapter.

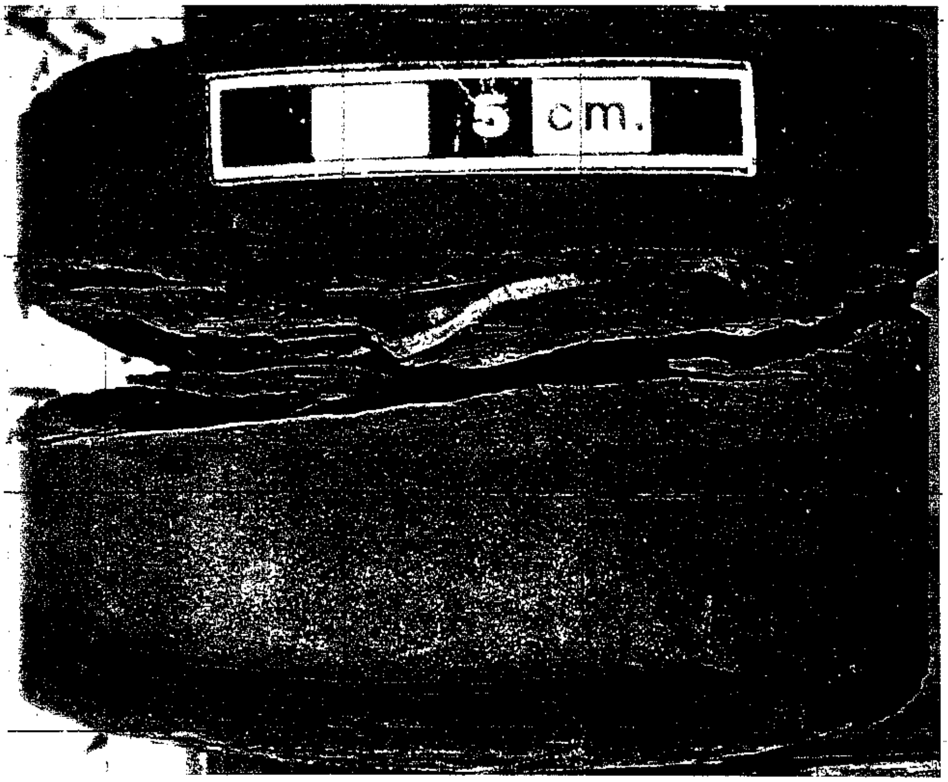
The substrate groups were classified as: 1) 10-30, 30, 2) 30, 3) 30, 30-60; 4) 30-60, 5) 30-60, 60, 6) 60, 7) 60, 60-125, 8) 60-125, 9) 60-125, 125 and 10) 125. This classification is based on the five random shutter speeds measured for each core segment. For example, Substrate 1 (10-30, 30) represents core segments measuring shutter speeds of 10-30 and 30. The facies classified in Substrate 2 have five shutter speed measurements of 30. The cleaner the substrate, the higher the reflectivity and the higher shutter speed. Of these ten categories, six core sections were adequately photographed to visually quantified by point counts the pale (sand) and dark (mud and silt) grains in random areas at the bottom, middle and top of a core segment. The remaining four categories were not quantified because suitable photographs for point counts were not taken. The substrate groups were categorized upon returning to McMaster. However, these categories are considered to have pale/dark grain proportions between those ratios of the end-member substrates. For example, Substrate 5 would contain more sand than Substrate 4 (41% by number of grains) and fewer than Substrate 6 (54% by number of grains).

The facies and trace fossils common to these substrate groups enabled generalizations to be made regarding animal-sediment relationships (Table 3.1).

Substrate 1 (10-30, 30) comprises laminated shales (Facies 1A) that lack discernable trace fossils. This substrate was quantified using a photograph from 5-17-64-23W5 (Figure 3.10). The percentages tabulated are 10% pale grains (very-fine-grained sand) and 90% dark grains (mud and silt particles). Distinguishing the total number of clay particles in the random sample squares was difficult,

Waskahigan Bottleneck Channel
Substrate Types and Associated Facies and Ichnofossils

Substrate Type	% Dark Grain	% Pale Grain	Facies	Ichnofossils
Substrate 1	90	10	1A	No traces
Substrate 2	79	21	1C, 1B, 3A	*Arenicolites, Asterosoma, Diplocraterion, Helminthopsis, Palaeophycus, Planolites, Rhizocorallium, ?Siphonichnus, Skolithos, Teichichnus, Terebellina, Thalassinoides, Zoophycos*
Substrate 3			1B	*Arenicolites, Diplocraterion, Helminthopsis, Palaeophycus, Planolites, Rhizocorallium, ?Siphonichnus, Teichichnus, Terebellina, Thalassinoides, Zoophycos*
Substrate 4	59	41	3A, 3B, 5	*Arenicolites, Asterosoma, Bergaueria, Chondrites, Cylindrichnus, Diplocraterion, fugichnia, Palaeophycus, Planolites, Rhizocorallium, ?Siphonichnus, Skolithos, Subphyllochorda, Teichichnus, Terebellina, Thalassinoides*
Substrate 5			2, 4, 5	*Arenicolites, Asterosoma, Cylindrichnus, Diplocraterion, fugichnia, Palaeophycus, Planolites, Rhizocorallium, ?Siphonichnus, Skolithos, Subphyllochorda, Teichichnus, Terebellina, Thalassinoides, Zoophycos*
Substrate 6	46	54	6A, 6D, 6E, 6F	1) No traces or 2) *Asterosoma, Bergaueria, Cylindrichnus, Diplocraterion, Helminthopsis, Ophiomorpha, Palaeophycus, Planolites, Rhizocorallium, ?Siphonichnus, Skolithos, Teichichnus, Thalassinoides, Zoophycos*
Substrate 7	38	62	6C, 6F	1) No traces or 2) *Asterosoma, Cylindrichnus, Ophiomorpha, Palaeophycus heberti, Palaeophycus tubularis, Planolites, Rhizocorallium, Skolithos, Teichichnus, Terebellina, Thalassinoides*
Substrate 8			6B, 6F, 6G, 6H	1) No traces or 2) *Anconichnus, Arenicolites, Asterosoma, Bergaueria, Chondrites, Cylindrichnus, fugichnia, Helminthopsis, Ophiomorpha, Palaeophycus heberti, Palaeophycus tubularis, Planolites, Rhizocorallium, ?Siphonichnus, Skolithos, Teichichnus, Terebellina, Thalassinoides, Zoophycos*
Substrate 9			5	*Asterosoma, Cylindrichnus, Diplocraterion, Palaeophycus, Planolites, Rhizocorallium, ?Siphonichnus, Skolithos, Teichichnus, Terebellina, Thalassinoides*
Substrate 10	35	65	6E, 6F	1) No traces or 2) *Bergaueria, Cylindrichnus, Diplocraterion, Palaeophycus heberti, Palaeophycus tubularis, Planolites, Rhizocorallium, Skolithos, Teichichnus, Thalassinoides*

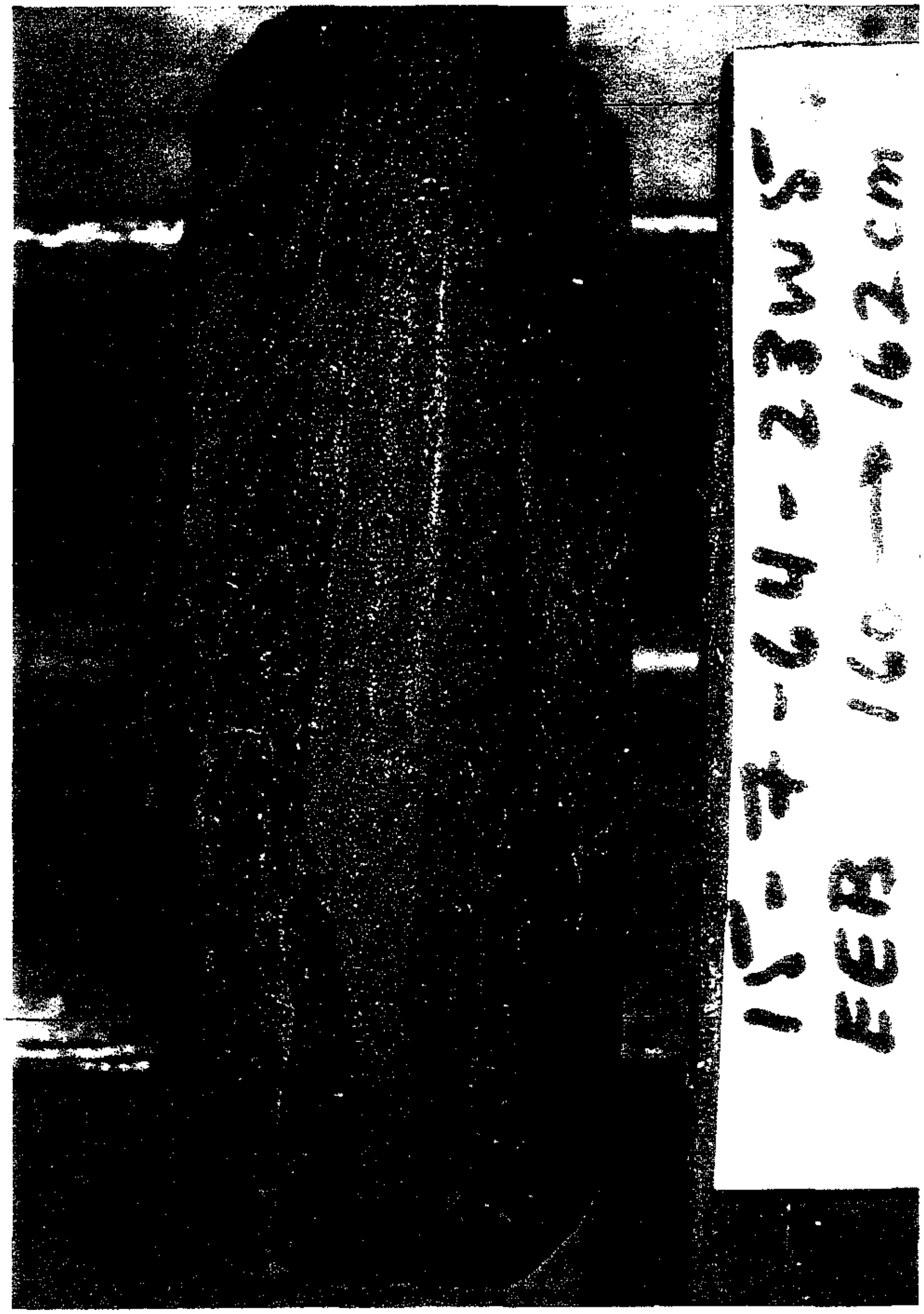

5 cm.

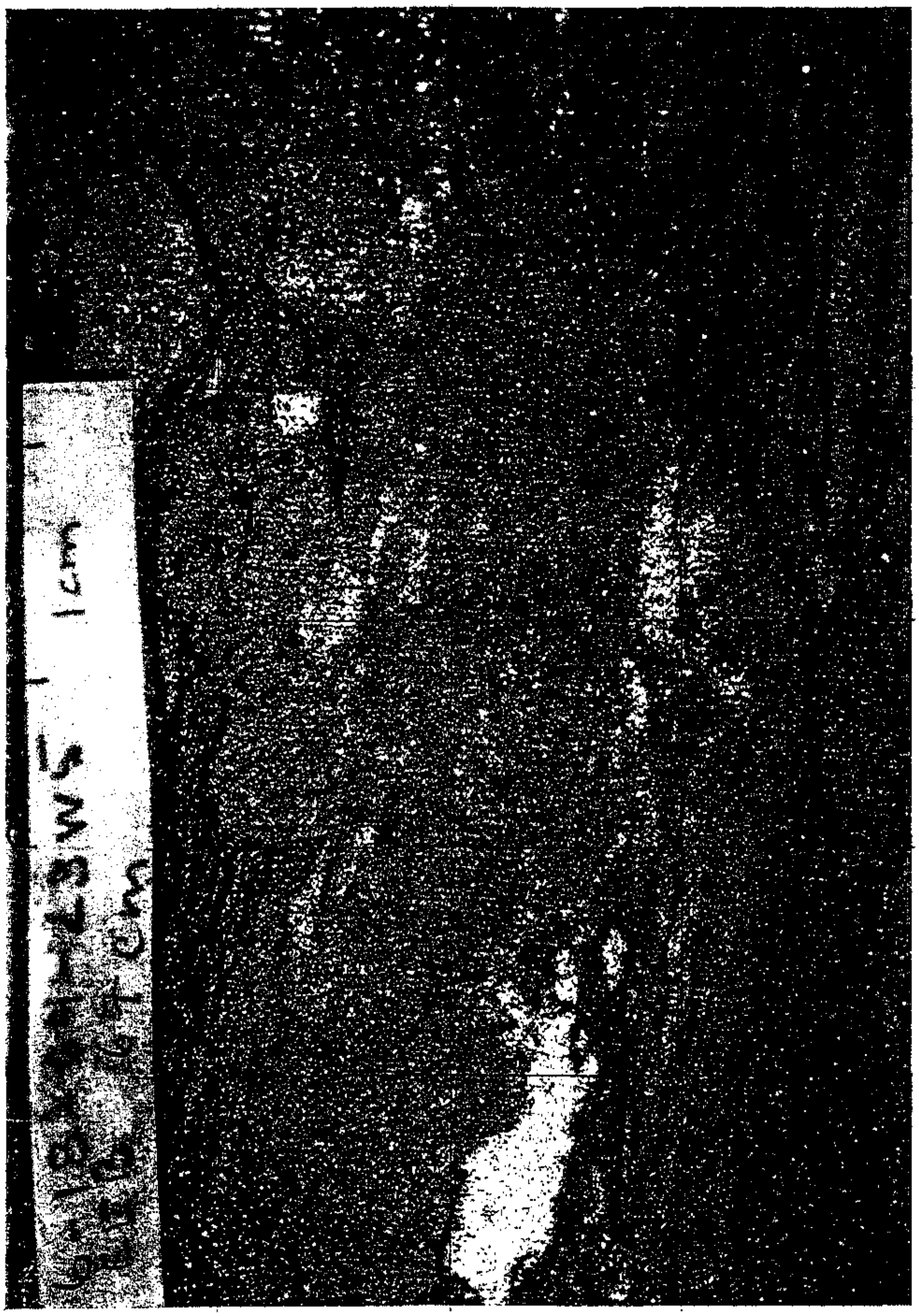
but these results can be useful for ecological implications.

Substrate 2 (30) is quantified with the number of dark and pale grains in a representative photograph of bioturbated shales (Facies 1B) (15-7-64-23W5, 1.60-1.62 m) (Figure 3.11). The tabulation of four squares (16 cm^2) suggests this example contains 79% dark grains (mud and silt) and only 21% pale grains (sand). The facies and biogenic structures are more diverse in this substrate than Substrate 1. The biogenic structures identified in bioturbated shales (Facies 1B), carbonaceous shales (Facies 1C) and pervasively bioturbated mudstones (Facies 3A) include: *Arenicolites, Asterosoma, Diplocraterion, Helminthopsis, Palaeophycus, Planolites, Rhizocorallium, ?Siphonichnus, Skolithos, Teichichnus, Terebellina, Thalassinoides* and *Zoophycos*. Deposit-feeding trace makers are common in Facies 1B, whereas Facies 3A contains both deposit- and suspension-feeding trace makers. Facies 1C was exclusively burrowed by *Planolites*-trace makers.

Substrate 3 (30, 30-60) was not quantified but its ratio of pale versus dark grains counts should result in pale grain proportions greater than Substrates 2 (21%) and fewer than Substrate 4 (41%). This assumption is based on higher reflectivities occurring in sediments having more pale grains (sand) than Substrate 2 but fewer than Substrate 4. The trace fossils documented in Substrate 3 include: *Arenicolites*, *Diplocraterion*, *Helminthopsis*, *Palaeophycus*, *Planolites*, *Rhizocorallium*, *?Siphonichnus*, *Teichichnus*, *Terebellina*, *Thalassinoides* and *Zoophycos*. These traces are most common in bioturbated shales (Facies 1B) but are present in other facies and substrate groups.

Substrate 4 (30-60) is characteristic of sandier deposits such as Facies 3A (pervasively bioturbated mudstones), Facies 3B (laminated-to-burrowed mudstones) and Facies 5 (banded mudstones). The quantification of these substrate textures was determined using a close-up photograph of pervasively bioturbated mudstone (6-18-64-23W5, Figure 3.12). This point count suggests that this facies contains 59% dark grains and 41% pale grains. The increase in sand content is reflected in the animals' functional responses. Suspension-feeding traces (e.g.,*Skolithos* and *fugichnia*) are more abun-


15-7-64-23W5
EEB 160 → 162cm


1cm

dant in this substrate than deposit-feeders. Each facies consists of substrate textures that were advantageous for a diverse population of deposit- and suspension-feeders. These animals made various ethological patterns representative of feeding, dwelling, locomotion and resting. The ichnofossils and associated facies representing these patterns include: *Arenicolites* (Facies 3B), *Asterosoma* (Facies 3, 5), *Bergaueria* (Facies 3B), *Chondrites* (Facies 3B), *Cylindrichnus* (Facies 5), *Diplocraterion* (Facies 3B, 5), *fugichnia* (Facies 5), *Palaeophycus* (Facies 3B, 5), *Planolites* (Facies 3, 5), *Rhizocorallium* (Facies 3B, 5), *?Siphonichnus* (Facies 5), *Skolithos* (Facies 3, 5), *Subphyllochorda* (Facies 3B), *Teichichnus* (Facies 3, 5), *Terebellina* (Facies 3A, 5), *Thalassinoides* (Facies 3, 5), and *Zoophycos* (Facies 3A, 5).

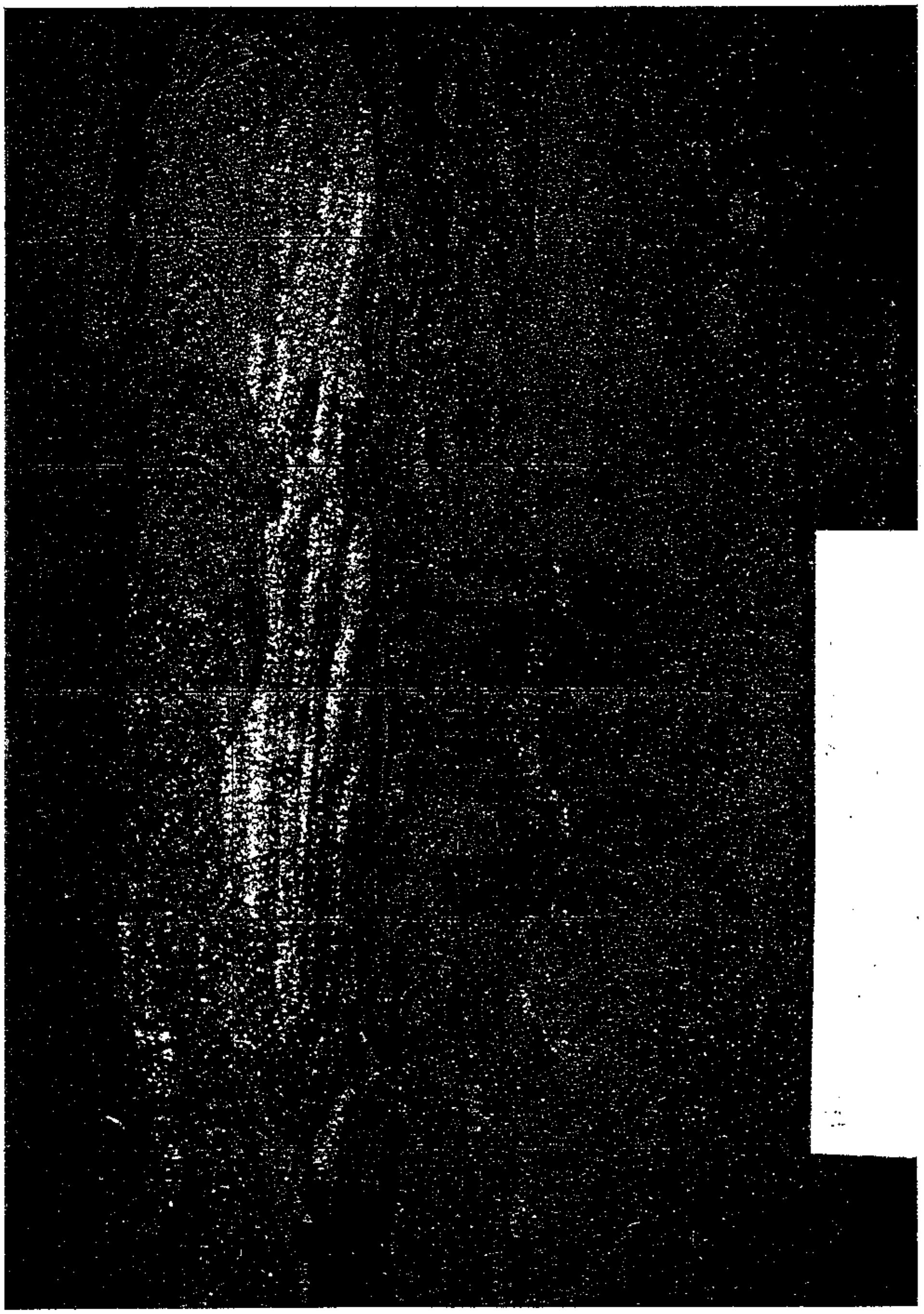
Substrate 5 (30-60, 60) is characteristic of interbedded mudstones and trace fossil assemblages produced by deposit-feeders. The facies common to this substrate group included blockstones (Facies 2), pinstriped mudstones (Facies 4) and banded mudstones (Facies 5). A suitable photograph was not taken for an accurate point count but the pale and dark grains range between the calculated percentages for Substrates 4 and 6. This would result in averages of 46-59% and 41-54% for the dark and pale grains, respectively. The trace fossils associated with this substrate include: *Arenicolites* (Facies 2), *Asterosoma* (Facies 5), *Cylindrichnus* (Facies 4, 5), *Diplocraterion* (Facies 5), *fugichnia* (Facies 2, 4, 5), *Palaeophycus* (Facies 4), *Planolites* (Facies 2, 4, 5), *Rhizocorallium* (Facies 2, 5), *?Siphonichnus* (Facies 2, 5), *Skolithos* (Facies 2, 4), *Subphyllochorda* (Facies 4), *Teichichnus* (Facies 4, 5), *Terebellina* (Facies 2, 4, 5), *Thalassinoides* (Facies 2, 4) and *Zoophycos* (Facies 2). A diagnostic feature of these deposits is the interbedded nature of the mudstones and sandstones, despite interbed thickness. The sandstones in Facies 5 are thicker, resulting in higher reflectivities of 30-60, 60 for the five random measurements.

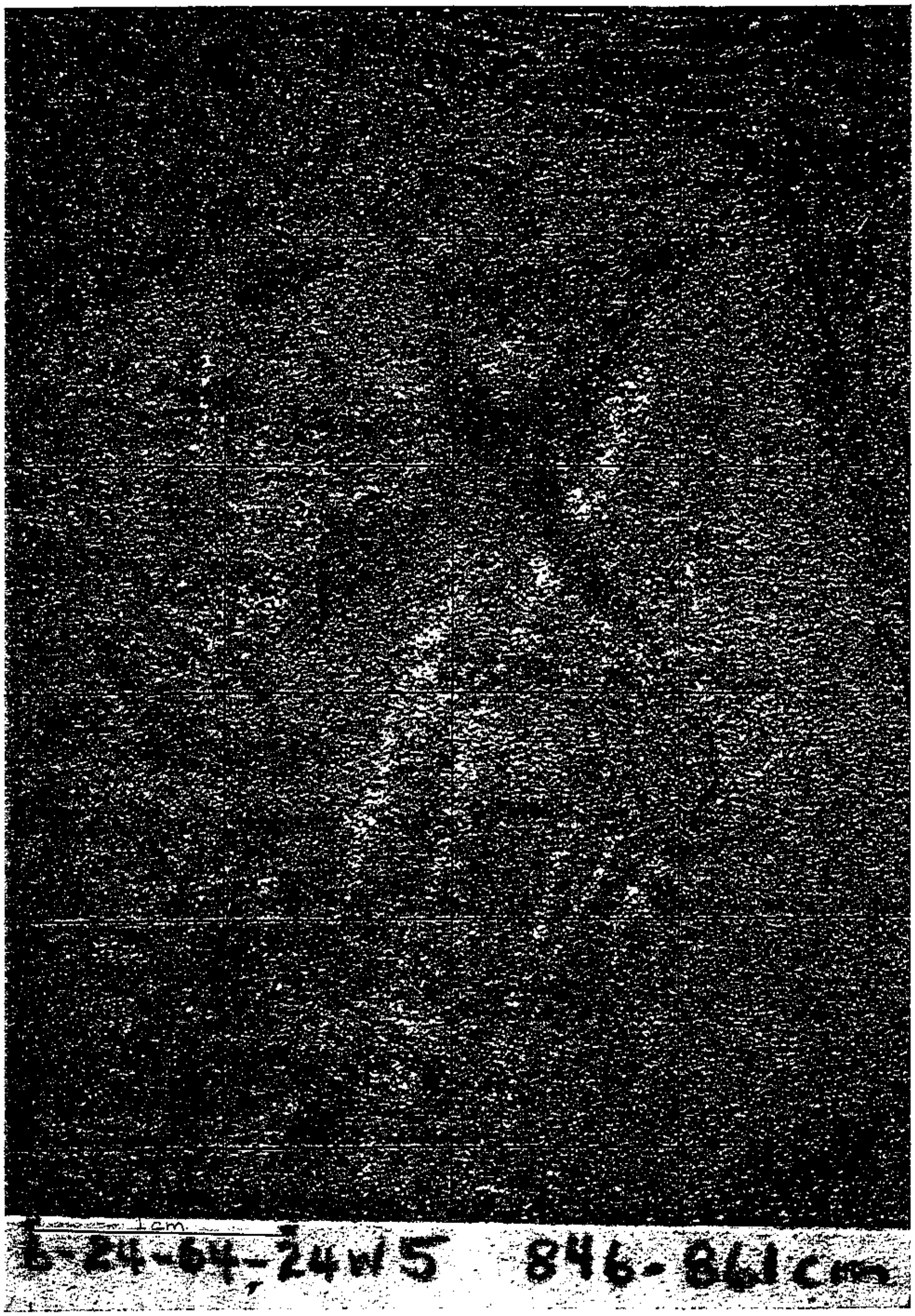
Substrate 6 (60) contains ethological patterns made by mud- and sand-adapted deposit- and suspension-feeders. The facies associated with this substrate group are clean sandstones including:

hummocky-cross-stratified sandstones (Facies 8C), wave-rippled sandstones (Facies 8E), cross-bedded sandstones (Facies 8G), cross-bedded sandstones containing paired mud partings (Facies 8H) and structureless sandstones (Facies 8I). Grains present in this substrate group were counted in ten 16 cm^2 areas randomly selected on the core face of the close-up photograph (14-4-64-23W5, Figure 3.13). The content of pale and dark grains averaged 54% and 46%, respectively. The following traces were produced by deposit-feeders that burrowed into the mudstones draping the sandstones: *Helminthopsis* (Facies 8C), *Planolites* (Facies 8C, 8E, 8G, 8I), *?Siphonichnus* (Facies 8C), *Teichichnus* (Facies 8C, 8E, 8G, 8I), and *Zoophycos* (Facies 8C). Traces present in the sandstones include: *Asterosoma* (Facies 8C), *Bergaueria* (Facies 8G), *Cylindrichnus* (Facies 8G, 8H), *Diplocraterion* (Facies 8G), *Ophiomorpha* (Facies 8C), *Palaeophycus heberti* (Facies 8E), *Palaeophycus tubularis* (Facies 8C, 8G, 8H), *Skolithos* (Facies 8C, 8E, 8G) and *Teichichnus* (Facies 8C, 8E, 8G, 8H).

Substrate 7 (60, 60-125) is typified by current-rippled and structureless sandstones (Facies 8F and 8I). Figure 3.14 comprises a sandstone (6-24-64-24W5) that has a pale (sand) grain component of 62% and a dark (mud/silt) grain component of 38%. These percentages represent cleaner sandstones than previous substrate groups. The biogenic structures identified in these facies, particularly those of sand-adapted trace makers, support this generalization. These sandstones lack biogenic structures or contain: *Asterosoma* (Facies 8F), *Cylindrichnus* (Facies 8I), *Ophiomorpha* (Facies 8F, 8I), *Palaeophycus heberti* (Facies 8F), *Palaeophycus tubularis* (Facies 8F, 8I), *Planolites* (Facies 8F, 8I), *Rhizocorallium* (Facies 8F, 8I), *Skolithos* (Facies 8F), *Teichichnus* (Facies 8F, 8I), *Terebellina* (Facies 8F) and/or *Thalassinoides* (Facies 8F).

Substrate 8 (60-125) is cleaner than Substrate 7 and mud-adapted trace makers are replaced by trace makers adapted to sandy sediments. Wave-rippled sandstones (Facies 8E) and flat-laminated sandstones (Facies 8D) lack biogenic structures. An appropriate photograph was not taken. The sand content range for this substrate group is 62-65%, representing the proportion of sand (by number) for



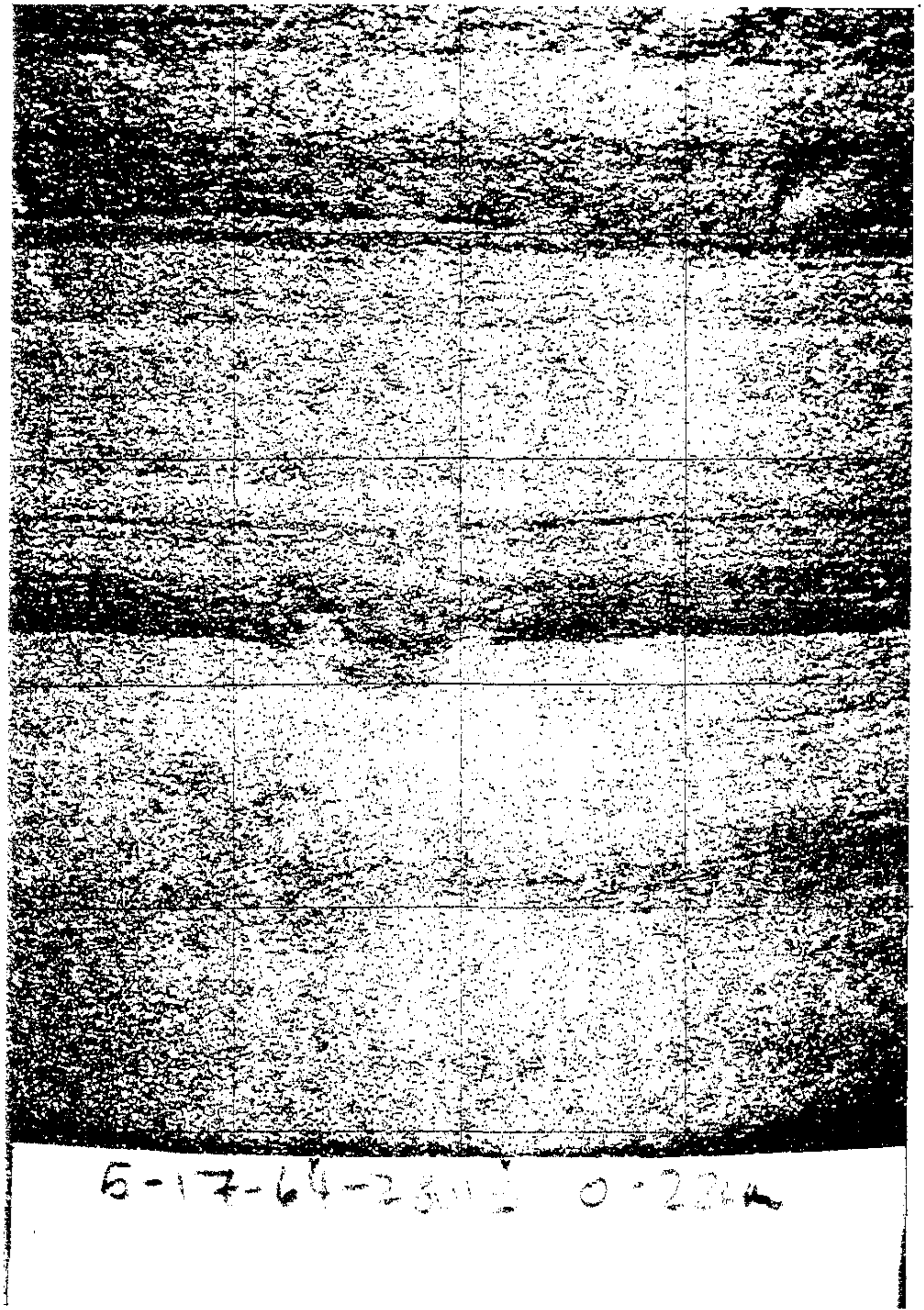

1cm
6-24-64-24W5 846-861cm

Substrates 7 and 10, respectively. Traces associated with pervasively bioturbated sandstones (Facies 8J) include: *Anconichnus*, *Chondrites*, *Helminthopsis*, *Planolites*, *Rhizocorallium*, *?Siphonichnus*, *Subphyllochorda*, *Teichichnus*, *Terebellina*, *Thalassinoides* and *Zoophycos*. *Planolites*, *Rhizocorallium* and *Teichichnus* are present in mud drapes contained in structureless sandstones (Facies 8I).

Substrate 9 (60-125, 125) is characteristic of banded mudstones consisting of thick sandstone intervals (Facies 5). A suitable photograph was not taken for accurate point counts of this substrate group. These clean sandstones are assumed to contain 62-65% sand. The trace fossil assemblages are dominated by sand-adapted trace makers. However, mud-adapted trace makers burrowed through mud drapes separating the sandstones. Trace fossil assemblages include: *Asterosoma*, *Cylindrichnus*, *Diplocraterion*, *fugichnia*, *Palaeophycus*, *Planolites*, *Rhizocorallium*, *Teichichnus*, *Terebellina*, *Thalassinoides*, *?Siphonichnus* and *Skolithos*. The burrows occur near the tops of sandstone and mudstone intervals.

Substrate 10 (125) is characteristic of cross-bedded sandstones with paired mud partings (Facies 8H) and structureless sandstones (Facies 8I) that lack or contain few trace fossils. This substrate was quantified using a close-up photograph of 5-17-64-23W5 (Figure 3.15). The average pale and dark grain percentages, as tabulated by point counts, were 65% and 35%, respectively. Trace fossils common in these sandstones include: *Cylindrichnus* (Facies 8H and 8I), *Diplocraterion* (Facies 8H), *Palaeophycus* (Facies 8H and 8I), *Skolithos* (Facies 8H) and *Teichichnus* (Facies 8H and 8I). *Planolites* (Facies 8H and 8I), *Thalassinoides* (Facies 8H), *Rhizocorallium* (Facies 8I) and *Bergaueria* (Facies 8H) are preserved in the mud drapes or the vague laminations associated with these facies.

These counts suggest that an upper sand content limit in a substrate be 65% by number. Most animals that colonized the Waskahigan Bottleneck Channel burrowed through substrates consisting of almost equal portions of mud and sand. Substrate 5 with a dark grain proportion of 46-59% represents


5-17-64-23W5 0-22cm

this type of softground. These ten substrate groups suggest another potential tool to describe the intricate and subtle relationships between benthic animals and the sediments through which they burrowed. These relationships enable generalizations to be made about the ethological behaviour of an animal and the sediment grain size and consistency.

3.3.2 SUBSTRATE CHARACTERISTICS AND ASSOCIATED ICHNOFOSSILS: IMPLICATIONS

The sediments measured in the Waskahigan Bottleneck were grouped into ten substrate groups, described in Section 3.3.1. The ramifications of these substrate groups indicate this semi-quantitative substrate analysis has the potential to predict the types of benthic animals that could have burrowed through the sediments. Even if the entire population is not represented "*due to accidents of deposition and preservation*" (Pierce, 1989, p. 101). Ecological conditions are reflected in the physical structures and the distribution of trace fossils made by deposit- and suspension-feeders. Most depositional environments were interpreted as marginal marine and some marine environments in relatively deep and protected areas.

Ecological Implications

Substrate 1 consists of laminated shales with no discernable biogenic structures. The muddy depositional environment was stable with essentially no transport of coarse-grained sediments. This substrate was deposited below storm wave base (Bhattacharya, 1989). The absence of trace fossils suggests bottom sediments may have been influenced by low oxygen levels that were potentially anaerobic (Savrda and Bottjer, 1986, 1989).

Substrate 2 facies and trace fossils suggest the palaeoecological environment was quiet and stable with deposition from suspension and silt and very-fine- grained sands. In this depositional environment, the functional benthos includes deposit-feeders adapted to relatively weak currents. Suspension-feeders and sand-adapted animals colonize coarser-grained event beds (Rhoads and Young, 1970).

The physical and impoverished-marine biogenic structures are characteristic of protected embayments in the lower estuary affected by lower salinities (25-30‰; Kamola, 1984), lower oxygen levels and grain size plus slower sedimentation rates (Warme, 1971; Marintsch and Finks, 1978; Miller, 1991). Sandstone event beds were infrequent and providing fair weather periods for biogenic reworking and resuspension of fine-grained material, limiting the number of vertical trace fossils (Rhoads and Young, 1970; Nichols *et al.*, 1978).

Substrate 3, characterized by Facies 1B, was interpreted as marine mudstones deposited below storm wave base in relatively quiet and stable environments (Bhattacharya, 1989). The trace fossils were produced by deposit-feeders and a few suspension-feeders. The uncommon vertical shafts suggest that weak currents existed during deposition and colonization of these mudstones (Bromley, 1990).

Substrate 4 is characteristic of sediments (Facies 3B, 5) deposited under fluctuating sedimentation and current rates. Most traces were produced by deposit-feeders during fair weather conditions. These trace makers present in laminated-to-burrowed and banded mudstones were adapted to stressed and potentially dysaerobic oxygen levels in protected marginal marine environments. Dysaerobic oxygen levels are suggested to have existed due to *Chondrites* burrows present in black mudstones (Savrda and Bottjer, 1986, 1989). An ichnofossil assemblage containing *Diplocraterion* and *Thalassinoides* burrows and synaeresis cracks support a brackish-water environment (Hallam, 1975; Frey *et al.*, 1978; Howard and Frey, 1985; Plummer and Gostin, 1981; Kamola, 1984; Bjerstedt and Erickson, 1989; Pemberton and Wightman, 1992).

Substrate 5, containing blockstones, pinstriped mudstones and banded mudstones, reflects stable and/or salinity-stressed environments with episodic deposition of very-fine to fine-grained sandstones (Bhattacharya, 1989). At some mudstone-sandstone contacts, synaeresis cracks occur. Low salinities (20-30‰) may have affected the sediment-water interfaces because *Diplocraterion* and

Thalassinoides burrows are present in trace assemblages (Frey *et al.*, 1978; Plummer and Gostin, 1981; Kamola, 1984; Howard and Frey, 1985; Bjerstedt and Erickson, 1989).

Substrate 6 consists of relatively clean sandstones deposited by storm waves, tidal currents and/or rapid sedimentation. Most ichnogenera identified are produced by sand-adapted animals. Mud-adapted animals colonized mud drapes during the quiescent periods between the high-energy events. The physical and biogenic structures suggest the sediments are marine in origin.

Substrate 7 sediments were deposited during rapid sedimentation and strong currents. These parameters are suggested by structureless sandstones and asymmetrical current-rippled sandstones with climbing ripples evident in some deposits. The trace fossil assemblages are dominated by sand-adapted trace makers (suspension- and deposit-feeders). Mud-adapted trace makers are confined to the mud drapes deposited during stable, fair weather periods.

Substrate 8 is cleaner than previous substrates. The biogenic structures (eg., *Skolithos*) found in these deposits represent the *Skolithos* Ichnofacies. Deposit-feeding traces (eg., *Planolites*) are confined to the mud drapes.

Substrate 9 facies suggest the palaeoenvironment was marginal marine with discontinuous sedimentation resulting in thicker, coarser sandstone intervals and thinner mudstones. Burrowing activity occurred in the sandstone tops and mudstones during slack water periods. The trace fossils preserved in the mud drapes and sandstones are remnants of pioneer community rather than fair weather climax community (Ekdale, 1985; Bromley, 1990).

Substrate 10 sediments were deposited in relatively high-energy environments. Trace fossil preservation was biased by the high-energy currents, rapid sedimentation rates and shifting substrates. Structureless sandstones containing few traces were deposited in a distributary channel. This channel was influenced by strong tidal currents as showed by sigmoidally-cross-bedded sandstones

(Bhattacharya, 1989). This depositional environment was optimal for colonization by suspension-feeders (e.g., *Skolithos*) and not deposit-feeders (Scott, 1978).

Ichnospecies Predictability

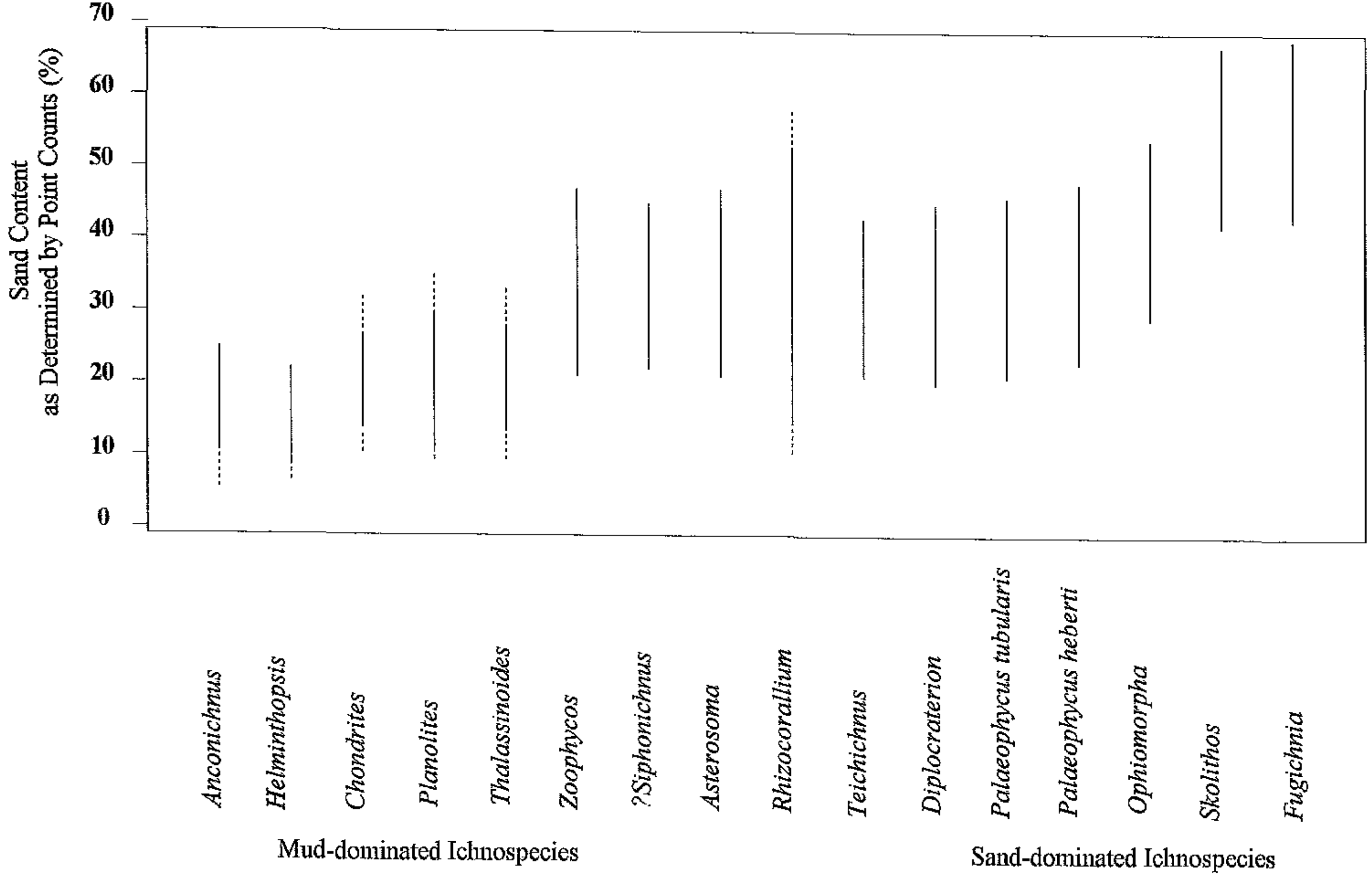
Traces are not exclusive to one substrate group but are preserved in sediments with specific textures, sand/mud percentages and functional grain sizes (Bromley, 1990). Sediment properties and physical parameters contro the preservation of biogenic structures (Rhoads and Young, 1970; Bromley, 1990). Usually, horizontal traces made by deposit-feeders are preserved in muddy substrates, whereas vertical shafts made by suspension-feeders are found in clean sandstones (Figure 3.16). Of the 24 ichnospecies present in the Dunvegan cores, animal-sediment predictability is summarized for *Planolites*, *Helminthopsis* and *Anconichnus*, *Rhizocorallium*, *Teichichnus*, *Palaeophycus heberti* and *Skolithos*.

Planolites

These simple, unlined burrows are preserved in most deposits, but are concentrated in black mud drapes deposited from suspension, characteristic of Facies 1C and Substrate 2. The mud/silt content of this substrate is 79%. The assemblages in these mud drapes are dominated by *Planolites* burrows.

Helminthopsis* and *Anconichnus

These ichnogenera represent discontinuous, fecal traces of deposit-feeding polychaetes (Häntzschel, 1975; Kern, 1978; Goldring *et al.*, 1991) preserved in bioturbated shales (Facies 1B). The shredded sediment texture is due to many, black pellet intersections (elliptical) that either lack a halo (*Helminthopsis*) or consist of a silty grey, possibly diagenetic, halo (*Anconichnus*) (Goldring *et al.*, 1991). The mud content of these sediments is approximately 79%, corresponding to Substrates 2 and 3. The shales are deposited in protected, low-energy and open marine environments as indicated by the inclusion of *Helminthopsis* and *Anconichnus* in the *Cruziana* and *Zoophycos* Ichnofacies (Häntzschel,


Sand Content and Common Trace Fossils in the Waskahigan Bottleneck Channel

1975; Goldring *et al.*, 1991).

Rhizocorallium

Sediments consisting of approximately 38-59% clay/silt particles and 41-62% sand grains (Substrates 2-8) have trace fossil assemblages that include *Rhizocorallium* burrows. The horizontal U-tubes are more common in muddy sediments (e.g., Facies 1B, 1C, 2, 3A, 3B and 5) than mud draped sandstones (e.g., Facies 8C, 8D, 8E, 8F, 8G, 8H, 8I). The common denominator associated with *Rhizocorallium* and sediment texture is the mud-sand content (46% and 54%, respectively). These percentages reflect shutter speed measurements equal to 60 (Substrate 6). It is hypothesized that deposits containing *Rhizocorallium* burrows are composed of 50% mud/silt and 50% sand to allow the colonization of these marine deposit-feeders. The abundance of organic-rich material in these muddy substrates may be more important to the animals but the apparent generalization of the sediment composition is also important (Bromley, 1990).

Teichichnus

The trace fossil *Teichichnus* occurs in a variety of facies associated with Substrates 2-7 [e.g., bioturbated shales (Facies 1B), mudstones (Facies 3B, 4, 5) and fine-grained sandstones (Facies 8C, 8F)]. Animals making this burrow of vertically stacked horizontal tubes are adapted to burrowing through relatively clean sandstones (Häntzschel, 1975). *Teichichnus* burrows are more abundant in muddy sediments because organic material necessary for sustaining a population is more abundant (Wolff, 1980).

Palaeophycus heberti

Palaeophycus heberti burrowers are only preserved in core 7-13-64-23W5. The deposits containing this burrow include fine- to medium-grained wave-rippled sandstones (Facies 8E) and pervasively bioturbated sandstones (Facies 8J). These sandstones, representing Substrates 7 and 8, consist of approximately 62% sand and 38% mud. *Palaeophycus heberti* is common in shoreface and sandstones of interbedded deposits (Pemberton and Frey, 1982; Frey and Howard, 1990).

Skolithos

The substrates containing *Skolithos* shafts are as predictable as those containing *Planolites* burrows. This vertical ichnospecies occurs in most fine-grained sandstone deposits: interbedded mudstones (Facies 2, 4, 5), bioturbated mudstones (Facies 3A, 3B) and sandstones (Facies 8C, 8D, 8E, 8F, 8G, 8H, 8I, 8J). These facies and associated substrates (2-10) range from 21-65% in sand content. The cleaner sandstones (e.g., Substrate 10) result from shifting sand grains in moderate to high energy waves and currents. This environment is well suited for these suspension-feeders (Scott, 1978).

The predictability of trace fossils in certain substrates can be beneficial in attempting to reconstruct a benthic community. The absence of suspected traces in a deposit can suggest potential ecological parameters or circumstances that could be overlooked when interpreting the palaeobiology and the palaeoenvironment.

3.4 STATISTICAL ANALYSIS

3.4.1 STATISTICAL ANALYSIS: RESULTS

In the Dunvegan cores, certain traces consistently occur together in various sediments. To detect if these trace fossil pairs represent true relationships between ichnospecies and substrate and/or preservation biases, correlations were run to evaluate thirteen trace fossil pairs and two associations involving the presence of synaeresis cracks. The sample sizes in these groupings are small, fewer than 20 intervals, thus it is difficult to assess the statistical significance.

Correlations show most trace fossil pairs and the synaeresis crack associations in the Waskahigan Bottleneck are not significant. This suggests that more parameters (e.g., time and/or noncontemporaneous populations) produced these trace pairs. Trace associations involving

Palaeophycus heberti burrows correlate well in core intervals containing *Skolithos*, *Palaeophycus tubularis* and *Planolites*. The association of *Planolites* and *Thalassinoides* intersections did not correlate as well for core intervals containing both ichnospecies.

Palaeophycus heberti **Associations**

Three trace fossil associations with *Palaeophycus heberti* are recognized in the fine- to medium-grained sandstones in 7-13-64-24W5 (Units 2-3): 1) *Skolithos* shafts, 2) *Palaeophycus tubularis* and 3) *Planolites* burrows. The correlations with *Palaeophycus heberti* are very good for the small data set (2-4 intervals containing both traces). This limited number of intervals containing *Palaeophycus heberti* burrows reflects the overall fine-grained texture of Waskahigan sandstones. The facies in which these trace fossils occur include current-rippled sandstones (Facies 8F), cross-bedded sandstones (Facies 8G) and pervasively bioturbated sandstones (Facies 8J).

Planolites-Thalassinoides **Association**

Planolites and *Thalassinoides* burrows are preserved together in twenty intervals. This association occurs in bioturbated shales (Facies 1B), blockstones (Facies 2), pervasively bioturbated mudstones (Facies 3A), laminated-to-burrowed mudstones (Facies 3B), pinstripe mudstones (Facies 4), current-rippled sandstones (Facies 8F) and pervasively bioturbated sandstones (Facies 8J). In these facies both burrow intersections are found in thick mud drapes.

These trace fossil associations are useful in determining if a particular ichnospecies had the potential for preservation in certain facies. For example, deposit-feeding burrows correlate poorly with suspension-feeding traces but two similar deposit-feeding traces (e.g., *Planolites* and *Thalassinoides*) correlate well in the Waskahigan Bottleneck.

3.4.2 STATISTICAL ANALYSIS: A DISCUSSION

The statistical analysis, using corelations, supports the analysis of biological functions. Overall, the vertical dwelling structures did not correlate with the horizontal feeding traces. Environmental parameters affecting the sediment-water interface determine the trophic structure able to colonize the sediment. Trace fossil associations of *Planolites-Thalassinoides* and those involving *Palaeophycus heberti* correlated well.

Palaeophycus heberti Associations

The good correlations of *Palaeophycus heberti* burrows with *Skolithos*, *Palaeophycus tubularis* and *Planolites* burrows are biased by the sample sizes (n = 2, n = 4). More intervals containing each pair of traces are necessary to decide if these correlations are reasonable. Correlations between *Palaeophycus heberti* and *Planolites* burrows are not as good because the latter occur in mudstones draping current-rippled and cross-bedded sandstones in which *Palaeophycus heberti* burrows are preserved. However, the correlations involving *Palaeophycus tubularis* and *Skolithos* are good because both burrow intersections occur in sand-dominated deposits. *Palaeophycus* and *Skolithos* represent feeding and dwelling structures for deposit- and suspension-feeders, respectively. In pervasively bioturbated sandstones these trace fossils can coexist but they may not be contemporaneous.

Planolites-Thalassinoides Association

This association reflects the trophic function of two horizontal structures (e.g., feeding and dwelling). *Planolites* and *Thalassinoides* intersections correlated well because the burrows are characteristic of mudstone. However, *Thalassinoides* occurs in thicker layers overlain by coarser-grained deposits. *Planolites* burrows are produced by sediment-ingesting polychaetes and other worm-like animals (Häntzschel, 1975; Pemberton and Frey, 1982; Frey and Howard, 1990). *Thalassinoides* burrows represent nonreinforced, box-like structures of animals analogous to the intertidal *Callianassa* shrimp (Häntzschel, 1975; Pemberton and Frey, 1982; Ekdale, 1985). In a core, the two traces are distinguished by burrow diameters: *Planolites* ranged from 2 mm to 10 mm and *Thalassinoides* burrows were greater than 10 mm (Pemberton and Frey, 1984; D. Becktel and I. Raychaudhuri, 1992, pers. comm.).

Most Waskahigan Bottleneck trace fossil relationships are statistically not significant because more than one dependent factor (e.g., salinity, hydraulic circulation, substrate and sedimentary processes) caused a physical bias in trace fossil preservation (Scott, 1978; Frey and Seilacher, 1980; Birks, 1985). These results suggest the ecology of the sea bed during colonization was different for most trace fossils. Time constraints are difficult to distinguish for biogenic assemblages because no crosscutting relationships are observed. Substrate composition (see Section 3.3.1-3.3.2) is a key factor for these apparent trace pairs because certain trace makers prefer specific substrate textures, grain sizes, mud-to-sand ratios and, indirectly, wave-energy (Rhoads and Young, 1970).

3.5 ENVIRONMENTAL CORE INTERPRETATIONS

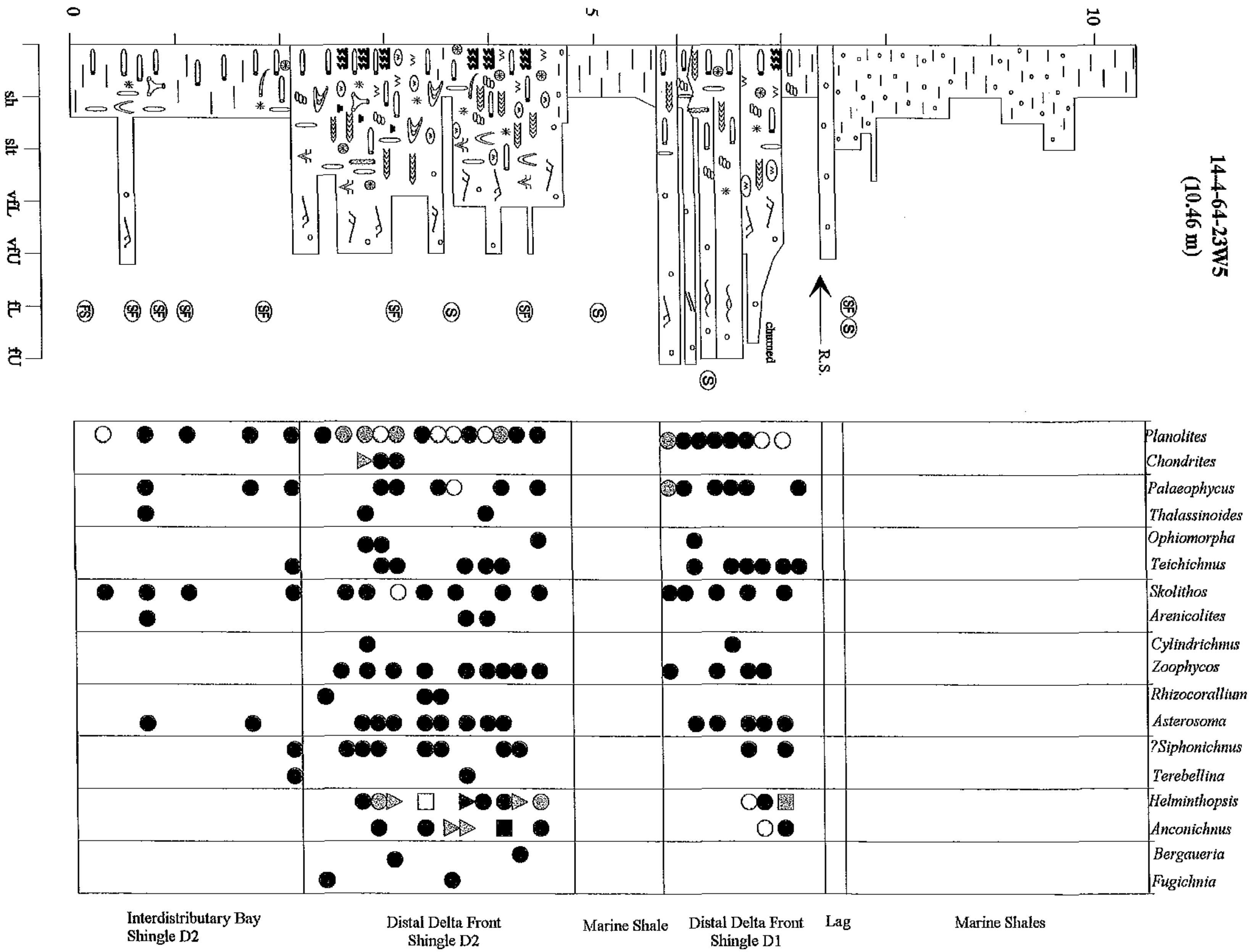
The Dunvegan cores are interpreted in the same order as described: from the most seaward (14-4-64-23W5) to the most landward (6-24-64-24W5). These interpretations depend on the quantification of biogenic structures to distinguish between different units containing comparable physical sedimentary structures. These environmental interpretations are based on each described unit (see Section 3.2) and the succession of depositional environments in each core. The core diagrams presented in Section 3.2 are modified to display depositional environments instead of unit numbers.

The trace fossil assemblages associated with the *Zoophycos*, *Cruziana* and *Skolithos* Ichnofacies suggest potential environmental conditions (e.g., sediment stability and consistency, and salinity fluctuations) that existed as the Waskahigan Bottleneck channel infilled and benthic animals colonized the sediments (Bromley, 1990; Seilacher 1967; Ekdale, 1985). These conditions affected the diversity and abundances of individual traces preserved in these assemblages. These variations support the following environmental interpretations and enable generalizations to be made about the palaeoecology and palaeogeography of the Waskahigan Bottleneck incised valley (Section 3.6).

14-4-64-23W5 Core Interpretation

This core has six units distinguished by the biogenic structures present (Figure 3.17). The eighteen ichnospecies present in this core characterize how the environments changed at the seaward limit of the Waskahigan Bottleneck. The ichnospecies found in this core are: *Anconichnus*, *Arenicolites*, *Asterosoma*, *Bergaueria*, *Chondrites*, *Cylindrichnus*, *fugichnia*, *Helminthopsis*, *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Rhizocorallium*, *Teichichnus*, *Terebellina*, *Thalassinoides*,*?Siphonichnus*, *Skolithos* and *Zoophycos*.

The silty mudstones (Unit 1, 0-2.15 m) are interpreted as prodelta/ interdistributary bay mudstones based on the well location (farthest seaward) and the overlying deposits. The mud was deposited from suspension with silt laminae suggesting a deltaic influence in deposition (Bhattacharya and Walker, 1992). Bioturbation is not as extensive as in offshore environments (Bhattacharya and Walker, 1992). The trace fossil assemblages in this environment are less diverse and have fewer i.p.s.a.s than the overlying units (Units 2-4). This trace assemblage is comparable to other silty mudstones containing biogenic structures made by marine organisms. It represents the *Zoophycos* and *Cruziana* Ichnofacies. The abundances of individual traces are fewer than 1.00 i.p.s.a. for most occurrences, but *Planolites* occurs in greater abundances (0.94-4.92 i.p.s.a.).


14-4-64-23W5
(10.46 m)
0
5
10
sh
slt
vfL
vfU
fL
fU
FS
SF
S
channeled
R.S.
Planolites
Chondrites
Palaeophycus
Thalassinoides
Ophiomorpha
Teichichnus
Skolithos
Arenicolites
Cylindrichnus
Zoophycos
Rhizocorallium
Asterosoma
?Siphonichnus
Terebellina
Helminthopsis
Anconichnus
Bergaueria
Fugichnia
Interdistributary Bay
Shingle D2
Distal Delta Front
Shingle D2
Marine Shale
Distal Delta Front
Shingle D1
Lag
Marine Shales

The sediment textures represent Substrates 1-3. The mud-dominated sediments supported marine deposit-feeding animals, primarily worms and worm-like animals. *Rhizocorallium* is absent from these mudstones suggesting that the sand content was insufficient for this trace maker. Few suspension-feeding shafts are present. The substrate stability, consistency and resuspension of mud and fecal pellets prevented these filter-feeding animals from colonizing the substrate. However, *Skolithos* shafts are relatively abundant (9.40 i.p.s.a.) near an upper-very-fine-grained event bed (0.27-0.34 m). The abundance of *Planolites* burrows in this interval is 4.92 i.p.s.a. suggesting that the conditions favoured *Skolithos* or these suspension-feeding vermiform animals burrowed into the banded mud from the overlying event bed they initially colonized.

The biogenic structures show the ecological conditions that existed at the sediment-water interfaces in this mudstone unit. The *Zoophycos* and *Cruziana* Ichnofacies suggest that the mud was deposited in a protected, stable depositional environment. These generalizations support Bhattacharya's (1989) interpretation that the mudstones were deposited in a prodelta/interdistributary bay associated with Shingle D2 of Allomember D.

The trace assemblages in Units 2 (2.15-4.73 m) and 4 (5.81-7.36 m) differ due to substrate textures. Unit 2's laminated-to-burrowed mudstones (Facies 3B) are characteristic of Substrate 4, whereas Unit 4's fine-grained sandstones (Facies 8C, 8E, 8F, 8I) are characteristic of Substrates 5 and 6. Increased wave energy and sand transportation resulted in a less diverse assemblage consisting of fewer i.p.s.a.s than present in Unit 2. Most sand beds in Unit 2 are beds thinner than 30 cm, whereas those in Unit 4 are thicker than 30 cm. This thickness is important because of the critical thickness through which bivalves and other animals can successfully escape in rapidly deposited sands (Rhoads and Young, 1970; Nichols *et al.*, 1978). This escape mechanism is suggested by *fugichnia* preservation in Unit 2 and their absence in Unit 4.

Changes in sand content and physical energies affecting these deposits are supported by

Zoophycos-grazers and *Rhizocorallium*-deposit-feeders. The complex trace *Zoophycos* is more abundant in the muddier Unit 2 sediments (0.31-2.35 i.p.s.a.) in comparison to 0.16-0.52 i.p.s.a. in Unit 4. The presence of *Zoophycos* suggests that the sediments in this core were deposited in protected embayments or below wave base on the continental slope (Häntzschel, 1975; Miller, 1991; Simpson, 1970). *Rhizocorallium* occurs only in Unit 2, confirming the generalization that this organism's presence is based on the proportionality of mud and sand. *Helminthopsis* and *Anconichnus* occur as the most abundant traces this core with maximum abundances of 39.15 i.p.s.a. and 27.41 i.p.s.a., respectively. These faecal traces are characteristic in muds deposited under normal marine conditions in the upper offshore-lower shoreface transition zone (Kern, 1978; Goldring *et al.*, 1991).

The presence of *Chondrites* (2.50-3.10 m, maximum 26.52 i.p.s.a.) suggests that the substrate was potentially dysaerobic at the time of deposition or later when this grazing trace maker burrowed down into the firmer, consolidated mud (Savrda and Bottjer, 1986). A potential anaerobic event may have caused the absence of trace fossils for 5 cm (3.10-3.15 m) above the last *Chondrites* intersections. Other mudstones, lacking traces, were sideritized from the early diagenesis of organic matter before burrowing, or conditions were not suitable for benthic colonization (Pemberton and Raychaudhuri, 1992).

Salinity fluctuations also affected the diversity and abundance of the trace assemblages, particularly in Unit 2. Spindle-shaped shrinkage cracks preserved at some mudstone-sandstone contacts represent these fluctuations. In this core, these cracks probably resulted from sediment compaction due to the dewatering of mud or major freshwater discharge (Plummer and Gostin, 1981; Pemberton and Wightman, 1992).

During fair weather periods, increases in diversity and abundance occur 5-10 cm below sediment-water interfaces (Rhoads and Young, 1970; Nichols *et al.*, 1978). Sediment texture and stability associated with intensely bioturbated mudstones and sandstones permit many animals (e.g., deposit- and suspension-feeders) to burrow through the sediment. Most biogenic structures decreased in abundance and became undiscernable due to biogenic reworking. These fair weather conditions are reflected by pervasively bioturbated sandstones (6.68-7.01 m) that cap undulating wave-rippled and hummocky cross-stratified sandstones (6.15-6.68 m). In contrast, storm events and associated deposits (e.g., HCS sandstones) can obliterate all signs of life except a few opportunistic animals that colonized the bed tops.

The banded mudstones containing the laminated-to-burrowed, current- and wave-rippled and HCS sandstones (Units 2 and 4) overlying Unit 1 are interpreted as two shingles of distal delta fronts associated with Shingles D1 and D2 of Allomember D (Bhattacharya, 1989; Bhattacharya and Walker, 1992). This interpretation is based on the more diverse and abundant ichnofossil assemblages. The biogenic and physical structures associated with these distal deltas show storm events were more common in Unit 4 (i.e., HCS sandstones and fewer traces).

The blockstones (Unit 3, 4.73-5.81 m) separating the two distal delta shingles suggest deposition occurred in a stable environment below storm wave base. This unit lacks discernable traces because few silt and sand grains are present to contrast the ethological patterns of the infauna and epifauna present in the mud (Bromley, 1990). Unit 3 is likely part of an interdistributary bay that formed due to lobe switching.

The cyclic distribution of the shingles (Units 2 and 4) and the blockstones (Unit 3) suggest autocyclic processes governed the emplacement of these deposits in the deltaic environment (Bhattacharya, 1989; Bhattacharya and Walker, 1992). The sediments of Allomember D (Shingle D1) were truncated and overlain by a silty mudstone lag (Unit 5, 7.36-7.46 m). This sharp-based erosion surface is interpreted as a ravinement surface (Bhattacharya, 1989). The silty mudstone corresponds to the end of Allomember D (Shingle D1) deposition. The absence of discernable biogenic structures in overlying black shales (Unit 6, 7.47-10.46 m) suggests that deposition occurred in a relatively deep marine environment that did not receive coarse sediments. These shales are associated with Allomember C deposition (Bhattacharya, 1989).

The ecological and environmental generalizations represented in 14-4-64-23W5 are based on the modern analogues of comparable biogenic structures. This location was marine as suggested by the *Zoophycos* and *Cruziana* Ichnofacies and the vertical succession of the depositional environments. These ichnofacies suggest that deposition and benthic colonization occurred in an offshore marine environment that was relatively quiet and influenced by storm events (e.g., hummocky cross-stratified sandstones preserved). The *Skolithos* Ichnofacies represented by *Arenicolites*, *Cylindrichnus*, *fugichnia*, *Ophiomorpha*, *Palaeophycus* and *Skolithos* suggest the shifting sand layers were deposited in higher energy circumstances (Bromley, 1990).

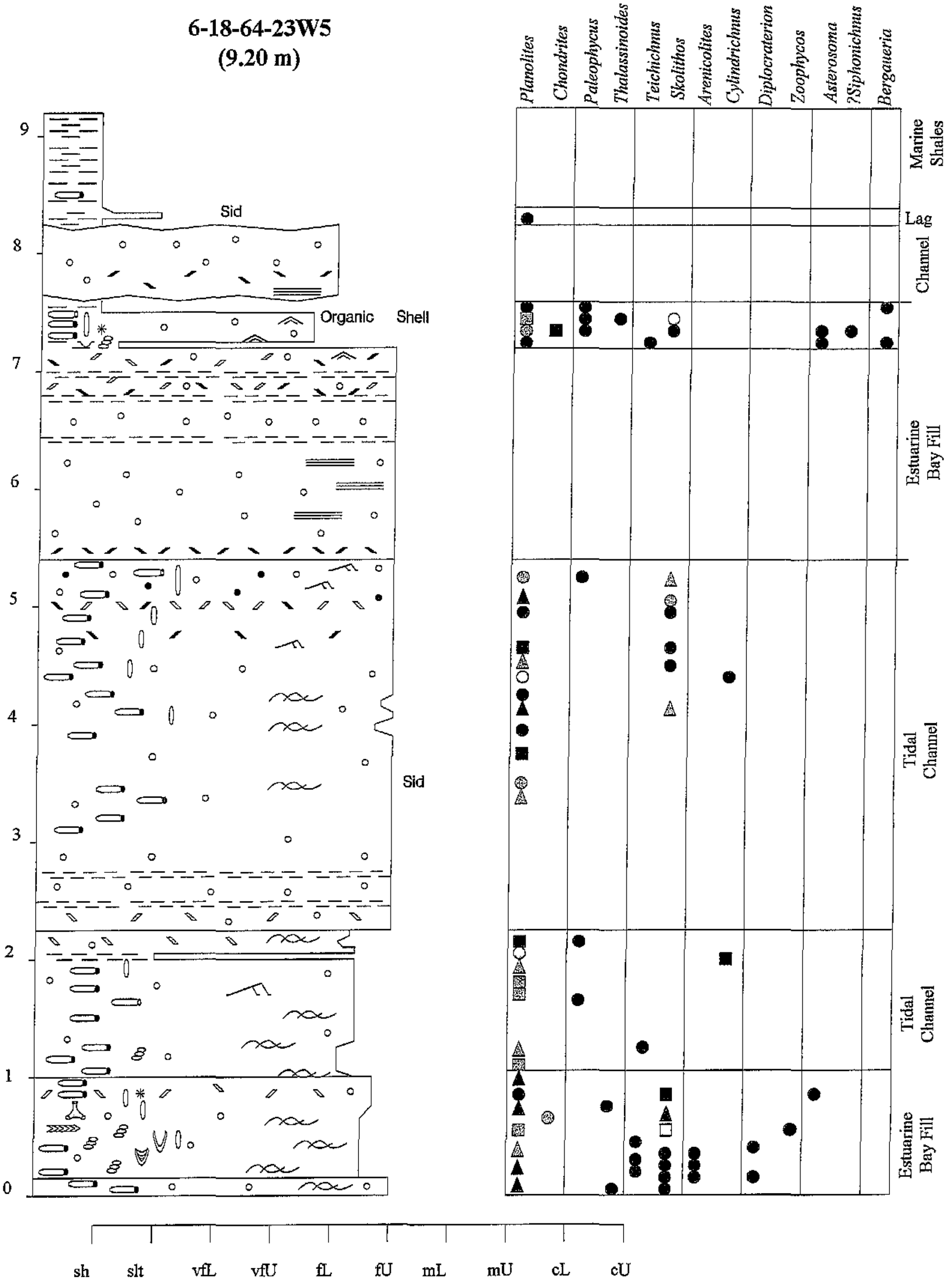
Prodelta/interdistributary bays (Units 1 and 3) separate the distal delta shingles (Units 2 and 4), with the younger shingle (D1) truncated by a marine flooding surface with a muddy siltstone lag deposited on this surface. Unit 3 was deposited in a potentially deeper marine environment than Unit 1 due to the absence of discernable trace fossils. Shingle D2 (Unit 2) was deposited in a relatively stable distal delta environment, whereas the Shingle D1 (Unit 4) environment was affected by more storm events. The ravinement surface and lag suggest that normal offshore marine conditions existed when the mud associated with Allomember C was deposited (Bhattacharya, 1989). *?Inoceramus* shell fragments common above most scour surfaces (Units 1, 2, 6) support the marine origin of the sediments deposited in this location because this bivalve rarely inhabits brackish-water sediments (E.G. Kauffman, 1993, pers. comm.).

6-18-64-23W5 Environmental Interpretation

The trace fossil assemblages described in the core description are based on the twelve ichnogenera and their quantified abundances: *Asterosoma*, *Bergaueria*, *Chondrites*, *Cylindrichnus*, *Diplocraterion*, *Palaeophycus*, *Planolites*, ?*Siphonichnus*, *Skolithos*, *Teichichnus*, *Thalassinoides* and *Zoophycos*. Trace morphologies include horizontal and vertical burrows of relatively simple construction. The exception being the complex structures produced by *Zoophycos*-trace makers. These morphologies suggest that the palaeoecology near the sediment-water interface varied with wave energies and other parameters (e.g., sedimentation rates and sediment supply). The core units described are based on the physical structures and the quantified biogenic structures to explain how depositional environments changed through time in this location. Quantification of trace abundances is effective in distinguishing ecological changes in units that contain comparable trace fossil assemblages, particularly between Units 2 and 3. These environmental interpretations are based on a modified lithology drawing of 6-18 presented in Section 3.2 (Figure 3.18).

Unit 1 (0-1.06 m) consists of pervasively bioturbated and laminated-to-burrowed sandstones (Facies 8B, 8J). The traces present in these sandstones include *Planolites*, *Chondrites* and *Zoophycos* in mudstones, and *Arenicolites*, *Diplocraterion* and *Skolithos* in sandstones. These sandstones are characteristic of Substrate 6 with an approximate sand content of 54%. The abundance of vertical shafts (e.g., *Skolithos*: 2.61-33.42 i.p.s.a.) suggest the substrate was unstable due to high energy currents (Alpert, 1974). The presence of *Diplocraterion* shafts shows erosion and deposition occurred at the sediment-water interfaces and suggest that the environment was intertidal (salinities of 20-30‰) (Bjerstedt and Erickson, 1989; Frey and Howard, 1986; E.G. Kauffman, 1993, pers. comm.). The exclusion of *Rhizocorallium* supports these physical parameters because the deposit-feeder making this structure is common in sediments associated with this substrate group.

The presence of *Chondrites* (2.78-6.96 i.p.s.a.) suggests that the deposit-feeder burrowed through organic-rich mud and subject to reduced oxygen conditions (Bjerstedt, 1988; Savrda and Bottjer, 1986, 1989; Raychaudhuri and Pemberton, 1992). *Zoophycos* (0.42 i.p.s.a.) trace makers support these benthic conditions because they burrow in muddy substrates deposited in relatively protected areas


6-18-64-23W5
(9.20 m)
0
1
2
3
4
5
6
7
8
9
Sid
Organic
Shell
Sid
sh
slt
vfL
vfU
fL
fU
mL
mU
cL
cU
Planolites
Chondrites
Paleophycus
Thalassinoides
Teichichnus
Skolithos
Arenicolites
Cylindrichnus
Diplocraterion
Zoophycos
Asterosoma
?Siphonichnus
Bergaueria
Marine Shales
Lag
Channel
Estuarine Bay Fill
Tidal Channel
Tidal Channel
Estuarine Bay Fill

(Häntzschel, 1975; Marintsch and Finks, 1978; Ekdale, 1988). Bioturbation by a community consisting of many organisms (e.g., *Planolites*, 2.09-39.68 i.p.s.a.) in organic-rich sediments can produce these reduced oxygen levels that influence the colonization by *Chondrites* animals.

Burrow morphologies are characteristic of the *Skolithos* and *Cruziana* Ichnofacies. This combination of ichnofacies is characteristic of estuarine sediments, reflecting the stressed, fluctuating environmental parameters (Pemberton and Wightman, 1992; Ranger and Pemberton, 1992). The biogenic structures confirm that Unit 1 was deposited in an estuarine bay environment as the distributary channel infilled.

Sand deposition in Units 2-4 (1.06-8.24 m) was controlled by fluctuating current velocities. Sedimentation rates are represented by various physical structures: 1) rapid sedimentation results in structureless sandstones, 2) strong tidal currents form cross-bedded sandstones containing paired mud partings, and 3) unidirectional or oscillatory currents produce current- or wave-rippled sandstones. As current velocities waned, mud drapes were deposited from suspension during slack-water periods. Currents in Unit 2 fluctuated between strong tidal currents and weaker currents, whereas current velocities decreased upward in Unit 3 with the biogenic structures preserved in the current-rippled sandstones and mud drapes. Unit 4 was influenced by weaker currents and punctated by episodes of rapid sedimentation as suggested by pervasively bioturbation sandstones and nonburrowed, structureless sandstones. The massive sandstones were thicker than 30 cm because *fugichnia* and other traces are absent or eroded from the substrate. Thirty centimetres is the critical bed thickness for successful escape and colonization at new sediment-water interfaces by bivalves and other animals (Nichols *et al.*, 1978). The diversity of the ichnofossil assemblages increased vertically through the deposits, particularly in Units 2-4, as currents waned. The horizontal, deposit-feeding traces (e.g., *Planolites*) present in mud drapes represent the *Cruziana* Ichnofacies. As current velocities increase, horizontal burrows are replaced by benthic animals that constructed vertical feeding/dwelling structures.

The abundances of the trace fossils present in Unit 4 are comparable to Unit 2. However, traces characteristic of marginal marine environments (eg., *Arenicolites*, *Diplocraterion* and *Zoophycos*) are absent. *Palaeophycus*, *?Siphonichnus* and *Bergaueria,* absence in Unit 2, are present in the pervasively bioturbated sandstone with densities of 1.04-2.92 i.p.s.a. This trace fossil assemblage suggests that conditions became more marine than those parameters influencing the underlying channel deposits. However conditions are not as stressed as the estuarine bay as suggested by the intense bioturbation produced by impoverished marine animals.

The physical parameters controlling deposition and bioturbation suggest that Unit 2- Unit 4 were deposited in a tidally-influenced channel. According to Bhattacharya (1989), these sediments were deposited near the cut bank he interpreted in the Waskahigan Bottleneck channel. The impoverished marine trace fossils associated with the *Skolithos* and *Cruziana* Ichnofacies characteristic of fluctuating parameters in marginal marine environment (Ekdale, 1985; Pemberton and Wightman, 1992; Ranger and Pemberton, 1992). The presence of *Diplocraterion* and *Thalassinoides* suggest a marginal marine environment with a salinity range of 20-30‰ (Bjerstedt and Erickson, 1989; Frey and Howard, 1986; E.G. Kauffman, 1993, pers. comm.).

Substrate stability, turbidity, organic-rich sediments and the number/thickness of mud drapes also affected the marine life colonizing the sea bed. For example, *Palaeophycus* burrows are documented only in the channel deposits and not in the estuarine bay sediments, suggesting sandier substrates were preferred by these trace makers (Substrates 8 and 10). The overall decrease in *Planolites* burrows in Unit 2 suggests ecological parameters changed near the interval containing *Cylindrichnus* shafts. Turbidity increased and currents decreased at the base of the channel deposits (Unit 2) because *Skolithos* shafts are absent and these trace makers require non-turbid, swift-flowing currents above the sediment-water interface (Alpert, 1974).

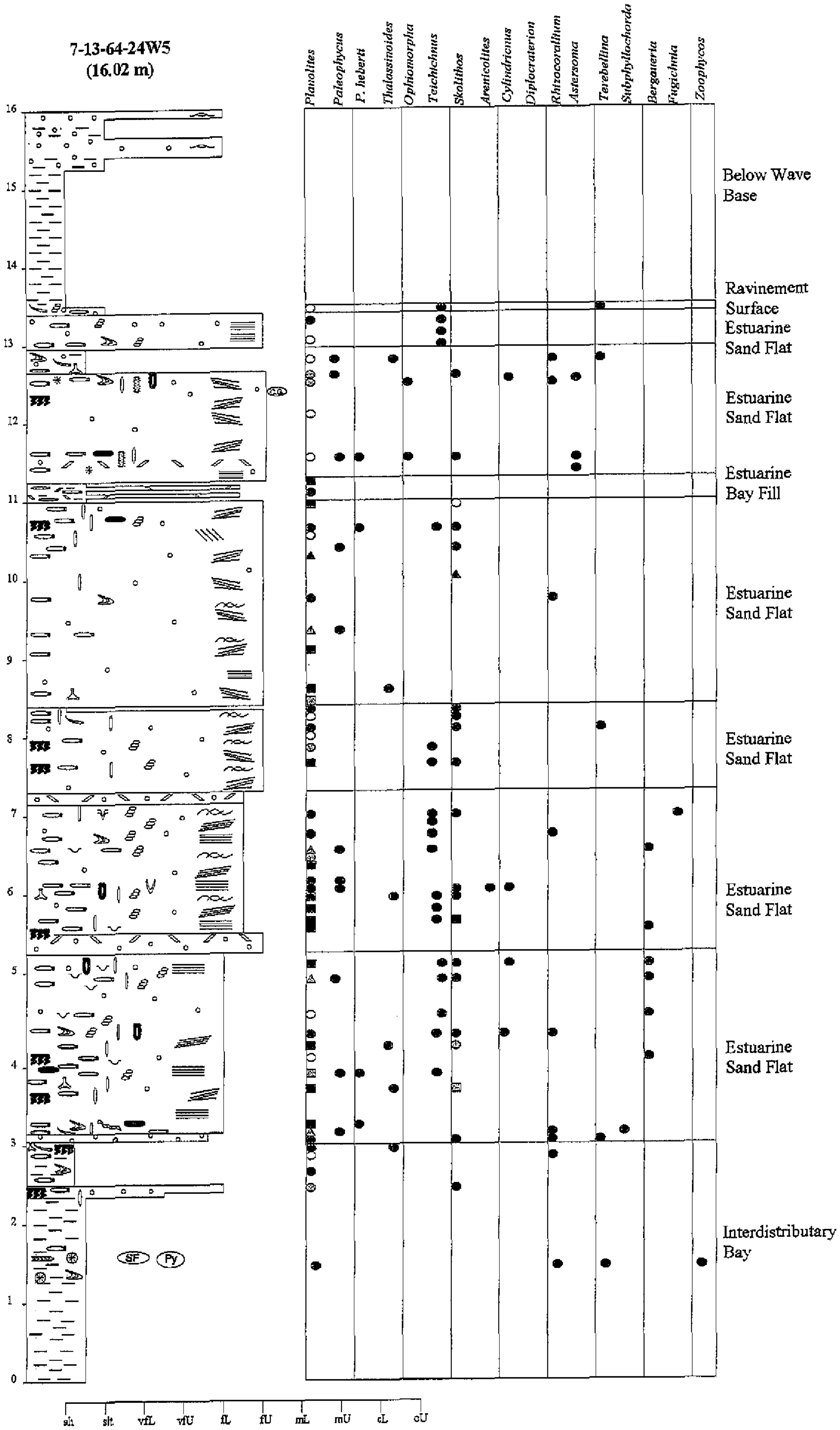
The physical and biogenic structures described in this core represent the transition from an estuarine bay to a tidally-influenced channel apparently filled by three successive stages of infill (Units 2-4). The ichnofossil assemblages show that conditions became progressively more marine during channel-filling but physical processes rather than biogenic processes dominated the deposits. This is supported by a more impoverished marine ichnofossil assemblage occurring in the estuarine bay deposit.

Shingle D1 is capped by the erosive truncation and deposition of a muddy siltstone. This sharp-based siltstone represents the ravinement surface and associated lag that defined the boundary between Allomember D and Allomember C (Bhattacharya, 1989). The lag was burrowed by *Planolites* and overlain by black marine shales (8.35-9.20 m) lacking discernable trace fossils.

7-13-64-24W5 Environmental Interpretation

The similarities between depositional units and biogenic assemblages suggest that subtle changes in the ecological conditions occurred during deposition and subsequent bioturbation of the sediments. The trace fossils present in this core include: *Asterosoma*, *Bergaueria*, *Cylindrichnus*, *Diplocraterion*, *fugichnia*, *Ophiomorpha irregulaire*, *Palaeophycus heberti*, *Palaeophycus tubularis*, *Planolites*, *Rhizocorallium*, *?Siphonichnus*, *Skolithos*, *Subphyllochorda*, *Teichichnus*, *Terebellina*, *Thalassinoides* and *Zoophycos*. Quantification of these traces enabled the sediments to be divided into 10 depositional units and show how the environment's physical and ecological parameters changed (Figure 3.19). Without biogenic quantification subtle changes in ecological and environmental conditions at the sediment-water interfaces in this marginal marine location would not have been possible.

Unit 1 (0-3.04 m) consists of blockstones with silt and fine-grained sandstone event beds that occur more frequently upwards (2.35-3.04 m). Trace fossils are undiscernable in the basal blockstones (1.35 m) because silt or sand is rare, so are textural contrasts. The blockstones (0-2.35 m) represent Substrate 4. The diversity and abundance of behavioural traces increased upwards with the event beds.


7-13-64-24W5
(16.02 m)
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1
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7
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11
12
13
14
15
16
SF
Py
slt
slt
vfL
vfU
fL
fU
mL
mU
cL
cU
Planolites
Palaeophycus
P. heberti
Thalassinoides
Ophiomorpha
Teichichnus
Skolithos
Arenicolites
Cylindricnus
Diplocraterion
Rhizocorallium
Asterosoma
Terebellina
Subphyllochorda
Bergaueria
Fugichnia
Zoophycos
Below Wave Base
Ravinement Surface
Estuarine Sand Flat
Estuarine Sand Flat
Estuarine Bay Fill
Estuarine Sand Flat
Estuarine Sand Flat
Estuarine Sand Flat
Estuarine Sand Flat
Interdistributary Bay

Marine deposit-feeders producing *Planolites*, *Rhizocorallium*, *?Siphonichnus*, *Terebellina* and *Zoophycos* burrows dominated the sandier blockstone interval (2.35-2.38 m). The presence of these deposit-feeding burrows, particularly *Rhizocorallium*, suggests that the mud contains ≈54% sand (Substrate 6). Above this interval (2.38-2.45 m) the sand content decreased to ≈41-54% (Substrate 5). Conditions became favourable for *Planolites* and *Skolithos* animals to colonize this interval resulted from salinity fluctuations (synaeresis cracks) and event bed deposition. The remainder of this unit (2.45-3.04 m) is characteristic of Substrate 2 (≈21% sand) and contains the most diverse trace assemblage in Unit 1 with *Planolites* having more than 1.00 i.p.s.a. (1.74-9.38 i.p.s.a.). This assemblage includes robust *Thalassinoides* burrows near shrinkage cracks (3.03-3.12 m), but the marine traces *?Siphonichnus*, *Terebellina* and *Zoophycos* are absent in these intervals. The presence of *Thalassinoides* burrows and *Skolithos* shafts suggest the depositional environment be marginal marine with salinities of 25-30‰. It was influenced by more turbulent, less turbid water flowing above the sediment-water interface (Alpert, 1974, Pemberton *et al.*, 1992). The mud was deposited in a relatively stable environment with rare event bed deposition. Shrinkage cracks associated with these event beds reflect compaction of the underlying mudstones and/or influxes of freshwater (Burst, 1965; Plummer and Gostin, 1981; Pemberton and Wightman, 1992). The ichnofossil diversity suggests that these spindle-shaped cracks reflect salinity fluctuations. Unit 1 is interpreted as an interdistributary bay deposit associated with Shingle D2.

An erosion surface, mantled with rip-up clasts, separates this deposit and the overlying deposit (Unit 2) (Bhattacharya, 1989). This surface and the overlying sandstones are not burrowed. The absence of burrows (i.e., *Glossifungites* Ichnofacies) suggests that the fluvial sediments were eroded and reworked by marine processes because the colonizing animals did not burrow down into the underlying marine blockstones (Boreen, 1989; MacEachern *et al.*, 1992; Pemberton *et al.*, 1992). Unit 2 - Unit 8 are distinguished by facies variations and abrupt changes of ichnofossil assemblages at erosion surfaces separating each depositional unit. These assemblages are similar, but differ in animal responses to current strength and grain size variations as suggested by diversity and abundance.

Unit 2 (3.04-5.26 m) and Unit 3 (5.26-7.32 m) contain similar facies (Facies 8D, 8F, 8I, 8J), but the trace fossil assemblages are different with respect to diversity and abundance. Although *Planolites* is the most abundant trace in both units, it occurs more commonly in Unit 2 (4.18-22.97 i.p.s.a.) than Unit 3 (0.28-18.56 i.p.s.a.). *Skolithos* shafts follow the same abundance pattern, with 0.28-16.39 i.p.s.a. in Unit 2 and 0.46-11.14 i.p.s.a. in Unit 3. However, *Teichichnus* displays a different abundance pattern, with increases from 0.21-1.39 i.p.s.a. to 0.46-2.89 i.p.s.a.

Variations in these abundances and diversity of traces are the response to variations in substrate textures. In Unit 2 sediment is characterized by Substrate 6 (3.04-3.20 m) and Substrate 8 (3.20-5.26 m). The coarser-grained sandstones in Unit 3 are characteristic of Substrate 8 (5.51-7.32 m) and Substrate 10 (5.26-5.51 m). These coarser sands (upper-fine-grained) were deposited under different hydraulic conditions. Consequently, fewer burrow intersections are present due to erosion and unsuitable of substrates for benthic colonization. The intensity of bioturbation increased when hydraulic energies waned for sufficient undisturbed periods during which time benthic animals colonized the substrate. The physical features suggest that current energies varied episodically from the upper-flow regime to weak currents and slack-water flows. Changes in salinity permitted the colonization of more deposit-feeders, particularly *Planolites*-trace makers. Alternatively, these abundances could have increased in response to more organic-rich sediments being deposited during slack-water periods. In Unit 2, the mud-adapted deposit-feeders tracemakers of *Planolites*, *Rhizocorallium*, *Teichichnus* and *Thalassinoides* ethological patterns are most common in mud drapes. *Skolithos* and *Cylindrichnus* shafts represent vertical suspension-feeders that colonized shifting, sandy substrates. These traces are typical of an ichnofacies containing characteristics of the *Cruziana* and *Skolithos* Ichnofacies. This combination of ichnofacies represents marginal marine environments (Ekdale, 1986, 1988; Frey *et al.*, 1990; Pemberton and

Wightman, 1992; Pemberton *et al.*, 1992b, 1992c; Ranger and Pemberton, 1992).

The presence of *Diplocraterion* and *Thalassinoides* burrows (5.14-5.98 m) suggests that these units were deposited in a brackish environment with a salinity range of 20-30‰ (Frey and Howard, 1986; Bjerstedt and Erickson, 1989; K.G. Kauffman, 1993, pers. comm.). As the environment became muddier, the bottom became stable and turbidity increased due to increased bioturbation by deposit-feeders. These ecological parameters are too stressful for suspension-feeders like *Skolithos* to colonize the substrate successfully.

Unit 4 (7.32-8.41 m) contains a trace fossil assemblage of *Planolites*, *Skolithos*, *Teichichnus* and *Terebellina*. This mixed burrow assemblage represents the *Cruziana* and *Skolithos* Ichnofacies. Salinity fluctuations at the base of this unit are suggested by synaeresis cracks. The fluctuations affected the burrowing activity of worms and worm-like animals. The abundance of simple burrows (e.g., *Planolites*) decreased as opposed to those observed in previous depositional units. This suggests that the drapes were firmer and less organically-rich, or that the shrinkage cracks were the result of compaction or major freshwater discharge (Plummer and Gostin, 1981; Pemberton and Wightman, 1992). The presence of *Terebellina* burrows 1-mm in diameter suggests that stressed, brackish-water conditions prevailed (Ekdale, 1985; Pemberton and Wightman, 1992). The reduced trace fossil diversity may reflect increased deposition and erosion at the sediment-water interface, therefore restricting benthic colonization and/or destruction of biogenic structures by currents (Bromley, 1990). The sand content of this unit characteristic of Substrate 8 (≈62-65% sand) may also have influenced the traces present. The marine deposit-feeders are only present in mud drapes.

Unit 5 (8.41-11.04 m) contains sandstones similar to the underlying unit. However, cross-bedded sandstones were deposited above and below bioturbated and the shrinkage crack deposits. The trace fossils present in these sediments represent a mixed *Skolithos* and *Cruziana* Ichnofacies similar to Unit 4, but the sediments are relatively coarser and are characteristic of Substrate 9. More sand-adapted animals burrowed through the sand as suggested by the presence of *Palaeophycus tubularis* (2.09 i.p.s.a.) and *Palaeophycus heberti* (0.32 i.p.s.a.). The physical structures and these ichnofacies characterize a stressed, brackish-water channel environment as showed by the cross-bedded sandstones (Pemberton and Wightman, 1992; Pemberton *et al.*, 1992b, 1992c).

Unit 6 (11.04-11.30 m) consists of banded mudstones containing very-fine-grained structureless event beds. This facies suggests physical parameters (e.g., sedimentation rates, wave energy) changed. The trace fossil assemblage reflects these changes because it consists only of *Planolites* burrows. These sediments represent Substrate 5 with a sand content of approximately 41-54% based on point counts. The monospecific trace assemblage resulted from other parameters because this substrate group is characteristic of many marine deposit-feeding traces including *Asterosoma, Palaeophycus, Planolites, Rhizocorallium, ?Siphonichnus, Teichichnus* and *Terebellina.* Monospecific assemblages reflect stressed conditions at the bed, but abundant trace intervals (eg., 2.28-11.97 i.p.s.a.) can occur in marginal marine depositional environments (Bromley, 1990; Pemberton and Wightman, 1992; Pemberton *et al.*, 1992b). A potential mechanism for this depositional change is river avulsion and/or variation in sediment supply.

If river avulsion or sediment supply was the probable cause for the banded mudstones (Unit 6), then Unit 7 (11.30-12.92 m) reflects the return to a stressed, brackish-water environment similar to the older depositional units (e.g., Unit 2). These sandstones (Facies 8D, 8F, 8I) show that energy conditions fluctuated and waned. The sediment supply changed in this fining-upward deposit, and the substrate fostered benthic colonization as displayed by more impoverished marine traces especially in the bioturbated shales (Facies 1B, 12.68-12.92 m). Locomotion and resting patterns (*Subphyllochorda* and *Bergaueria*) and the deposit-feeding trace *Teichichnus* are absent in this unit. The relatively sparse tunnels of the *Ophiomorpha irregulaire* networks occur only in this unit. This dwelling structure suggests sediments were easily shifted by marine bottom waters as inferred by *Ophiomorpha*'s modern analogue *Callianassa major* (Frey *et al.*, 1978; Ekdale, 1985, 1988). The relative abundance of *Planolites* (0.28-7.66 i.p.s.a.) suggests that many deposit-feeding worms and worm-like animals created this simple unlined burrow (Pemberton and Frey, 1984). This assemblage of impoverished marine traces consists of feeding and dwelling structures and characterizes the marginal marine *Skolithos-Cruziana* Ichnofacies (Pemberton and Wightman, 1992). Substrate 8 characterizes the lower portion of this unit (11.30-12.68 m) and reflects an increase in trace diversity upwards in the sandstones below the bioturbated shales that cap Unit 7. These traces are sand-adapted and robust, as displayed by *Ophiomorpha* burrows (0.28-0.70 i.p.s.a.) which are present only in this unit. The mud content is insufficient for *Rhizocorallium* deposit-feeders to burrow through the sandy sediment.

These bioturbated shales (12.68-12.92 m) contain a trace fossil assemblage dominated by mud-adapted, deposit-feeding trace makers that produced *Planolites*, *Terebellina*, *Rhizocorallium* and *Thalassinoides* burrows. These shales are characteristic of Substrate 5, but unlike Unit 6, this depositional environment was not stressed because animal traces present in this substrate group are present in this bioturbated shale. Trace fossils present represent the *Cruziana* Ichnofacies, reflecting a depositional environment that was quieter and relatively deeper than the underlying marginal marine deposits.

The final unit in Shingle D1 (Unit 8, 12.92-13.40 m) consists of parallel-laminated sandstones burrowed by *Teichichnus*-, *Planolites*- and *Palaeophycus*-trace makers. Organic-rich, well oxygenated, fine-grained sediments allowed these marine deposit-feeders to burrow. *Palaeophycus*-trace makers burrowed through the parallel-laminated sandstones during waning low periods or at slack-water (Pemberton and Frey, 1984). The upward decrease in trace diversity suggests the physical parameters became less tolerable at the sediment-water interface for deposit-feeders. The sediment consists of cleaner sand than mud-adapted animals can tolerate (Substrate 8 with ≈62-65% sand).

Shingle D1 was truncated by a sharp-based muddy siltstone (Unit 9, 13.40-13.50 m). This sharp-based erosion surface is interpreted as the ravinement surface reflecting the maximum flooding surface separating Allomember D and Allomember C (Bhattacharya, 1989; Bhattacharya and Walker, 1991a, 1991b). A 10-cm lag was colonized by marine deposit-feeders that produced *Planolites*, *Terebellina* and *Teichichnus* burrows.

Overlying this lag is a coarsening upwards succession of shales interbedded with hummocky-cross-stratified sandstones (Unit 10, 13.50-16.02 m). These marine shales are associated with Allomember C and lack discernable ethological patterns characteristic of the *Cruziana* Ichnofacies. The event beds suggest that sediment-water interfaces were below fair-weather wave base but above storm wave base (Bhattacharya, 1989; Bhattacharya and Walker, 1991a, 1991b).

In this core, biogenic quantification permitted distinctions to be made about sediments deposited or burrowed in more marine conditions. The less stressful depositional environments became, the more marine animals colonized the sediments, producing more burrow intersections. Three depositional environments are interpreted in this core: 1) an interdistributary bay (Unit 1), 2) an estuarine sand flat (Units 2-8), and 3) offshore (Units 9-10). The primary distinctions between units for this interpretation are the trace fossil assemblages and corresponding ichnofacies, synaeresis cracks and the relative position of units in 7-13-64-24W5.

In the interdistributary bay deposits the maximum diversity occurs in the seaward core (14-4-64-23W5) showing that the marine conditions in this depositional environment changed landward. This is evident by changes in animal trophic functions from deposit- and suspension-feeders to more deposit-feeders and fewer suspension-feeders and dominated by marine deposit-feeders with greater abundances of *Zoophycos*, *Teichichnus* and *?Siphonichnus* in this core than the interdistributary bay deposits in 2-24-64-24W5.

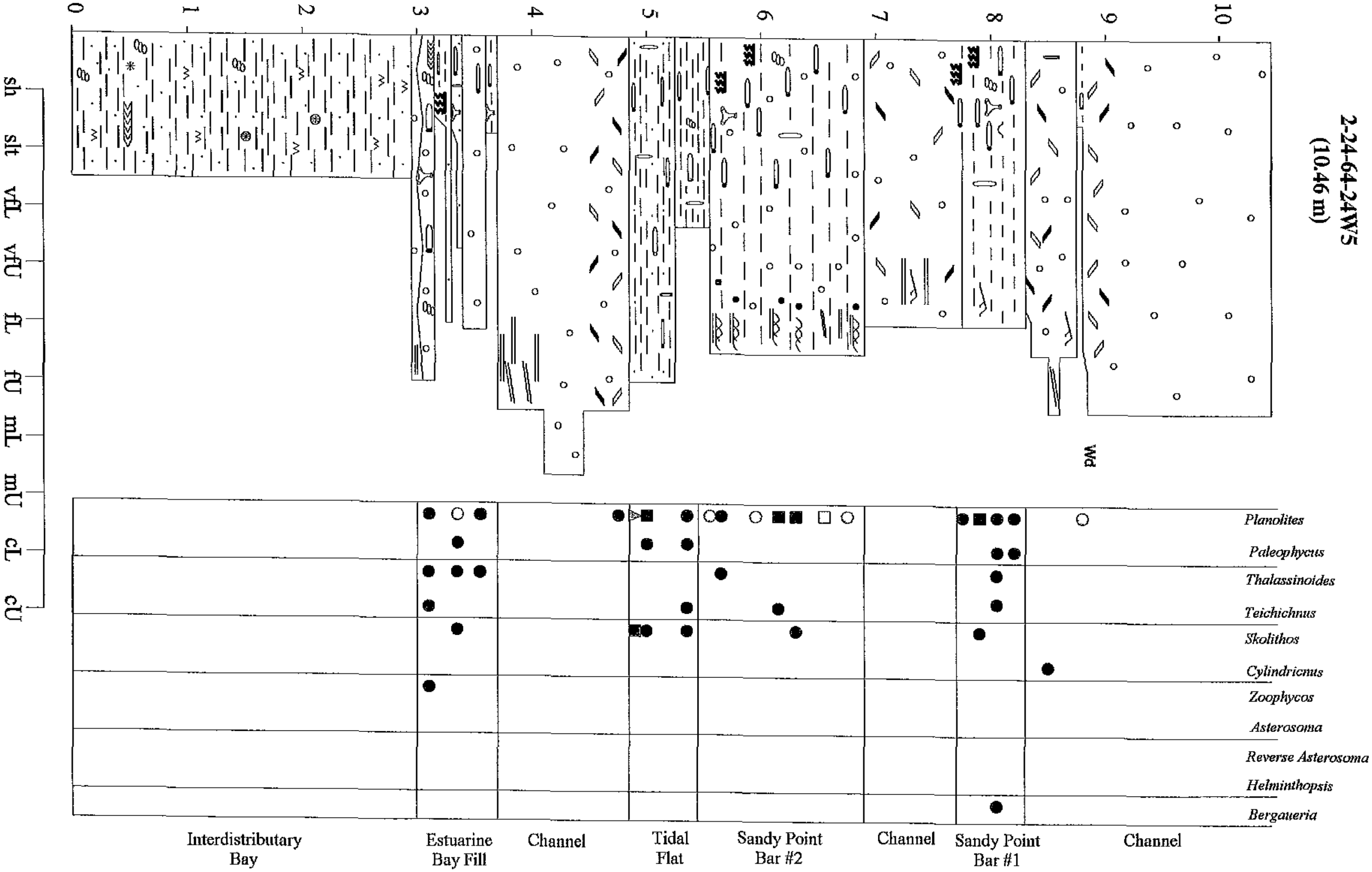
Sand flats are only present in this core but the different depositional units within this environment suggest that physical and ecological parameters were controlled by marginal marine to marine conditions. This suggests six pulses of sediment deposition occurred in this estuarine sand flat environment, based on the physical and biogenic structures. The physical features are comparable in all units with differences found in an overall coarsening upwards from upper-very-fine- to upper-fine-grained sandstones with cross-bedded sands deposited only in Unit 5 and the banded mudstone facies (Unit 6) punctuating this succession. Most substrate textures in this core represent Substrates 6 and 8 with cleaner sands characteristic of Substrates 9 and 10, whereas muddier sediments represent Substrates 2, 4 and 5. Trace assemblages, found in these substrate groups, differ due to the physical parameters influencing the deposition and bioturbation of bottom sediments.

2-24-64-24W5 Environmental Interpretation

The eight depositional units described in this core are interpreted bases on sedimentary facies and ichnofacies. The succession of depositional environments is shown in Figure 3.20 illustrating the lithology and biogenic data. Eleven trace fossils are present in various assemblages: *Arenicolites*, *Asterosoma*, *Bergaueria*, *Helminthopsis*, *Palaeophycus*, *Planolites*, *?Siphonichnus*, *Skolithos*, *Teichichnus*, *Thalassinoides*, and *Zoophycos*. These ichnospecies represent the *Cruziana* and *Skolithos* Ichnofacies in various substrate groups (4, 5, 6, 9 and 10).

Unit 1 (0-2.93 m) consists of blockstones with silt to very-fine grained sandstones and is burrowed by marine deposit-feeders. These event beds were colonized by *Teichichnus*- and *Asterosoma*- trace makers. *Helminthopsis* is the only ichnospecies present in the upper blockstone. The trace fossil assemblage suggests that the sediments were deposited in a low energy lagoon or protected interdistributary bay. In the Waskahigan Bottleneck area, this environment is associated with Shingle D2 (Bhattacharya, 1989). The thin silt and sand layers were deposited from weak wave and current activity, and represent overbank splay deposits (Pemberton and Wightman, 1992; Ranger and Pemberton, 1992).

2-24-64-24W5
(10.46 m)



The abundance and diversity of trace fossils in this unit are comparable to other interdistributary bay deposits (e.g., cores 14-4-64-23W5 and 7-13-64-24W5). *Helminthopsis* and *Anconichnus* are very abundant and difficult to quantify accurately. *Teichichnus*, *Zoophycos* and *?Siphonichnus* burrows (0.42 - 1.67 i.p.s.a.) are also present in this marine-influenced environment.

Unit 2 (2.93-3.72 m) consists of banded mudstones. The scour-based massive sandstones (1-25 cm) are void of dwelling or escape structures. The mudstones and the pervasively bioturbated sandstones contain burrows of marine animals (*Palaeophycus tubularis*, *Planolites*, *Skolithos* *Teichichnus*, *Thalassinoides* and *?Zoophycos*). These ichnospecies are characteristic of a mixed *Skolithos-Cruziana* Ichnofacies (Pemberton and Wightman, 1992; Ranger and Pemberton, 1992). Shrinkage cracks and noncompacted, nonelliptical burrow intersections suggest that salinities fluctuated due to freshwater influxes and sand transported by traction currents (Plummer and Gostin, 1981; Pemberton and Wightman, 1992; Pemberton *et al.*, 1992a). Intertidal, brackish-water conditions are implied by the preservation of *Thalassinoides* burrows that are found in modern tidal flats and estuaries (Weimer and Hoyt 1964; Frey *et al.*, 1978). The low diversity of both mud- and sand-adapted marine ichnospecies confirm this environment was a shallow brackish bay with crevasse splays due to fluvial discharge.

This estuarine bay deposit is similar to that in core 6-18-64-23W5. However, *Arenicolites*, *Asterosoma*, *Chondrites* and *Diplocraterion* are absent in core 2-24-64-24W5. The relative abundances of common traces (e.g., *Planolites*, *Skolithos*, *Teichichnus*, *Thalassinoides* and *Zoophycos*) are comparable. For example *Planolites* burrows are the most abundant in this depositional environment, but fewer i.p.s.a.s occur in core 2-24-64-24W5 (2.59-5.48 i.p.s.a.) than core l 6-18-64-23W5 (2.09-45.96 i.p.s.a.). This lack of animals, common in the intertidal zone, suggests benthic conditions were more stressful and closer to the turbidity maximum in the estuary. This core location was also influenced more by freshwater influxes as reflected by synaeresis cracks.

Unit 3 (3.72-4.82 m) is a fine- to medium-grained structureless sandstone deposit with crude parallel- and current-rippled laminations at the base, and shale and sideritized mud rip-up clasts near the top. Biogenic structures are absent. The depositional environment is interpreted as a fluvial channel based on these physical and biogenic features.

Unit 4 (4.82-5.52 m) consists of interbedded mudstones containing very-fine-grained laminations that differed from any deposit previously described in this chapter. These closely-spaced laminations are gently dipping and resemble flaser bedding. It is similar to Unit 2 regarding physical structures, but fewer traces are present. The assemblage of four horizontally- and vertically-oriented ichnospecies in this deposit represent a stressed and impoverished marine environment. These impoverished marine ichnofossils are characteristic of a mixed *Cruziana-Skolithos* Ichnofacies. Increased abundances of *Planolites* burrows and *Skolithos* shafts besides the absence of *Thalassinoides* burrows, a biogenic salinity indicator, this deposit was influenced by more fluvial conditions, a result of river avulsion and lobe switching (Ranger and Pemberton, 1992). The depositional environment of this unit is interpreted as an abandoned estuarine bay with frequent thin crevasse splay sandstones that are commonly structureless (Pemberton and Wightman, 1992; Ranger and Pemberton, 1992).

Unit 5 (5.52-6.92 m) is coarser than the underlying fining upward unit, and consists of fine-grained laminated-to-burrowed muddy sandstones. The preserved ichnospecies (*Planolites*, *Skolithos*, *Teichichnus* and *Thalassinoides*) are less abundant than Unit 4, but physical structures show that wave and tidal current activities varied during deposition. This assemblage of impoverished marine ichnospecies is characteristic of the *Skolithos-Cruziana* Ichnofacies (Ranger and Pemberton, 1992). The presence of siderite represents early *in situ* diagenesis, which predominantly occurs in marginal marine environments, supports this environmental interpretation (Pemberton and Raychaudhuri, 1992). Oxygen levels are reduced in these sediments, and can be lethal to many benthic organisms, particularly suspension-feeders (Pieńkowski, 1985). The restricted diversity, fewer i.p.s.a.s than Unit 4 and the presence of *Thalassinoides* burrows, and synaeresis cracks support lower salinities as fresh water is discharged and sand is deposited. This depositional environment is interpreted as an abandoned estuarine chute channel or tidal flat (Ranger and Pemberton, 1992).

Unit 6 (6.92-7.72 m)is similar to Unit 3. The fine-grained sandstone contains scattered shale and siderite mud rip-up clasts, and parallel- and current-rippled laminae in the middle of the deposit. Rapid sedimentation and sand deposits greater than 30 cm are inferred from the lack of biogenic features (e.g., feeding, dwelling and escape structures). This deposit is interpreted as fluvial channel.

Unit 7 (7.72-8.32 m) is similar to Unit 5, but a more diverse marine benthic community is evident. The fine-grained laminated-to-burrowed muddy sandstones contain *Bergaueria, Palaeophycus, Planolites, Skolithos, Teichichnus* and *Thalassinoides* intersections. However, the i.p.s.a.'s are fewer than those in Unit 5. These sediments are finer-grained and potentially firmer softgrounds to preserve resting patterns such as *Bergaueria*. In this unit, *Skolithos* shafts occur in one interval suggesting the sediment-water interface was turbid and/or destruction by prevailing physical parameters. This assemblage represents impoverished marine ichnospecies characteristic of the *Cruziana* Ichnofacies rather than a mixed *Cruziana-Skolithos* Ichnofacies because vertical structures are rare. However, bioturbation occurred in a stressed brackish environment as reflected by the ichnofossil assemblage and synaeresis cracks support lower salinities of 20-30‰ (Weimer and Hoyt 1964; Frey *et al.*, 1978; Howard and Frey, 1985; Ranger and Pemberton, 1992). Unit 7 is interpreted as tidal flat that was influenced by more marine conditions based on the ichnofacies comprising more diverse trace fossils.

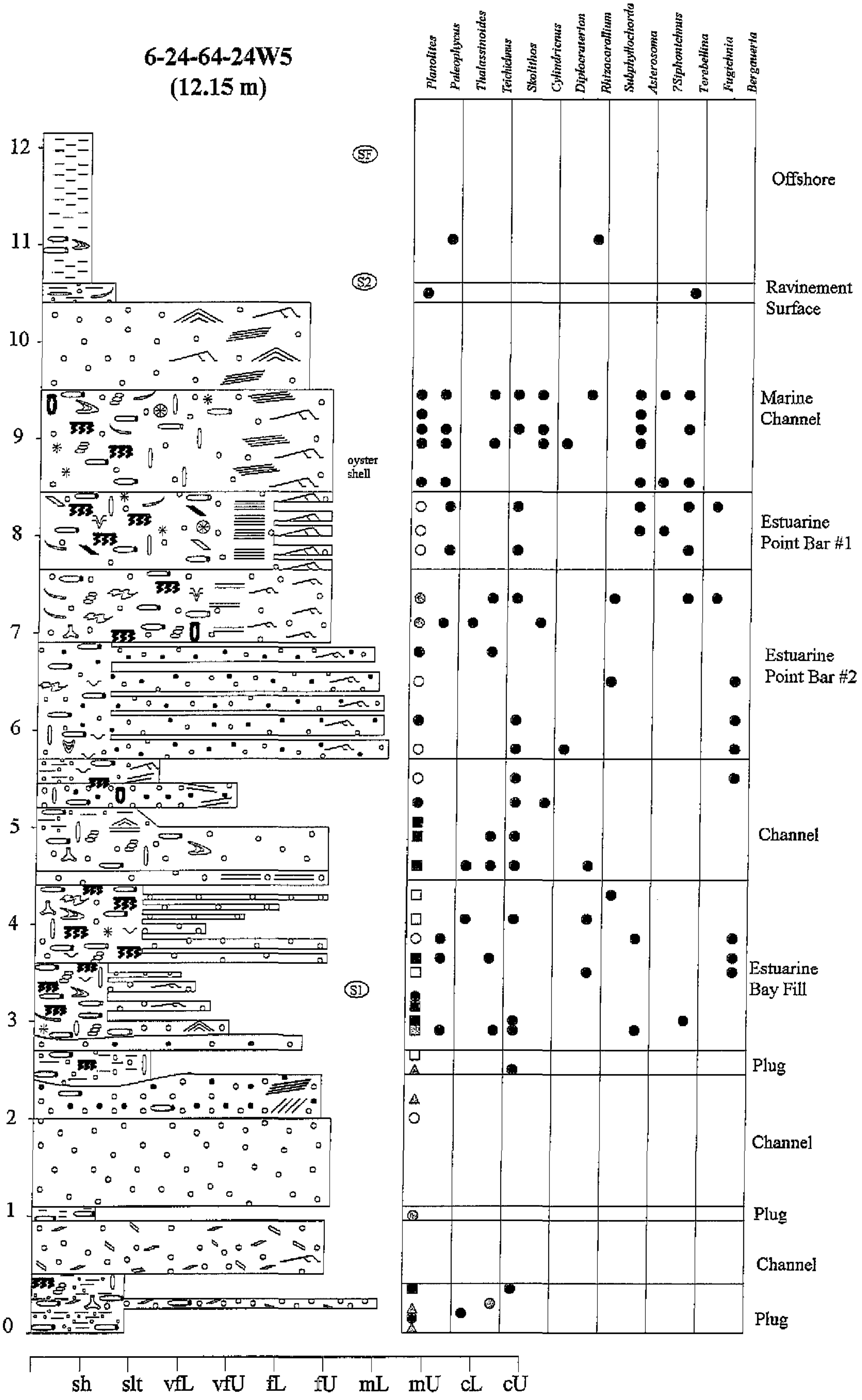
Planolites and *Skolithos* intersections are the most common traces in the three tidal flat/abandoned estuarine chute channels with the greater abundances present in the Unit 4. The *Planolites* abundances ranged from 8.35-20.89 i.p.s.a. (Unit 4) to 4.75-11.89 i.p.s.a. (Unit 5) and 2.78-12.53 i.p.s.a. (Unit 7). These abundances, and those of *Skolithos* 0.70-18.10 i.p.s.a. (Unit 4), 1.93 i.p.s.a. (Unit 5) and 0.84 i.p.s.a. (Unit 7), show that marine-influences conditions became less tolerable upwards for suspension-feeders due to increased mud deposition that controlled the benthic community. *Thalassinoides*, *Teichichnus* and *Bergaueria* burrow intersections are present in greater abundances in Unit 7 than Units 4 and 5.

Unit 8 (8.32-10.46 m) consist of sandstones with few physical and biogenic structures. Scattered shale and sideritized mud rip-up clasts are common in these sandstones. *Arenicolites* and *Planolites* intersections plus wood fragments and rip-up clasts are present in the basal 50 cm. Current and low-angle laminations are present in sandstone interval containing the traces. Above this interval, the remainder of this unit is structureless. The sand was deposited in a channel influenced by different parameters because the preserved biogenic and physical structures are different from the other channel deposits. In a tripartite estuarine model and due to this core's location these channel sandstones are inferred to be proximal to the bayline where sparse burrowing can occur (Howard and Frey, 1985).

Core 2-24-64-24W5 exhibits an overall brackish-water environment in the upper reaches of the Waskahigan Bottleneck Channel. Variations and similarities of depositional units suggest that the channel changed its relative position due to river avulsion during a relative rise in sea level (Miall, 1984; Bhattacharya, 1988, 1989). This core is found near the bayline where the river meanders resulting in the superposition of similar depositional environments (e.g., channels and tidal flats).

6-24-64-24W5 Environmental Interpretation

Several depositional environments are interpreted in this core (Figure 3.21). The vertical succession suggests a meandering aspect to the Waskahigan Bottleneck distributary channel in this location. Based on the biogenic assemblages these deposits are considered marginal marine near the base with increased marine influences upward through the core. Estuarine point bar deposits are present in this, the most landward core. The sediments and trace fossils contained in this core represent Substrates 1-8, depending on the unit and the proportions of mud and sand.


6-24-64-24W5
(12.15 m)
Planolites
Paleophycus
Thalassinoides
Teichichnus
Skolithos
Cylindricnus
Diplocraterion
Rhizocorallium
Subphyllochorda
Asterosoma
?Siphonichnus
Terebellina
Fugichnia
Bergaueria
12
11
10
9
8
7
6
5
4
3
2
1
0
SF
S2
S1
oyster shell
Offshore
Ravinement Surface
Marine Channel
Estuarine Point Bar #1
Estuarine Point Bar #2
Channel
Estuarine Bay Fill
Plug
Channel
Plug
Channel
Plug
sh
slt
vfL
vfU
fL
fU
mL
mU
cL
cU

Unit 1 (0-2.67 m) is a mudstone-sandstone complex interpreted as a single depositional unit with varying channel dynamics as reflected by the preserved ichnospecies and sedimentary facies. The pervasively bioturbated basal mudstones, containing *Planolites*, *Teichichnus*, *Thalassinoides* and *Skolithos* burrows (in sand lenses), suggest that during deposition and subsequent colonization the environment was brackish and relatively stable as inferred by the abundance of *Planolites* (4.18-25.06 i.p.s.a.). The other trace abundances are fewer than 1.00 i.p.s.a., except one interval containing *Teichichnus* (7.52 i.p.s.a.). This assemblage of ichnospecies represents the *Cruziana* and *Skolithos* Ichnofacies. This ichnofacies combination is common in stressed environments with fluctuating sediment supplies of mud and sand (Pemberton and Wightman, 1992). In this environment, shrinkage cracks result from salinity fluctuations (e.g., fresh water influx) and/or compaction of overlying sandstones (Plummer and Gostin, 1981). The preservation of *Thalassinoides* burrows supports the interpretation of salinity fluctuations and brackish conditions (25-30‰) (Frey and Howard, 1985; Pemberton and Wightman, 1992; E.G. Kauffman, 1993, pers. comm.). This deposit was truncated by wave-rippled sandstones containing rip-up clasts. This deposit was overlain by structureless sandstones void of discernable trace fossils.

The fining upward sandstones overlying these mudstone intervals display decreasing sedimentation rates. Cross-bedded and parallel-laminated sandstones were deposited on top of structureless sandstones. *Planolites* are present in the mudstones draping these sandstones. Their abundances increased upwards toward the erosion surface that separates this and the overlying deposit (Unit 2).

The biogenic and physical structures were used to interpret Unit 1 as channel sandstones separated by abandoned estuarine chute channels (e.g., plugs) (Ranger and Pemberton, 1992). The similarities between the sandstones and mudstones suggest that different portions of this channel were influenced by brackish or fluvial conditions. Both conditions can produce monospecific trace fossil assemblages (e.g., *Planolites*) (Pemberton and Wightman, 1992).

The trace fossil assemblage in Unit 2 (2.67-4.39 m) consists of *Planolites*, *Palaeophycus*, *Thalassinoides*, *Teichichnus*, *Skolithos*, *Rhizocorallium*, *Subphyllochorda*, *Asterosoma*, *Terebellina* and *Bergaueria*. *Planolites*, *Palaeophycus* and *Skolithos* are the only traces to have burrow densities greater than 1.00 i.p.s.a.. These impoverished marine trace fauna represents a mixed *Skolithos* and *Cruziana* Ichnofacies. Shrinkage cracks associated with this unit are interpreted as the result of salinity-induced changes and are common in brackish-water deposits (Plummer and Gostin, 1981). The relatively low density of the ichnogenera and the episodic deposition of sand and mud intervals suggest a marginal marine environment (Frey and Howard, 1986; Pemberton *et al.*, 1992c; Pemberton and Wightman, 1992). The above observations suggest that Unit 2 is an estuarine bay fill.

The estuarine bay deposits interpreted in cores 6-24-64-24W5, 6-18-64-23W5 and 2-24-64-24W5support the conclusion that this is a marginal marine deposit in the middle estuary and the marine-influences changed landward as showed by the abundance of the biogenic structures present. Unlike the previous deposits, Unit 2 contains fewer i.p.s.a.s for *Planolites*, *Palaeophycus* and *Skolithos*. The assemblage consists of the marine deposit-feeding traces of *Rhizocorallium* and *Terebellina* and the resting trace *Bergaueria*. *Chondrites* and *Zoophycos* are absent, suggesting that the muddy substrate and bottom waters were well oxygenated, but the bottom was relatively unprotected from currents. The sediments, characteristic of Substrates 3 and 5, also controlled the animal communities.

Unit 3 (4.39-5.69 m) contains laminated-to-burrowed, fine-grained sandstones fining upwards to very-fine-grained, cross-laminated sandstones (Substrate 5). The traces present in this unit include vertical shafts (*Skolithos* and *Cylindrichnus*) and horizontal burrows (*Planolites*, *Rhizocorallium*, *Thalassinoides* and *Teichichnus*). Unlike the estuarine bay fill, animal locomotion patterns (*Subphyllochorda*) are absent but resting traces (*Bergaueria*) are preserved at mudstone-sandstone contacts. This functional mixture of traces (feeding, dwelling and resting) depicts the *Skolithos* and

Cruziana Ichnofacies (Ekdale, 1985, 1988; Frey *et al.*, 1990; Pemberton and Wightman, 1992). To support these functional behaviours, sediment grain sizes and wave-energy levels at the sediment-water interface varied for adequate periods to support foraging animals and invertebrates constructing dwelling structures. The water content of these sediments limited the locomotion but promoted the preservation of resting traces. This stressed environment was influenced by well-aerated currents, relatively low turbidity and sufficient food resources in order for *Skolithos* animals to colonize the sandy substrate (Scott, 1978). The mud drapes were burrowed by opportunistic deposit-feeders adapted to changes in the substrate due to sandstone deposition.

The environment in which these sandstones were deposited is interpreted as an estuarine channel. Sediment deposition, benthic colonization and the core location suggest this estuarine channel was close to the bayline (Dalrymple, 1992; Dalrymple *et al.*, 1993; Reinson, 1992).

Unit 4 (5.69-7.65 m) consists of sharp-based, fine-grained, current-rippled sandstones (1-15 cm) draped with 1-20 mm sparsely bioturbated mudstones. Some mudstones, particularly the basal drapes, were sideritized after burrowing by *Planolites*-trace makers. These facies represent Substrates 6 and 4, and the sand content decreased upwards from ≈54% to ≈41%. Associated with the decrease in sand content was a change in the biogenic assemblages. More marine deposit-feeders are present in the upper portion of this deposit due to increased mud and thinner sand interbeds.

The diversity and abundance of these ichnofossils reflect sandstone thicknesses, sediment consistency, turbidity and other bottom water conditions. The basal assemblage contains feeding (deposit- and suspension-feeders) plus resting and locomotion patterns (*Planolites*, *Bergaueria*, *Skolithos*, *Diplocraterion*, *Subphyllochorda* and *Teichichnus*). Upward changes in ethological patterns are more diverse and escape structures (*fugichnia*) replace resting traces in response to the physical parameters that affected burrowing. Vertical traces (*Cylindrichnus* and *Skolithos*) and lined horizontal burrows (*Palaeophycus* and *Terebellina*) are more common in this upper assemblage. Both assemblages represent the *Cruziana* and *Skolithos* Ichnofacies.

The interbedded sediments show that current flows waxed and waned in this depositional environment. Siderite, present in some mudstones, forms during *in situ* decomposition of organic matter in marine, brackish or freshwater environments (Berner, 1980; Raychaudhuri and Pemberton, 1992). The *Cruziana-Skolithos* Ichnofacies and the presence of *Thalassinoides* burrows suggest the environment was marginal marine. The physical features, local scouring and less diverse biogenic structures suggest the marginal marine unit was deposited in a laterally accreting estuarine point bar environment (Rhoads and Young, 1974; Nichols *et al.*, 1978; Scott 1978; Ekdale, 1985). The local scouring of mud drapes was associated with this lateral accretion. Lateral accretion is recognized by the gentle dips in the heterolithic deposits (Ranger and Pemberton, 1992).

Unit 5 (7.65-9.48 m) contains finer-grained sandstones and interbedded mudstones than Unit 4, but the substrate groups (5, 7 and 8) represent cleaner sediments with greater sand contents. The ichnospecies reflect this change in grain size with a more diverse assemblage: *Asterosoma, Cylindrichnus, Diplocraterion, fugichnia, Palaeophycus, Planolites, Rhizocorallium, ?Siphonichnus, Skolithos, Subphyllochorda, Teichichnus, Terebellina* and *Thalassinoides. Planolites* is the most common and abundant ichnospecies, especially above shrinkage crack intervals. These cracks are interpreted as salinity-induced synaeresis cracks (Plummer and Gostin, 1981; Pemberton and Wightman, 1992). The presence of *Diplocraterion* and *Thalassinoides* burrows support this interpretation of salinity stress. These ichnospecies represent the *Skolithos* and *Cruziana* Ichnofacies. Based on the biogenic structures, the physical structures were deposited in a stressed, impoverished marine environment. This environment was influenced by swift, well-oxygenated currents and turbid waters associated with waning tidal flows in this distributary channel (Rhoads and Young, 1970; Scott, 1978). Gentle dips in this heterolithic deposit suggest that the unit laterally accreted (Ranger and Pemberton, 1992). The similarity between this relatively sandy unit and the underlying unit suggest that it was also deposited in an estuarine point bar environment.

Fine-grained sandstones (Unit 6, 9.48-10.39 m) truncated the estuarine point bar deposit, but lack biogenic structures. These clean sandstones contain low-angle, ripple-cross laminations, current- and wave-ripples (Substrate 8). These structures are used to interpret Unit 6 as marine sandstones associated with channel deposition. The upper contact of these marine sandstones is knife-sharp and overlain by a silty mudstone lag (Unit 7, 10.39-10.59 m). This lag contains *Planolites* and *Terebellina* burrows. The erosion surface represents a ravinement surface as the result of a marine flooding event, confirmed by the trace assemblage characteristic of the *Cruziana* Ichnofacies. This ravinement surface marks the allocyclic boundary between Allomembers D and C (Bhattacharya, 1989).

Above the ravinement surface lag, blockstones and shales were deposited (Unit 8, 10.59-12.15 m). Bioturbation is sparse but *Palaeophycus* and *Rhizocorallium* burrows occur close to a fine-grained sandstone event bed above the ravinement surface. Bioturbated mudstones containing marine ichnospecies and the vertical context of this core suggest that these shales and blockstones were deposited in an offshore environment. These sediments are associated with Allomember C deposition (Bhattacharya, 1989).

The Waskahigan Bottleneck Channel is interpreted as a meandering channel, in core 6-24-64-24W5, as suggested by the succession of channel sandstones and estuarine point bars. These depositional environments responded to a relative rise in sea level. In an estuarine tripartite model, the sediments in this core were deposited near the bayline (Dalrymple, 1992; Dalrymple *et al.*, 1993; Reinson, 1992).

3.6 PALAEOGEOGRAPHY OF THE WASKAHIGAN BOTTLENECK CHANNEL, DUNVEGAN ALLOFORMATION

Bhattacharya (1989) concluded that the Waskahigan Bottleneck was a tidally-influenced distributary channel in a deltaic environment, and that the sediments, in Township 64, Ranges 23W5-24W5, are estuarine in character. He did not interpret the palaeogeography and ecology of this marginal marine environment. This distributary channel is part of a larger bifurcated channel to the northwest of my study area. The other distributary channel fed the D1 Lobe, west of the bottleneck. This meandering channel was subjected to micro-mesotidal conditions and low to moderate wave energy (Bhattacharya, 1989). These physical conditions influenced the overall fine-grained texture of the channel sediments ranging from clay to medium-grained sand. The backfilling of this channel reflects the autocyclic processes associated with river avulsion or lobe switching, rather than erosion due to a drop in relative sea level and/or tectonic subsidence (Bhattacharya, 1989; Bhattacharya and Walker, 1992).

This quantitative study of trace fossil assemblages shows that the sediments deposited in this channel are estuarine in origin and evidence is presented to suggest that ecological conditions (ie. marine influences) changed laterally and vertically at sediment-water interfaces during the transgression of this distributary channel. Subtle variations in ichnofossil assemblages result from localized animal-sediment relationships, but the signature of one impoverished-marine, trace fossil assemblage is comparable to another assemblage in a unit deposited in the same environment. The preserved facies and biogenic structures support the interpretation of marine influences increasing in the upper reaches of this wave-influenced deltaic system. Descriptive ichnology will provide similar results, but subtle changes will not be evident without quantitative ichnology. For example, in core 7-13-64-24W5, six pulses of deposition in the estuarine sand flat environment are defined by physical and biogenic changes in diversity and abundance (i.p.s.a.). The interpreted depositional environments also support a shift in marine influences in a relatively landward direction: fluvial deposits were overlain by point bars and estuarine bay fills (2-

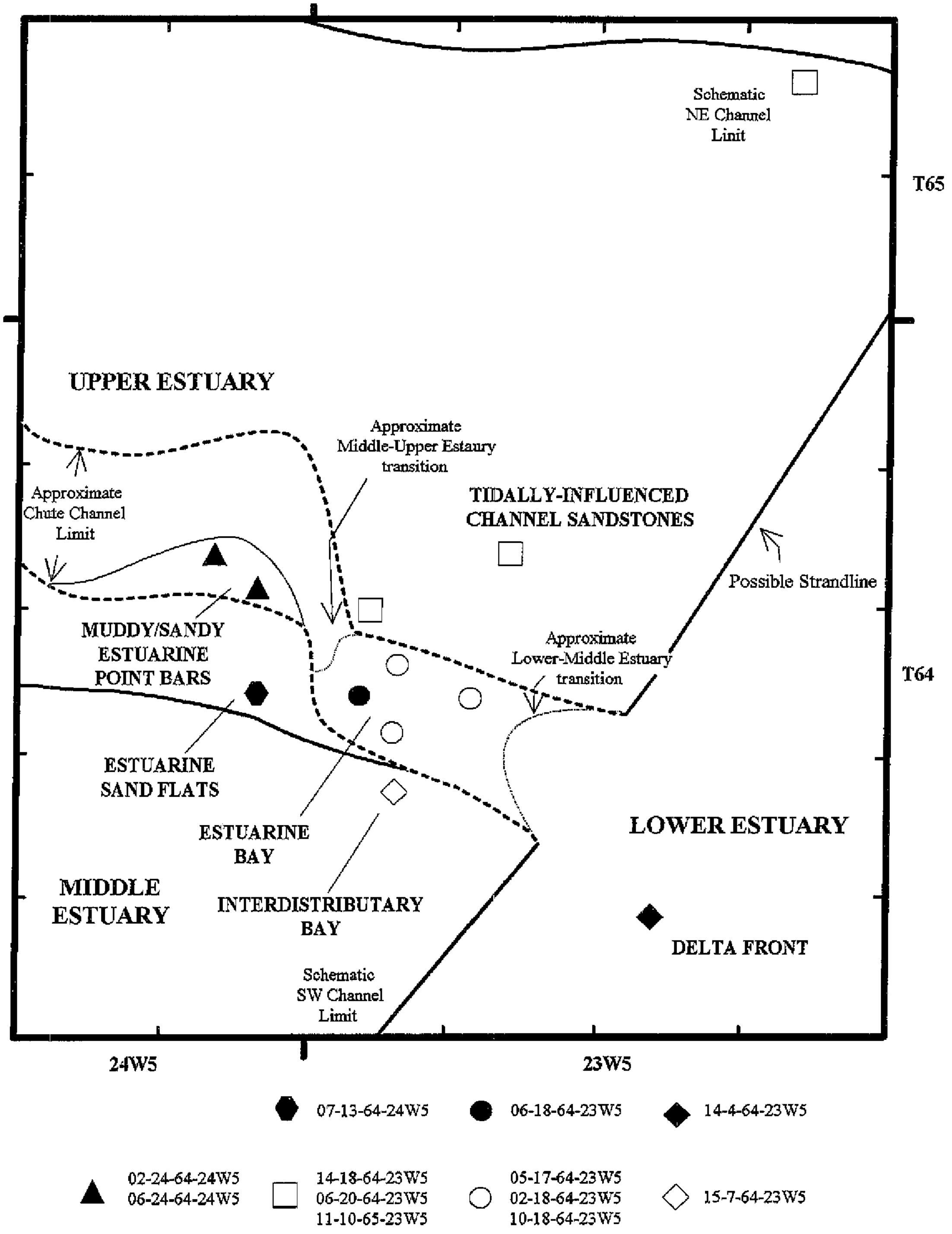
24-64-24W5 and 6-24-64-24W5).

Channel incision is marked by non-marine facies lacking biogenic structures overlying an erosion surface that cut into the marine interdistributary bay deposits associated with Shingle D2 (Bhattacharya, 1989). A basal lag of shale and sideritized mud rip-up clasts mantles this erosion surface. Sediment deposition and subsequent bioturbation by impoverished-marine and marine animals suggest that the depositional environments were influenced by more marine parameters as the channel infilled. The five cores examined in the Waskahigan Bottleneck display a tripartite zonation typical of incised-valley fills (Figure 3.22) (Dalrymple *et al.*, 1993). Interbedded mudstone-sandstone deposits and ichnospecies representing a mixed *Cruziana* and *Skolithos* Ichnofacies are common in estuarine channels. Lateral changes from the lower to middle estuary are observed in this incised valley-fill, but cores are unavailable landward of 6-24-64-24W5. West of this core is the postulated location of the upper estuary. Generally, cores in this area have few biogenic structures preserved because physical parameters destroy traces or inhibit colonization by benthic organisms (Birks, 1985; Frey and Howard, 1986; Pierce, 1989; Bromley, 1990).

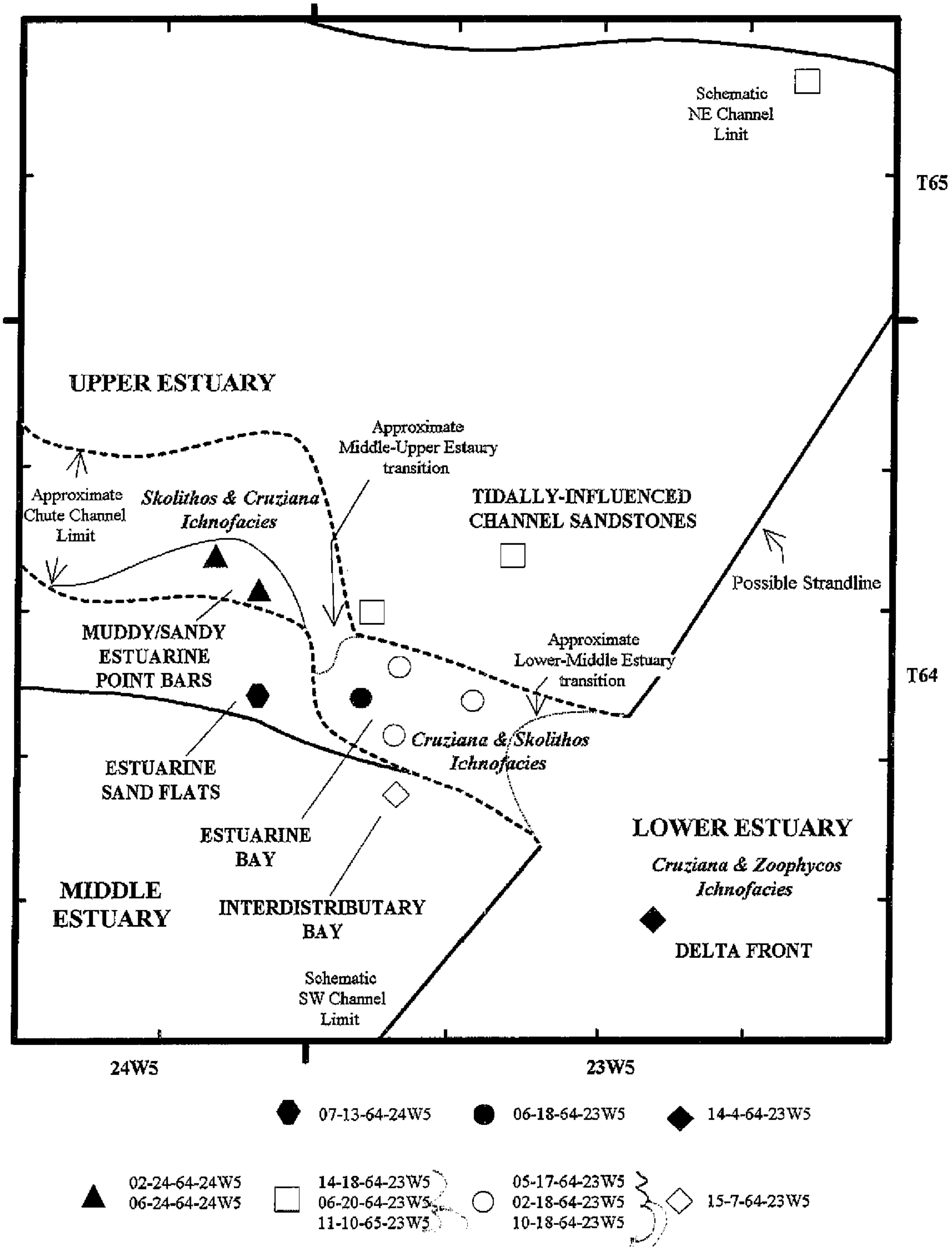
Marine ichnospecies (e.g., *Terebellina*, *Zoophycos*, *Helminthopsis* and *Anconichnus*) and intertidal ichnospecies (e.g., *Diplocraterion*, *Thalassinoides* and *Ophiomorpha*) occur in most wells but they are present in specific depositional environments. Since these depositional environments cannot be traced in each well, the ichnofacies show the change in marine influences during deposition and subsequent bioturbation. Figure 3.23 summarizes the main lateral changes in the Waskahigan Bottleneck Channel ichnofacies.

Core 14-4-64-23W5 contains trace fossil assemblages associated with the *Cruziana* and *Zoophycos* Ichnofacies. *Helminthopsis* and *Anconichnus* are the most abundant ichnospecies characteristic of these stable marine ichnofacies. *Planolites*, *Terebellina* and *Zoophycos* are also common in this core.

**Palaeogeography of the Waskahigan Bottleneck Channel,
Dunvegan Alloformation, Shingle D1**



Ichnofacies of the Waskahigan Bottleneck Channel, Dunvegan Alloformation, Shingle D1



Why not
label these
on diagram?

The cores in the middle estuary display characteristics of *Cruziana*, *Skolithos* and *Cruziana-Skolithos* Ichnofacies. These assemblages are common in intertidal brackish deposits (Pemberton and Wightman, 1992). The trace fossil assemblages in these ichnofacies are based on the eighteen ichnospecies present in this depositional environment. These deposits contain the only occurrences of *Chondrites*, *Arenicolites* and *Ophiomorpha* in the Waskahigan Bottleneck area. *Chondrites* burrows suggest that oxygen levels were low and potentially dysaerobic in some mudstones (Savrda and Bottjer, 1986, 1989; Bjerstedt, 1989). The sandier sediments are controlled by stronger currents and shallower water depths because the vertical trace fossils are more common. The vertical extent of burrows suggests whether the environmental parameters are marine or stressed (e.g., brackish). The sizes of traces in marine deposits are larger than those in brackish deposits (Pemberton and Wightman, 1992; Pemberton *et al.*, 1992b, 1992c).

The upper estuary is not cored but the ichnofossil diversity of tidal flats and estuarine point bars increased near the middle-upper estuary transition from no trace fossils to that characteristic of the *Skolithos* and *Skolithos-Cruziana* Ichnofacies. The end of Shingle D1 and Allomember D deposition is represented by a sharp-based erosion surface overlain by a 10-cm silty mudstone lag. This lag contains *Planolites* and *Teichichnus* burrows. These marine deposit-feeding traces are characteristic of the *Cruziana* Ichnofacies. This erosion surface represents a maximum marine flooding surface reflecting the allocyclic processes associated with tectonic subsidence and a eustatic rise in relative sea level in the foreland basin (93.5 Ma) (Bhattacharya, 1989; Bhattacharya and Walker, 1992). Above this flooding surface, marine shales were deposited in an offshore marine environment corresponding to Allomember C (Bhattacharya, 1989).

Overall, bioturbation was intense in the deposits influenced by marine conditions or undisturbed by storms for long periods. In the middle estuary, tidal and wave energies dominate but are punctuated with long fair weather periods resulting in pervasive bioturbation of mudstones and sandstones. This depositional environment contains low to moderate abundances of the traces because the fluctuating current flows result in interbedded mudstone and sandstone deposits thus, changing the ecology of the sediment-water interface.

CHAPTER 4

SOUTH WILLESDEN GREEN INCISED VALLEY, VIKING ALLOFORMATION

4.1 INTRODUCTION

This ichnological investigation of the brackish-water sediments of the Viking Alloformation in the Willesden Green region follows the interpretations made by Boreen (1989, Chapter 6). His conclusions regarding trace fossil assemblages in these incised valleys are the building blocks of this study that encompasses Townships 40-42 and Ranges 6-7W5 (Appendix B.2). Five of the six wells measured in this alloformation are in the southern channel trending ENE-WSW. One core was measured from the northern channel that trends NNW-SSE. The north channel is not the target of this study, but the core was used for comparison with its southern counterpart.

The South Willesden Green Channel is a major incised channel in the Viking Alloformation (Allomember C). This alloformation's stratigraphy was briefly discussed in Chapter 1. Detailed discussions are found in Boreen (1989), Pattison (1991), and Boreen and Walker (1991). The sediments of Allomember C, in the Willesden Green area, erosively truncate the gradually coarsening upwards successions of intensely bioturbated mudstones, siltstones and fine-grained sandstones (Allomembers A and B). A transgressively modified regressive surface of erosion (Viking Erosion surface 2, VE2) separates these marine facies ("Regional Viking") and the marginal-marine facies associated with the channel fill (Allomember C). The ichnogenera *Arenicolites*, *Rhizocorallium*, *Skolithos* and *Thalassinoides* penetrate this erosion surface because these burrows are passively filled with pebbles and sand from the overlying deposits (Boreen, 1989; Pemberton and MacEachern, 1992). These marine ichnofossils represent the *Glossifungites* Ichnofacies. This surface suggests that fluvial sediments were subaerially removed and reworked by marine processes, after which marginal marine conditions prevailed during the infilling of the channel (Pemberton and Frey, 1984; Boreen, 1989; Pemberton *et al.*, 1992a, 1992b, 1992c). The channel is truncated by the "Viking regressive facies" of Allomember D (Leckie, 1986; Boreen, 1989). The Viking Erosion surface VE4 truncated Allomember D sediments before the deposition of shales (Allomember E). Bloch *et al.* (1993) named the shales blanketing the Viking sediments, the Westgate Formation.

The cores described in this chapter are organized from the most seaward core (4-5-41-6W5) to the most landward core (7-10-41-6W5) (Figure 4.1). The original interpretations (Boreen, 1989) are supported and enhanced by this ichnological investigation. Subtle generalizations are proposed regarding the ecological and environmental circumstances during colonization of the sediment-water interface. These environmental variations are recognized by vertical and lateral variations in the trace fossil assemblage diversities and abundances with facies changes.

This chapter will use the ideas established in Chapter 3 to assess ecological and environmental parameters that governed the benthic animals in the coastal region during Viking time. It will also strengthen the palaeogeography for the South Willesden Green incised valley-fill as interpreted by Boreen (1989).

4.2 VERTICAL VARIATIONS IN ICHNOFOSSIL ASSEMBLAGES

The abundance and diversity of trace fossil assemblages reflect the benthic communities that burrowed through sediments during the Late Albian. Benthic environmental conditions can alter the composition of the animals and their traces. These changes in trace assemblage and sediment composition suggest probable environmental conditions within the South Willesden Green Channel.

Core Locations in the Willesden Green Channel, Viking Alloformation

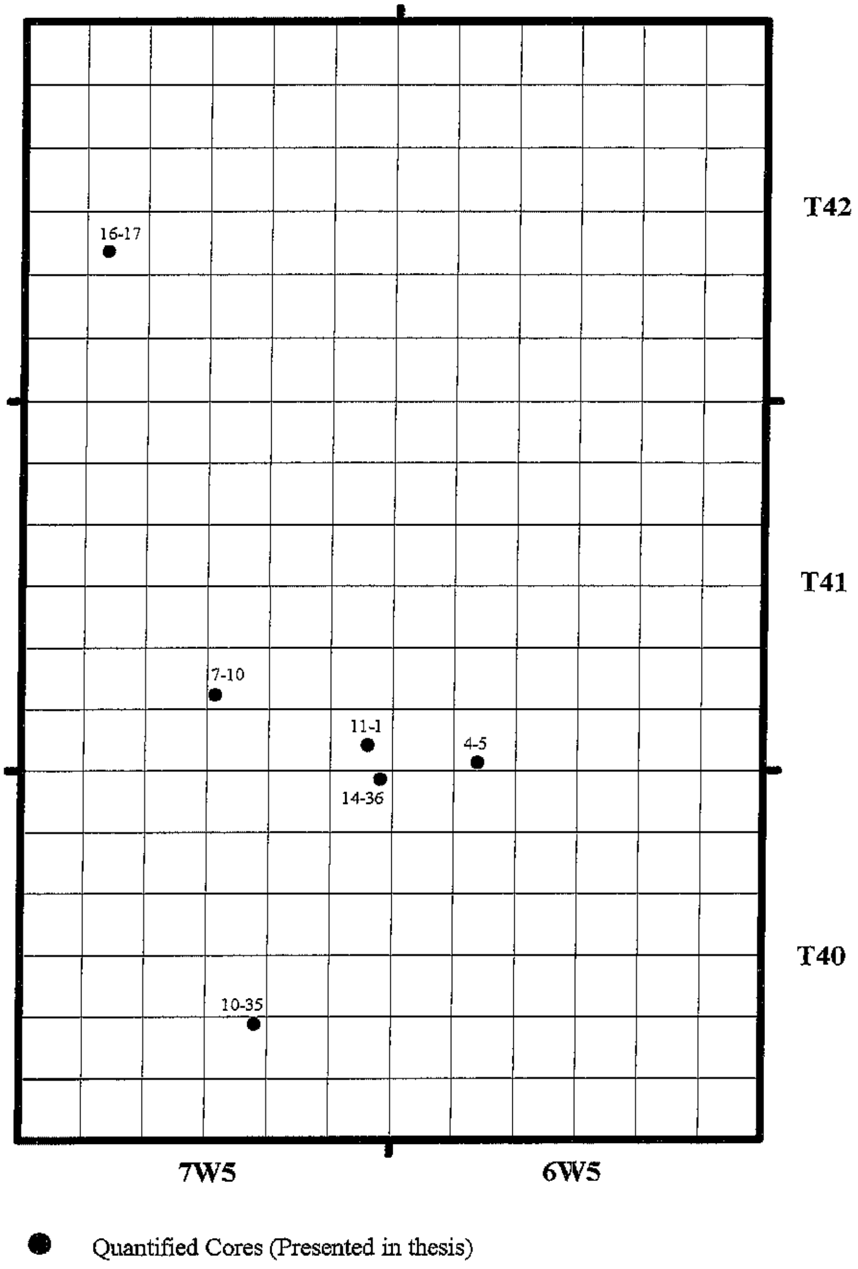


Figure 4.1 The Willesden Green study area cores in Townships 40-42 and Ranges 6-7W5. The solid circles show the cores presented in this chapter.

The abundance and diversity of trace fossils herein are displayed graphically and as coloured symbols (Figure 2.4, Pocket 1). The following five cores are described to show subtle and distinct vertical changes in ichnofossil assemblages. These measured core sections are drawn to show changes in depositional environments, as determined by physical and biogenic structures (Figure 2.3, Pocket 1).

The cores, representing different depositional environments, are organized from the most seaward (4-5-40-6W5) to the landward (7-10-41-6W5). This order permits lateral changes in depositional environments to be discussed during a landward progression of benthic communities as the sea transgressed this incised valley. The cores interpreted as estuarine flats (sand and mud) are organized as to their proximity to the channel axis (i.e., proximal or distal). This layout also helps in the discussion of lateral variations in the South Willesden Green Channel.

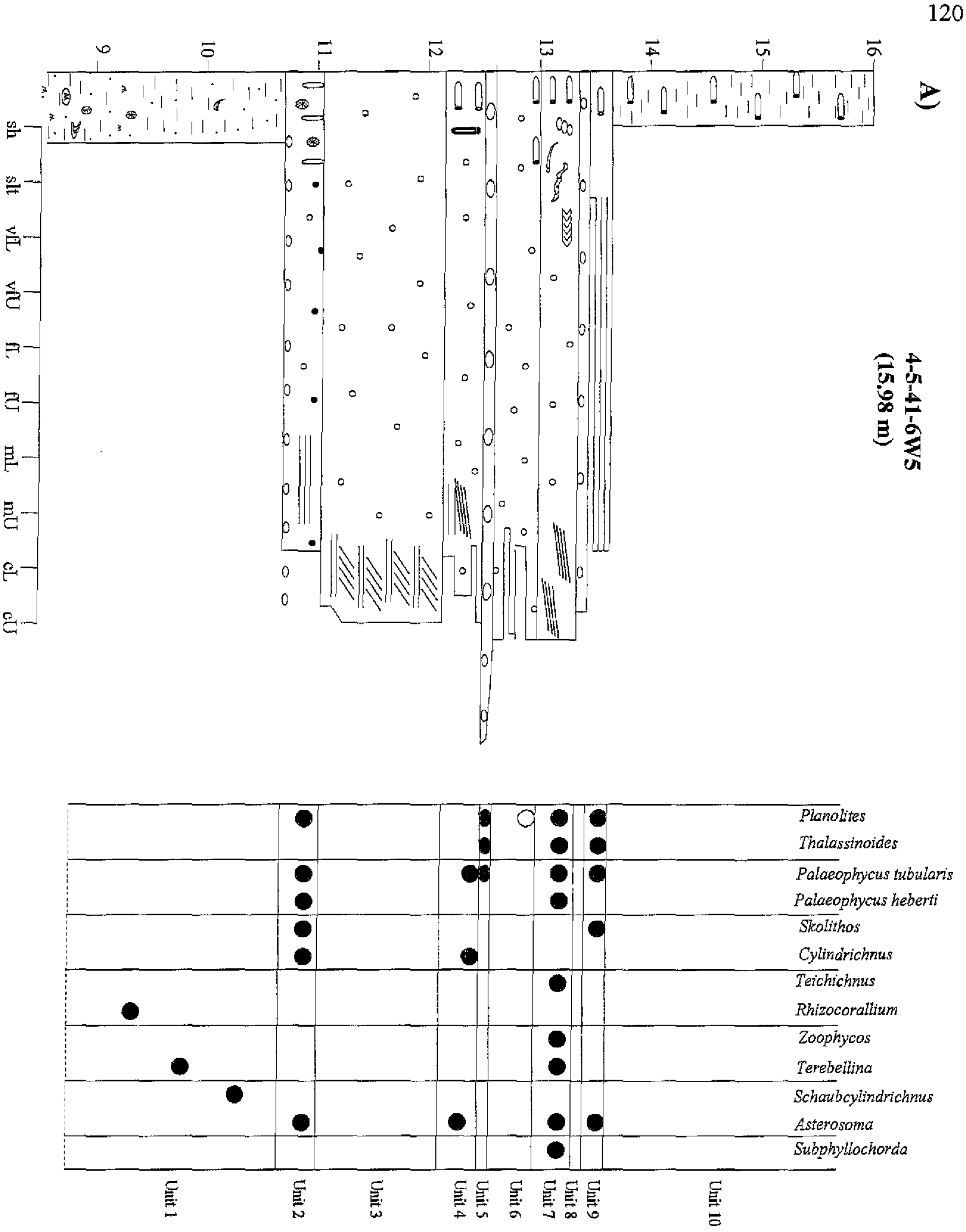
In 1989, Boreen outlined vertical and lateral variations in trace fossil assemblages. Herein, I attempt to show subtle variations in ecological conditions at the sediment-water interface, which are not possible with lists of trace fossils.

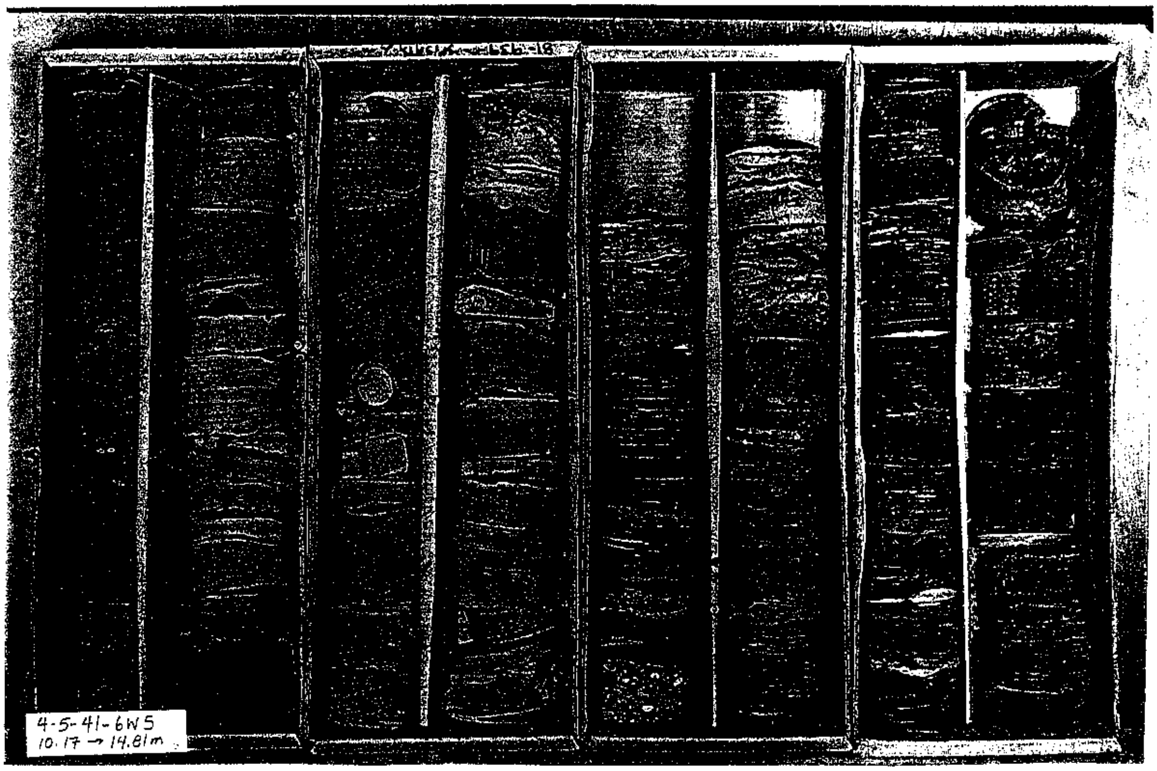
4-5-41-6W5 Core Description

The 14.81 m core is divided into ten depositional units based on preserved physical structures and the abundance and diversity of the biogenic assemblages (Figure 4.2).

Unit 1 (0-10.72 m) consists of muddy siltstones (Facies 7A) with rare intervals of discernable biogenic structures. *Rhizocorallium*, *Terebellina* and *Schaubcylindrichnus* are present, approximately 1.5 m below the erosion surface separating Unit 1 and Unit 2 (Figure 4.3). *Anconichnus*, *Helminthopsis* and *?Siphonichnus* also occur in this unit.

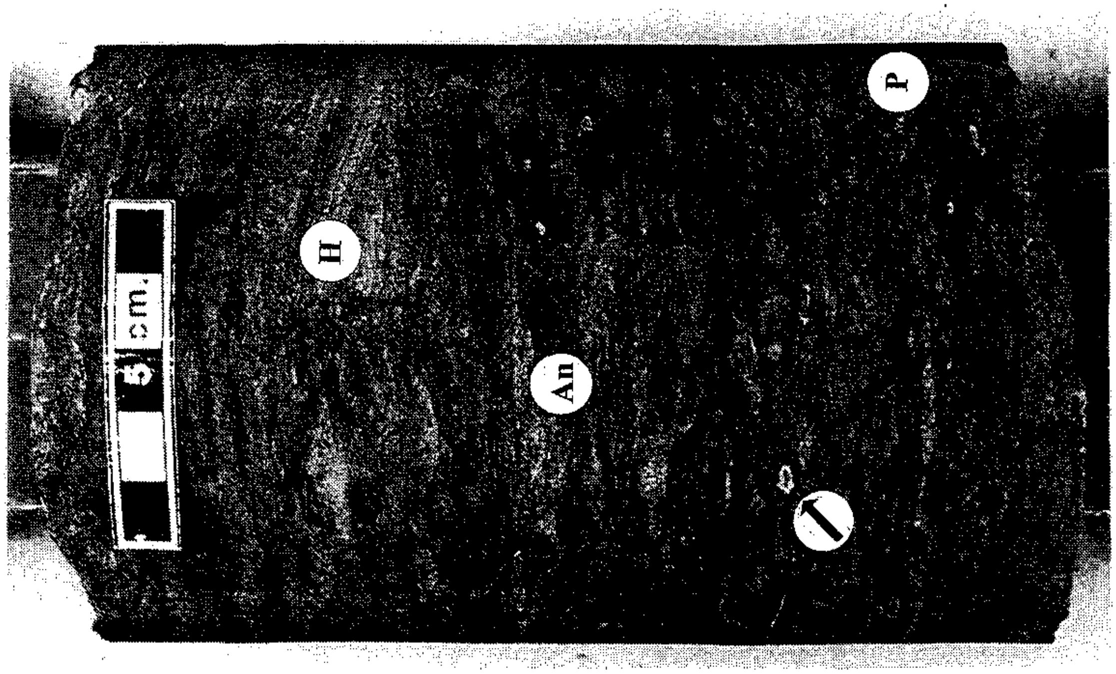
Unit 2 (10.72-11.06 m) consists of interbedded mudstones and parallel-laminated, fine-grained sandstones (Facies 2). This deposit overlies a knife-sharp erosion surface that is not penetrated with vertical shafts, unlike the other cores described in this region. Near the upper contact of this unit,


A)
4-5-41-6W5
(15.98 m)
9
10
11
12
13
14
15
16
sh
slt
vfL
vfU
fL
fU
mL
mU
cL
cU
Planolites
Thalassinoides
Palaeophycus tubularis
Palaeophycus heberti
Skolithos
Cylindrichnus
Teichichnus
Rhizocorallium
Zoophycos
Terebellina
Schaubcylindrichnus
Asterosoma
Subphyllochorda
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6
Unit 7
Unit 8
Unit 9
Unit 10

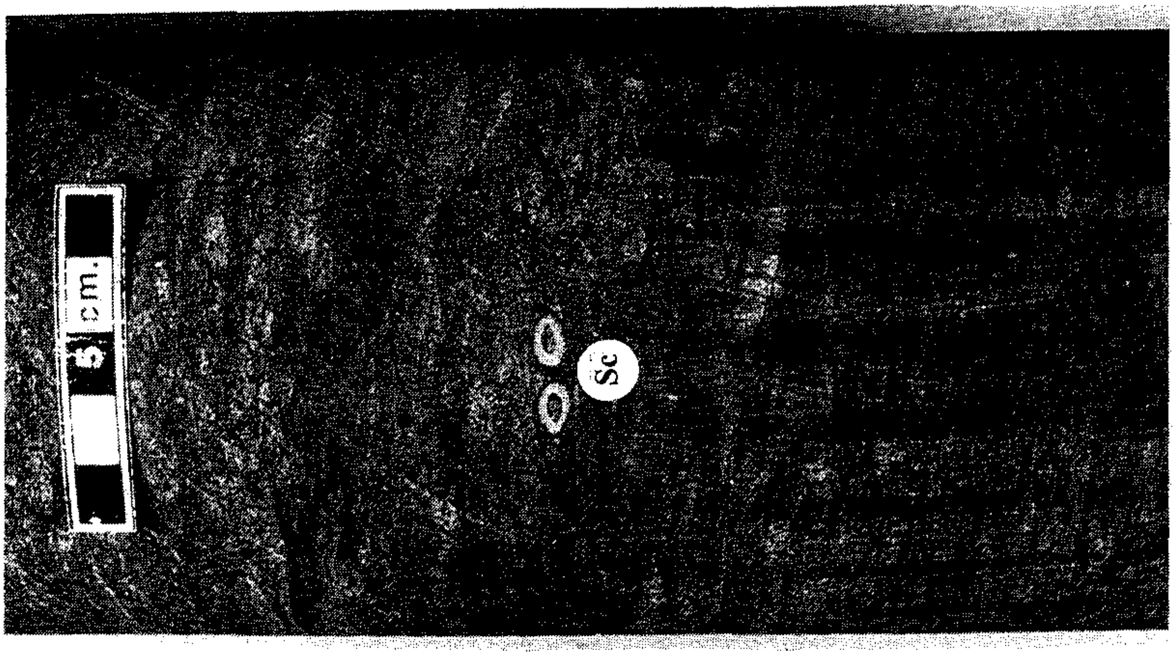


Top

Bottom ⟶



A)



B)

Skolithos shafts and *Asterosoma* burrows are present with sideritized mud clasts. This unit is truncated by coarser-grained sandstones (Unit 3).

Unit 3 (11.06-12.18 m) comprises a coarsening upward unit of fine- to medium-grained, parallel-laminated sandstones (Facies 8D) interbedded with the trough cross-bedded sandstones (15-25 °, Facies 8G). No traces are discernable in this deposit.

Unit 4 (12.18-12.49 m) consists of interbedded parallel-laminated cross-bedded sandstones (10-15 °). Sideritized mud clasts define the laminae. Sand-adapted deposit-feeders (e.g., *Palaeophycus* worm-like animals) and the vertical *Cylindrichnus* shafts are present. *Planolites* intersections are preserved in some mud drapes.

Unit 5 (12.49-12.59 m) consists of a poorly-sorted conglomerate (Facies 9) containing sub-round to round chert pebbles and cobbles. This conglomerate fines upward into a muddy conglomerate with a medium-grained sand matrix with mud drapes capping the unit. Trace fossils are not preserved in this unit.

Unit 6 (12.59-12.90 m) contains fine- to medium-grained sandstones interbedded with fissile black shale (Facies 1C). Bioturbation is rare. However, a few mud drapes, especially near the upper contact, are burrowed by *Planolites* trace makers.

Unit 7 (12.90-13.38 m) is comparable to Unit 3. The dip of the reactivation surfaces has decreased to 5-10° and the ichnofossil assemblage increased in abundance and diversity. The trace fossils present include *Asterosoma*, *Planolites*, *Subphyllochorda*, *Teichichnus*, *Terebellina* and *Zoophycos*. The upper contact with the overlying pebbly mudstone is knife-sharp.

Unit 8 (13.38-13.46 m) consists of a poorly-sorted, sub-rounded to rounded pebbly mudstone (Facies 6) which coarsens upward. Biogenic structures are absent in this unit.

Unit 9 (13.46-13.63 m) contains muddy siltstones (0.5-2 cm thick) interbedded with pebbly sandstones (Facies 8K) lacking internal structures (1-6 cm thick). *Palaeophycus* occur in some siltstone beds.

Unit 10 (13.63-15.98 m) consists of black blockstones (Facies 2). Rare very fine to fine-grained sand layers (1-2 cm thick) and stringers (<4 mm thick) are present. *Planolites*-trace makers burrowed through the mud layers.

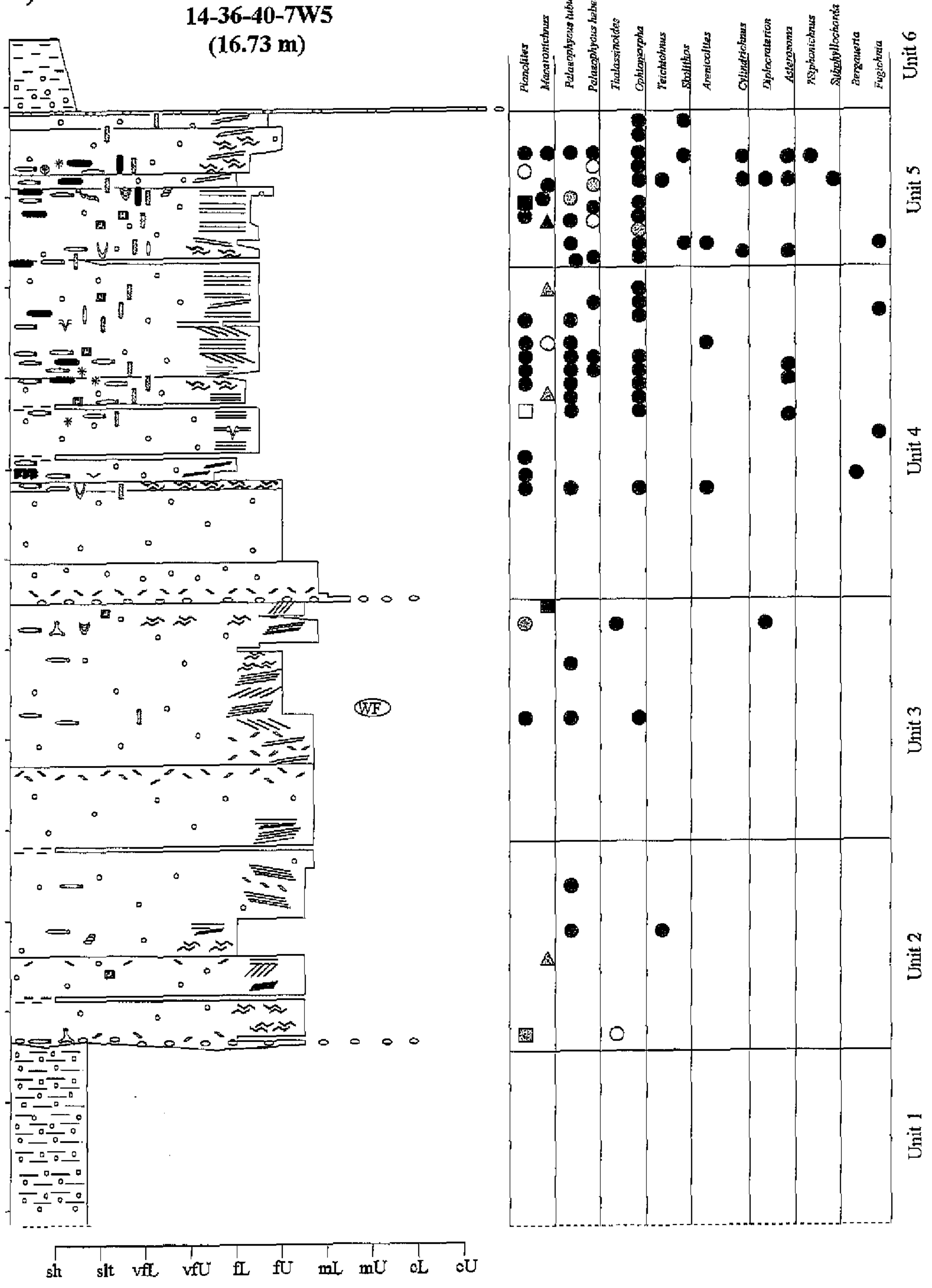
14-36-40-7W5 Core Description

This 16.73 m core comprises sandstone facies deposited under varying energy conditions. This core is divided into seven depositional units based on physical features, biogenic structures and pebble lags (Figure 4.4).

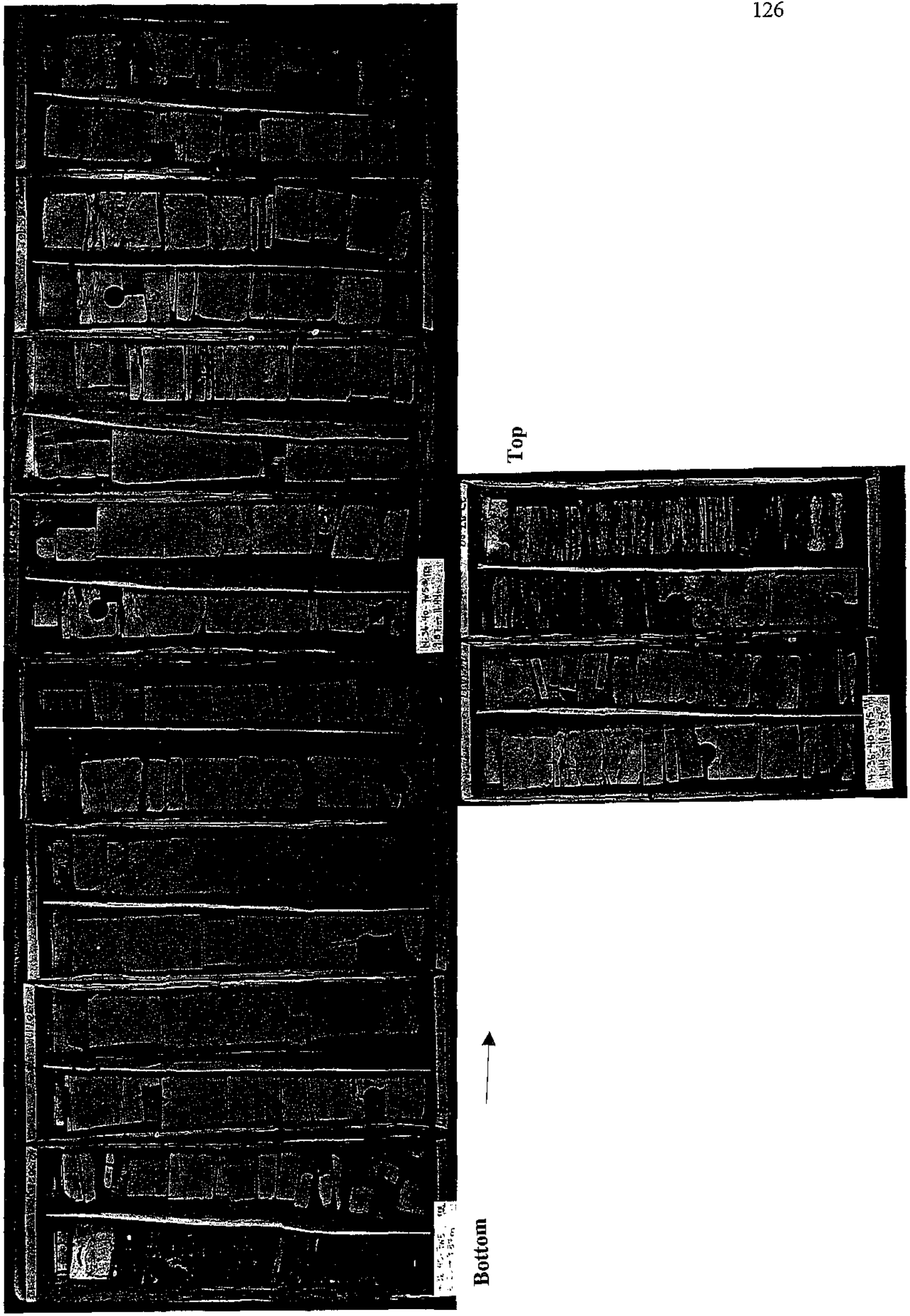
Unit 1 (0-5.69 m) comprises muddy siltstones (Facies 7A, 0-1.03 m) and sandy siltstones (Facies 7B, 1.03-5.69 m). Only the upper sediments (5.20-5.69 m) are drawn on the lithological log and shown in the core boxes (Figure 4.4). Bioturbation is rare in this unit but in the silty mudstone intervals (eg., *Helminthopsis*, *Anconichnus* and *Terebellina*). The upper contact of Unit 1 is marked by an erosion surface mantled with chert pebbles, and *Planolites* (16.71 i.p.s.a.) and *Thalassinoides* (4.18 i.p.s.a.) domiciles extending down into the siltstones.

Unit 2 (5.69-7.75 m) consists of fine- to medium-grained sandstones with pebbles and shale rip-up clasts scattered in the bottom 20 cm. No traces are observed in the lower portion (5.69-6.11 m), which also contains discontinuous stylolitic mud partings (i.e., crinkly laminations) and low-angle, parallel-laminations (0-5°). The middle of Unit 2 (6.11-6.62 m) is similar to the underlying sandstones, but *Macaronichnus segregatis* are present in cross-bedded sandstones (≈15°, 6.47-6.62 m, Figure 4.5). The remaining sandstones (6.62-7.75 m) coarsen upward and contain crinkly laminations. *Palaeophycus tubularis* and *Teichichnus* burrows are present in the cross-bedded sandstones (≈5-10°, 6.71-6.99 m). *Palaeophycus* is the only trace found in low-angle to parallel-laminated sandstones interbedded with

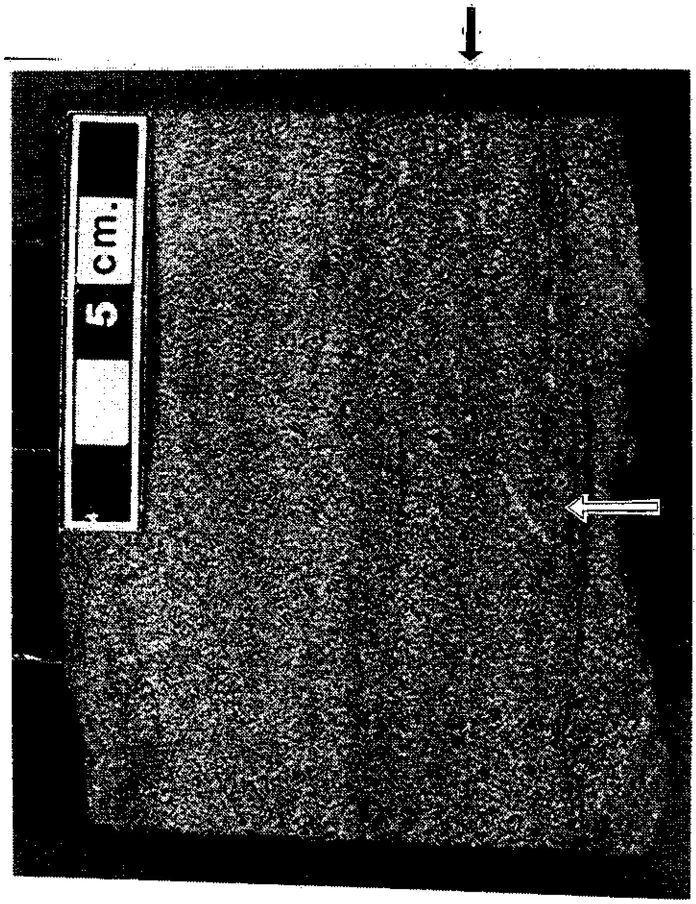
A)


14-36-40-7W5
(16.73 m)
15
10
5
WF
sh
slt
vfL
vfU
fL
fU
mL
mU
cL
cU
Planolites
Macaronichnus
Palaeophycus tubularis
Palaeophycus heberti
Thalassinoides
Ophiomorpha
Teichichnus
Skolithos
Arenicolites
Cylindrichnus
Diplocraterion
Asterosoma
?Siphonichnus
Subphyllochorda
Bergaueria
Fugichnia
Unit 6
Unit 5
Unit 4
Unit 3
Unit 2
Unit 1

B)



A)



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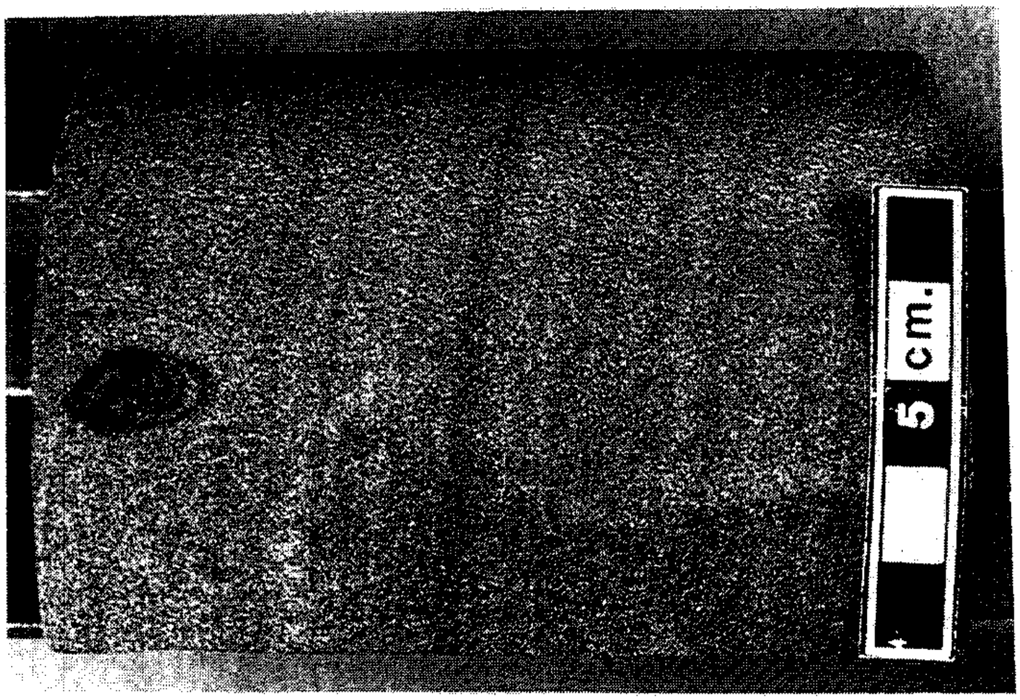


massive sandstones with scattered rip-ups clasts at the top of this unit (7.39 m).

Unit 3 (7.75-10.48 m) consists of the same fine- to medium-grained sandstone facies as preserved in Unit 2. However, it contains a different suite of biogenic structures. Low-angle to parallel-laminated sandstones, lacking trace fossils, are overlain by massive sandstones. Shale rip-up clasts occur within the massive sandstones (Facies 8I) and on some reactivation surfaces of cross-bedded sandstones and low-angle laminated sandstones. Wood fragments are present where sandstones become finer (upper-fine/lower-medium to upper-fine, 9.16-9.26 m). *Palaeophycus tubularis*, *Planolites* and *Ophiomorpha* occur in this interval. Sandstones containing discontinuous crinkly laminations (9.79-9.97 m) exhibit an increase in trace abundances and diversity. The assemblage includes *Macaronichnus*, *Thalassinoides* (instead of *Ophiomorpha*) and *Diplocraterion*. Unit 3 is truncated by a sharp-based erosion surface with a pebble lag (Facies 10).

Unit 4 (10.48-11.75 m) is a massive fining upward sandstone unit (Facies 8I). The pebbly sandstone at the base is poorly-sorted and contains angular sideritized mud rip-up clasts. No biogenic structures are present in this unit.

Unit 5 (11.75-14.30 m) contains notable changes in the physical and biogenic structures. The following facies are present in this unit: parallel-laminated (Facies 8D), ripple cross-laminated (10-15°, Facies 8E, 8F), cross-bedded (25-30°, Facies 8G) and pervasively bioturbated (Facies 8J) sandstones. This unit is capped with a bioturbated mudstone (Facies 1B). *Arenicolites*, *Asterosoma*, *Bergaueria*, *fugichnia*, *Macaronichnus*, *Ophiomorpha*, *Palaeophycus heberti*, *Palaeophycus tubularis*, *Planolites* and *Skolithos* are present in this unit.

Unit 6 (14.30-15.89 m) is similar to Unit 5, but the cross-bedded sandstones are absent. The diversity and relative abundances of ichnofossils have increased from nine (Unit 5) to fourteen ichnospecies (Unit 6). *Teichichnus*, *Cylindrichnus*, *Diplocraterion*, *?Siphonichnus* and *Subphyllo-*

chorda are present in Unit 6 and *Bergaueria* traces are absent. The upper contact of Unit 6 is knife-sharp and mantled by a matrix supported conglomerate (Facies 9).

Unit 7 (15.89-16.73 m) comprises sand layers that dominate the base of this fining upward mudstone unit. No discernable traces are evident (Figure 4.6).

10-35-40-7W5 Core Description

This 9.82 m core is divided into seven depositional units based on the diversity and abundance of the biogenic assemblages, and preserved physical structures. Fine- to coarse-grained sandstones and pebbles overlie muddy siltstones, and they are interbedded with mudstones (Figure 4.7).

Unit 1 (0-0.70 m) consists of pervasively bioturbated muddy siltstone (Facies 7A) with only *Helminthopsis* burrows present, except near the upper contact (0.66-0.70 m) where *Planolites* (8.62 i.p.s.a.), *Skolithos* (7.05 i.p.s.a.) and *Rhizocorallium* (4.70 i.p.s.a.) are present (Figure 4.8). These feeding/dwelling structures are filled with medium- to coarse-grained sand and pebbles derived from Unit 2.

Unit 2 (0.70-2.75 m) is an upper-fine- to coarse-grained sand deposit above an erosion surface mantled with chert pebbles. The medium- to coarse-grained cross-bedded sandstones (Facies 8G) have reactivation surfaces dipping 10-25 °. The medium-grained sandstones have low-angled surfaces dipping 0-5 °. Fine-grained sands have a pervasively bioturbated texture (Facies 8J) with *Planolites* (1.25-14.10 i.p.s.a.) and *Ophiomorpha* (0.45-0.95 i.p.s.a.) dominating the assemblage of six ichnospecies. Wood, coal debris, shale and sideritized mud rip-up clasts occur in the pebbly sandstones (Facies 8K).

Unit 3 (2.75-4.86 m) consists of pervasively bioturbated upper-fine/ lower-medium-grained sandstones interbedded with flaser-type bedding (e.g., lenticular wave-rippled sand lenses encased in mud, Facies 1B). *Planolites* (0.42-15.66 i.p.s.a.) burrows dominate the eight ichnofossils present. Both

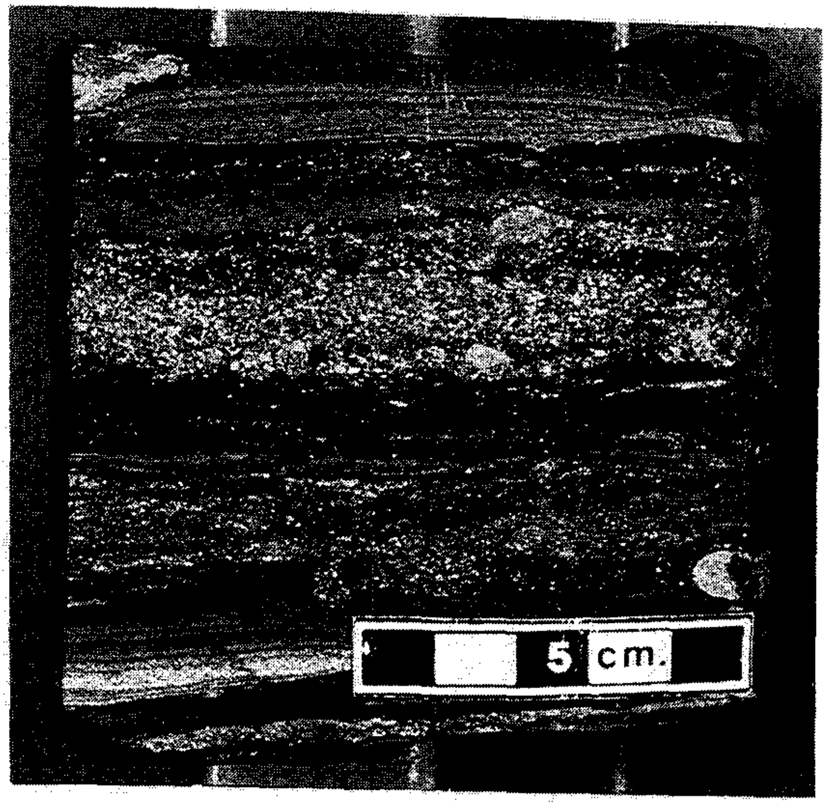
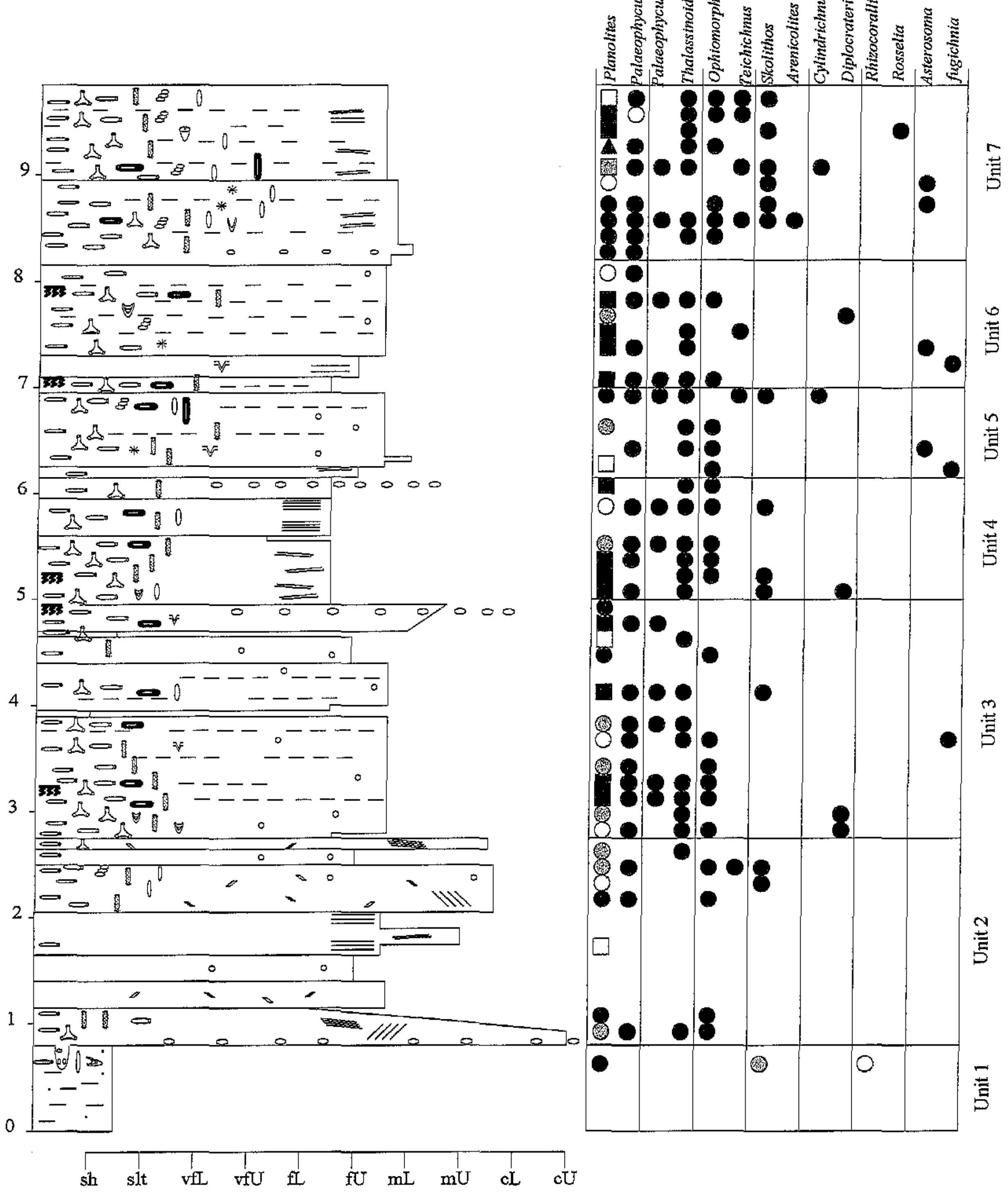


Figure 4.6 The basal sediments of Unit 7 (15.89-15.98 m, 14-36-40-7W5) consist of laminated gritty mudstones (Facies 3C) with scattered, well-rounded chert granules and pebbles.

A)

10-35-40-7W5
(9.82 m)



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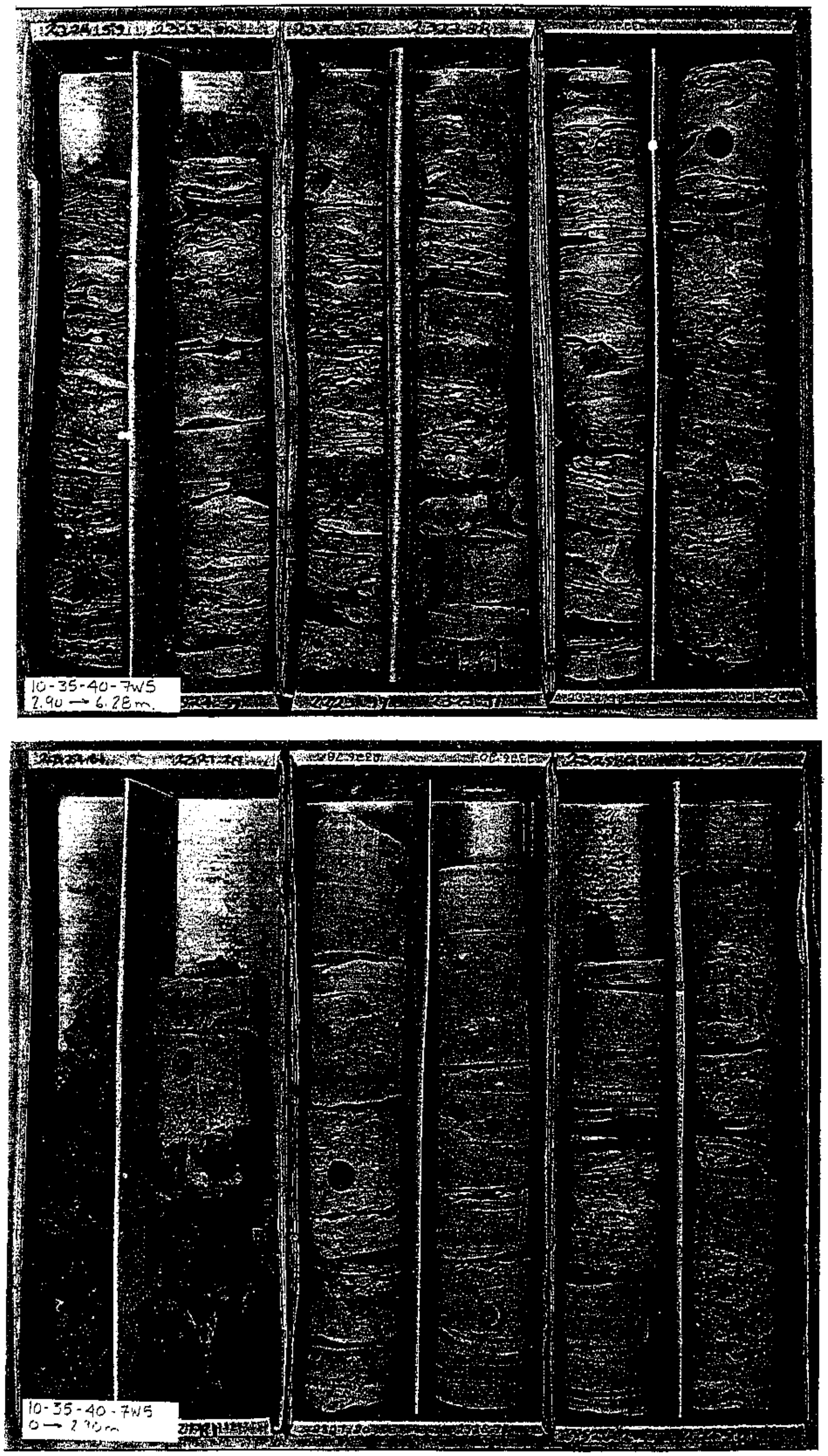
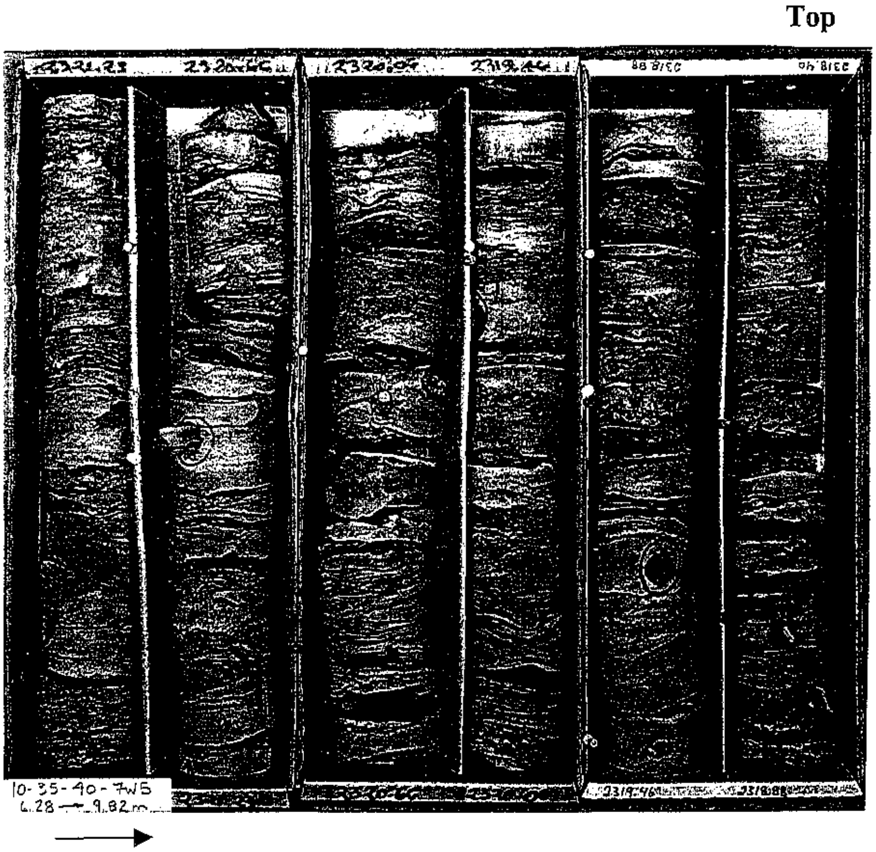
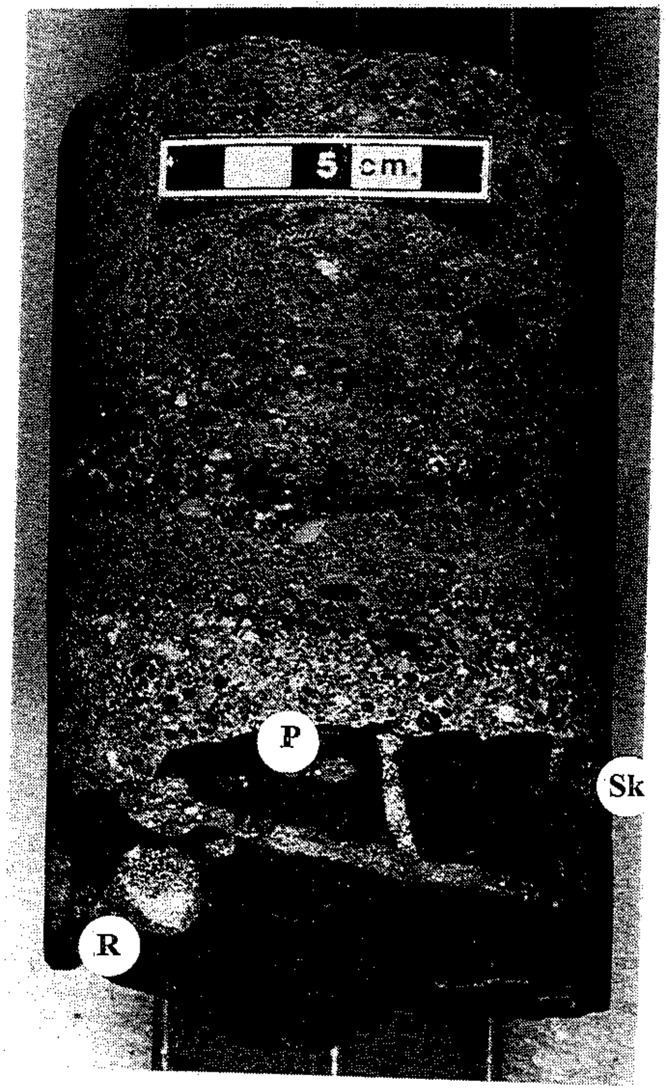


Bottom ⟶


Top
2319.46
2318.88
10-35-40-7W5
6.28 → 9.82 m


5 cm.
P
Sk
R

Palaeophycus heberti and *Palaeophycus tubularis* are present. Unit 3 contains the first occurrences of *Diplocraterion* burrows and synaeresis cracks. The upper 18 cm of Unit 3 comprises a coarsening upwards, pervasively bioturbated sandstone with pebbles and burrowed by *Planolites*, *Palaeophycus* and *Thalassinoides* at the knife-sharp upper boundary of this unit.

Unit 4 (4.86-6.17 m) lies above the pebble lag associated with Unit 3 and contains more ichnofossils than Unit 3. This finer-grained unit comprises wave-rippled fine-grained sandstones (Facies 8E), pinstripe mudstones (Facies 4) and laminated-to-burrowed sandstones (Facies 8B). Siderite is present in some mud drapes. The biogenic diversity and abundances are comparable to Unit 3, but no escape traces are present. The coarsening upward pervasively bioturbated sandstones (Facies 8J, 6.0.8-6.17 m) resemble Unit 3 in that they contain pebbles and *Planolites*, *Thalassinoides* and *Ophiomorpha* burrows at the upper contact.

Unit 5 (6.17-6.96 m) is coarser than Unit 4 and contains ripple-laminated sandstones (Facies 8E, 8F) and mud rip-up clasts. Pervasively bioturbated sandstones, containing *Palaeophycus* and *Ophiomorpha* burrows, are draped with carbonaceous mud. This mud contains abundant *Planolites* burrows. Poorly-sorted pebbles form crude parallel-laminations (6.35-6.38 m) in a nonburrowed portion of the pervasively bioturbated sandstones. *Diplocraterion* is absent from this assemblage of ten ichnospecies; however, *Cylindrichnus*, *fugichnia* and *Bergaueria* are present.

Unit 6 (6.96-8.20 m) consists of pervasively bioturbated sandstones that coarsen upward, and synaeresis cracks occur near the top. *Fugichnia* are the only biogenic structures present in the parallel-laminated sandstones (7.16-7.28 m). The remainder of this unit comprises laminated-to-burrowed sandstones (Facies 8B) with the same ichnospecies present as in Unit 4.

Unit 7 (8.20-9.82 m) comprises low-angle laminated-to-burrowed sandstones with scattered pebbles (8.27-8.37 m). This unit is similar to Unit 6, but the trace assemblage is different. *Rosselia* and

Arenicolites occur only in Unit 7. *Asterosoma* occurs in more intervals than in Unit 6.

The upper boundary of Allomember C (VE) was not cored in this well.

16-17-42-7W5 Core Description

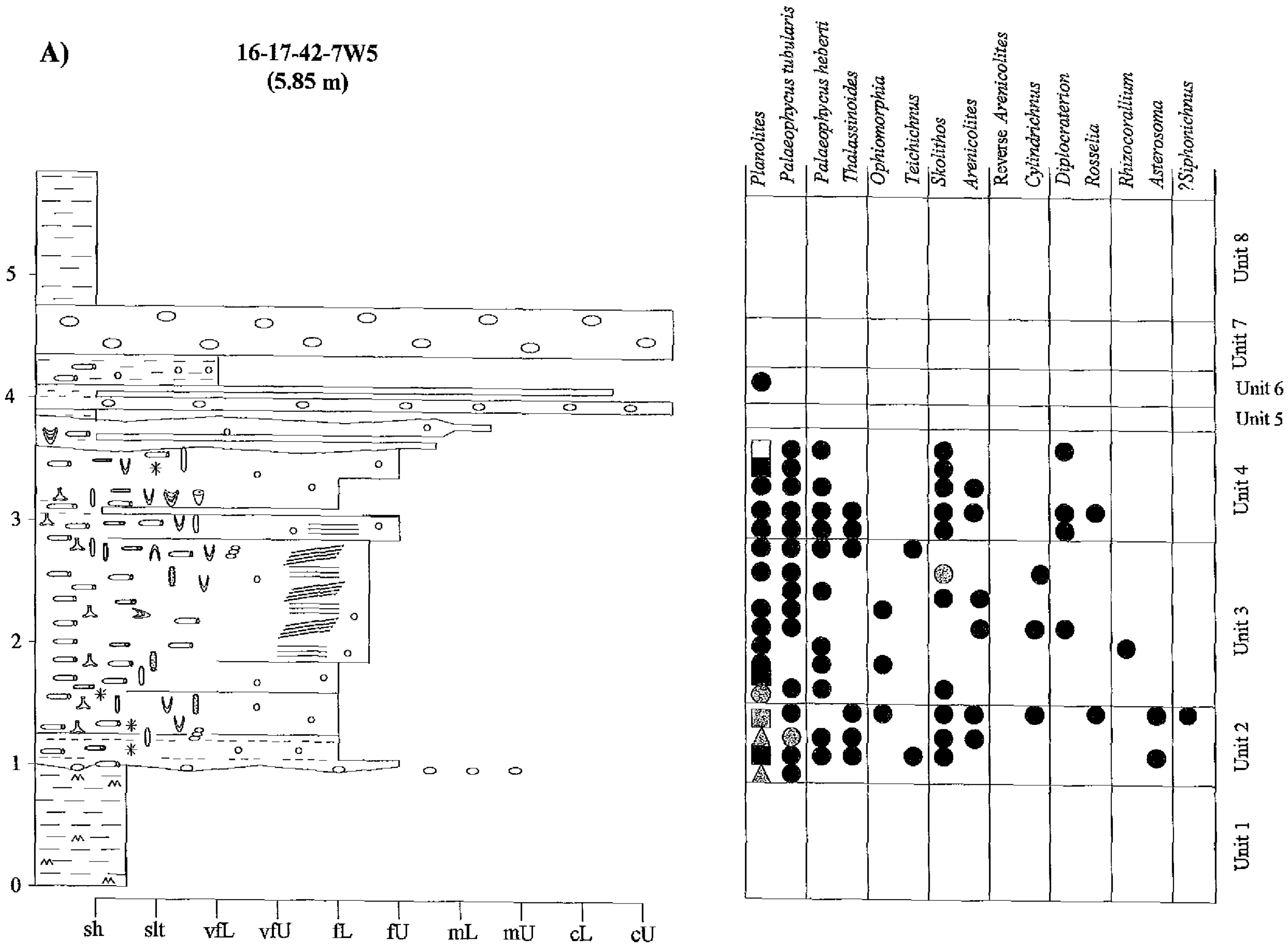
This 5.85 m core contains eight units divisible by lithologies and ichnofossil assemblages (Figure 4.9). This core is found in the North Willesden Green Channel, and is used as a comparison for similar deposits (11-1-41-7W5) in the South Willesden Green Channel. Fifteen trace fossils are present in this core.

Unit 1 (0-1.02 m) contains muddy siltstones (Facies 7A). The only trace present is *Helminthopsis*, the abundance of which cannot be accurately quantified. The upper erosional contact of this unit is knife-sharp and was not penetrated by the domiciles of suspension-feeders. However it is covered with well-rounded chert pebbles (Figure 4.9).

Unit 2 (1.02-1.62 m) consists of lower-fine-grained parallel-laminated sand with bioturbated mud tops. Twelve ichnospecies measured in this unit are: *Arenicolites*, inverted *?Arenicolites*, *Asterosoma*, *Cylindrichnus*, *Diplocraterion*, *Ophiomorpha*, *Palaeophycus heberti*, *Palaeophycus tubularis*, *Planolites*, *Rhizocorallium*, *Rosselia*, *?Siphonichnus*, *Skolithos*, *Teichichnus* and *Thalassinoides*. *Planolites* burrows are the most abundant traces (2.09-22.28 i.p.s.a.) followed by *Palaeophycus tubularis* burrows (0.95-3.13 i.p.s.a.).

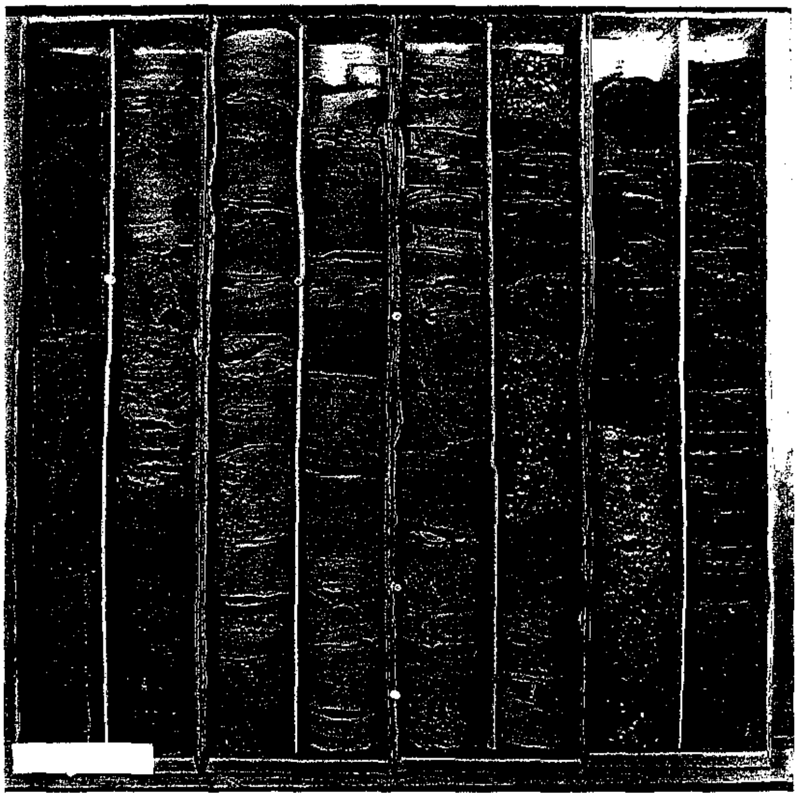
Unit 3 (1.62-3.07 m) is sedimentologically similar to Unit 2. The trace fossil diversity is different but the abundances are similar to those in Unit 2. Figure 4.10 shows some dwelling structures found in laminated-to-burrowed sandstones (Facies 8B).

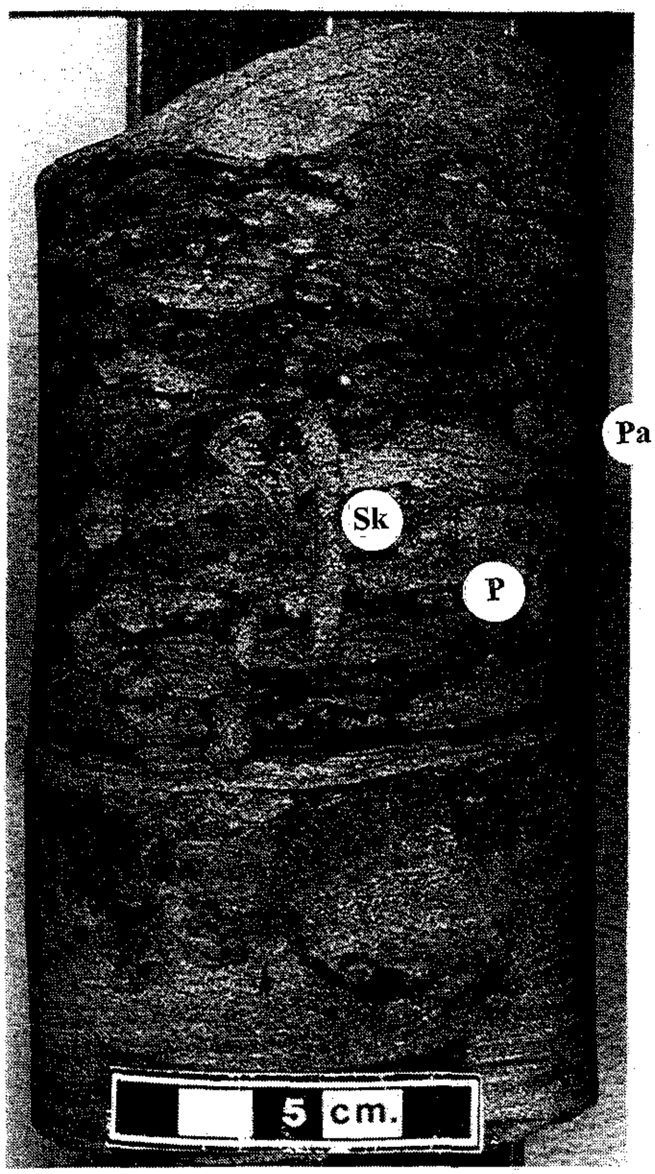
Unit 4 (3.07-3.84 m) comprises fine-grained parallel to rippled-laminated sandstones (Facies 8D, 8E/8F). Mud drapes in the lower part of the unit contain abundant *Planolites* (1.23-11.93 i.p.s.a.)



A) 16-17-42-7W5 (5.85 m)

B)

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and few *Thalassinoides* burrows (0.25 i.p.s.a.). The sandstones contain *Skolithos*, *Palaeophycus heberti*, *Palaeophycus tubularis*, *Diplocraterion*, *Cylindrichnus* and *Arenicolites*. *Rosselia* is also present. The upper portion of this unit (3.79-3.84 m) consists of sideritized mud and *Planolites* burrows. The upper contact is a knife-sharp erosional surface.

Unit 5 (3.84-4.06 m) rests abruptly on Unit 4, and consists of a polymictic chert conglomerate composed of well-rounded granules and pebbles interbedded with thick mud drapes (Facies 9). Biogenic structures are absent in this unit.

Unit 6 (4.06-4.32 m) consists of black shales and siltstones. Only *Planolites* burrows occur in the mud draping very-fine-grained sandstones lenses. This unit is erosively truncated.

Unit 7 (4.32-4.74 m) consists of a conglomerate comparable to Unit 5. Biogenic structures are not discernable.

Unit 8 (4.74-5.85 m) is composed of black shale with no sand layers nor any evidence of burrowing activity.

11-1-41-7W5 Core Description

Core 11-1-41-7W5, in the Southern Willesden Green Channel, does not have a complete ichnological data base (Figure 4.11). However, its sedimentary units and ichnofossil assemblage and distribution is similar to core 16-17-42-7W5 found in the North Willesden Green Channel.

This core provides several good specimens to be photographed. Many of these ichnospecies are found in the other Viking cores. However, the best photographs were taken of this core; therefore, Figures 4.12-4.14 show these specimens. Figure 4.12 shows *Asterosoma, Rosselia, Planolites* and *Palaeophycus tubularis*, common ichnofossils, in pervasively bioturbated sandstones (Facies 8J). Most deposits in this core are parallel-laminated and current-rippled sandstones. These deposits contain

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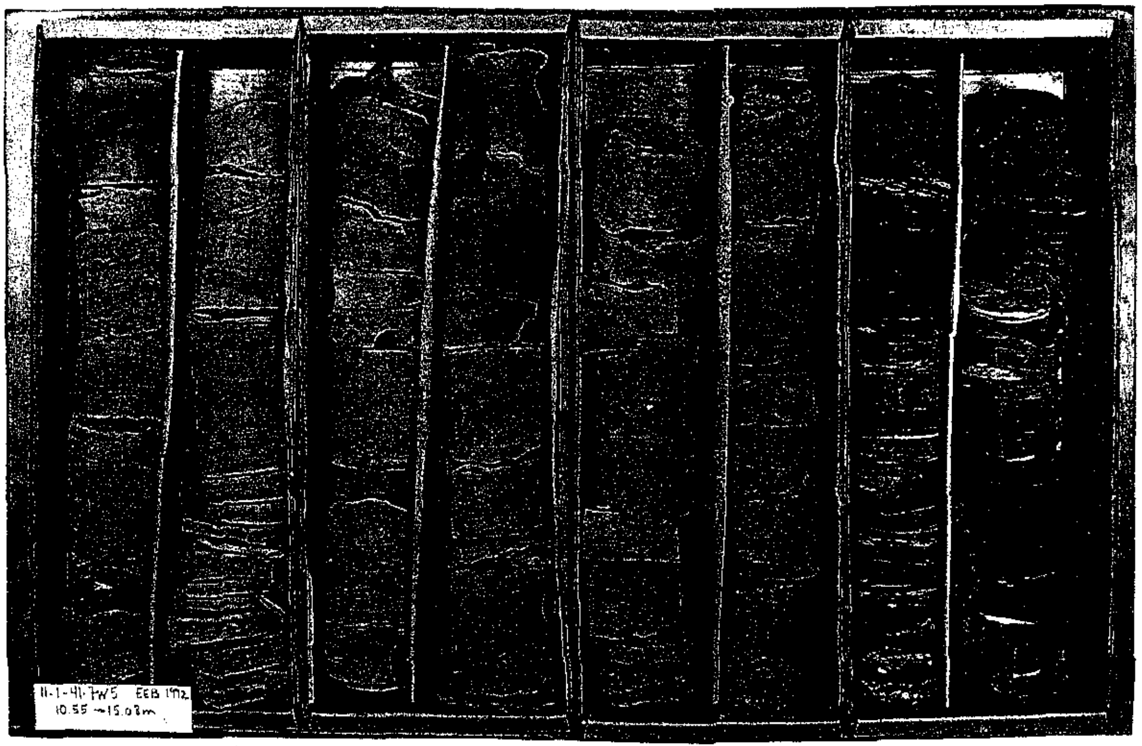

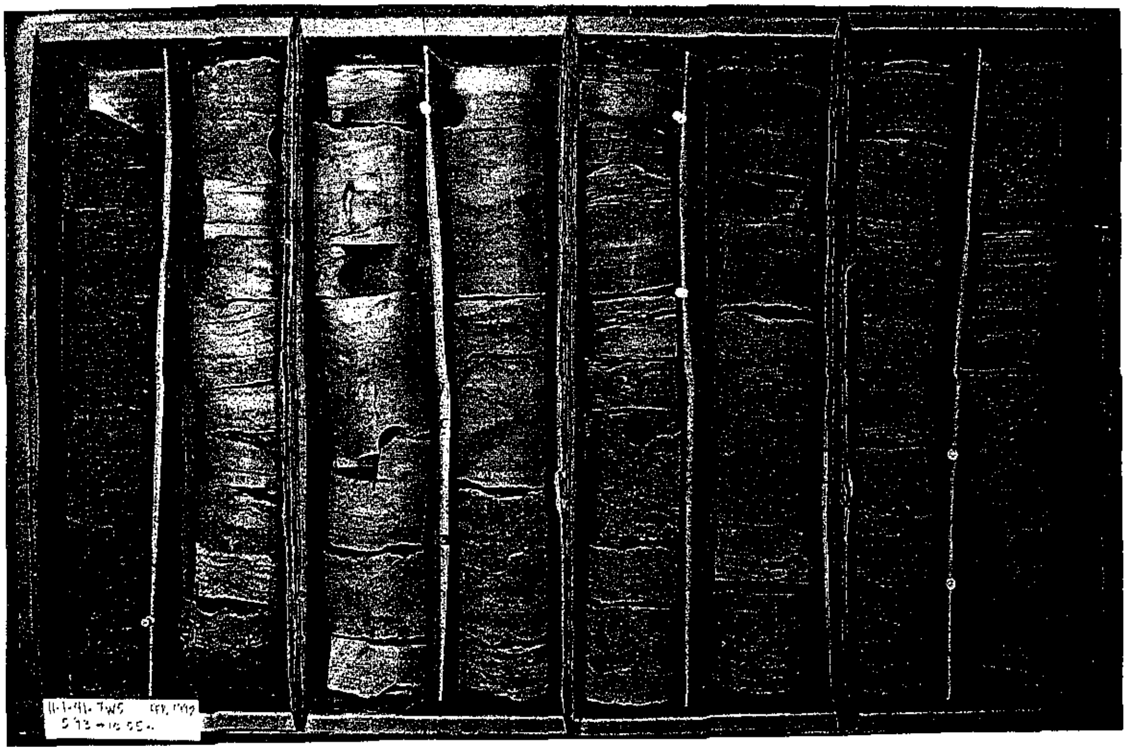

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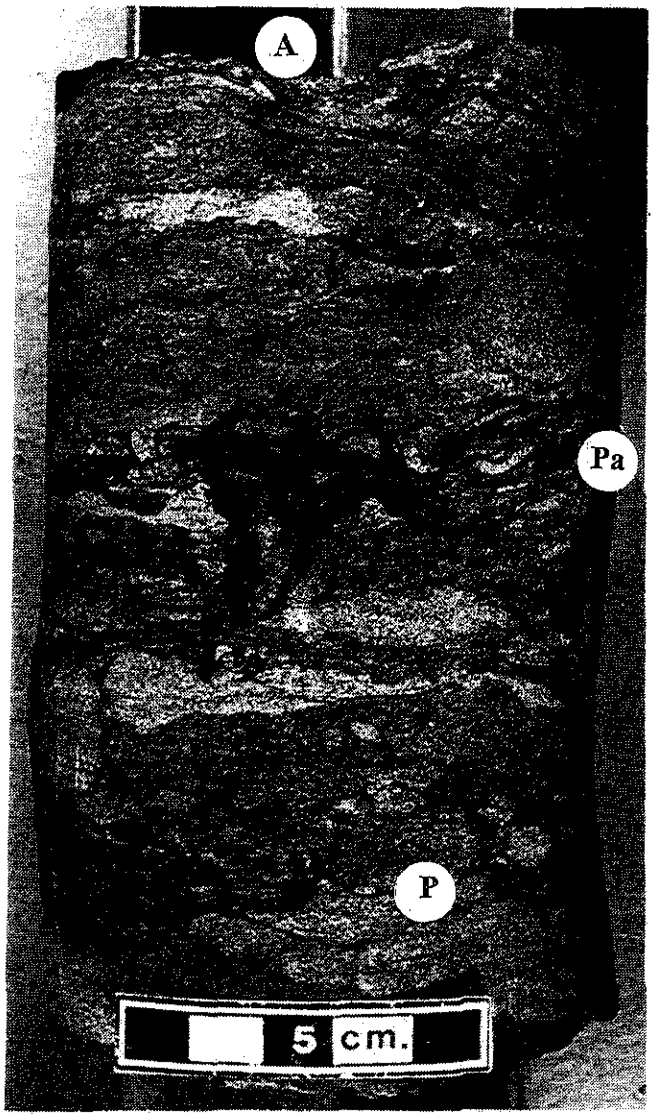
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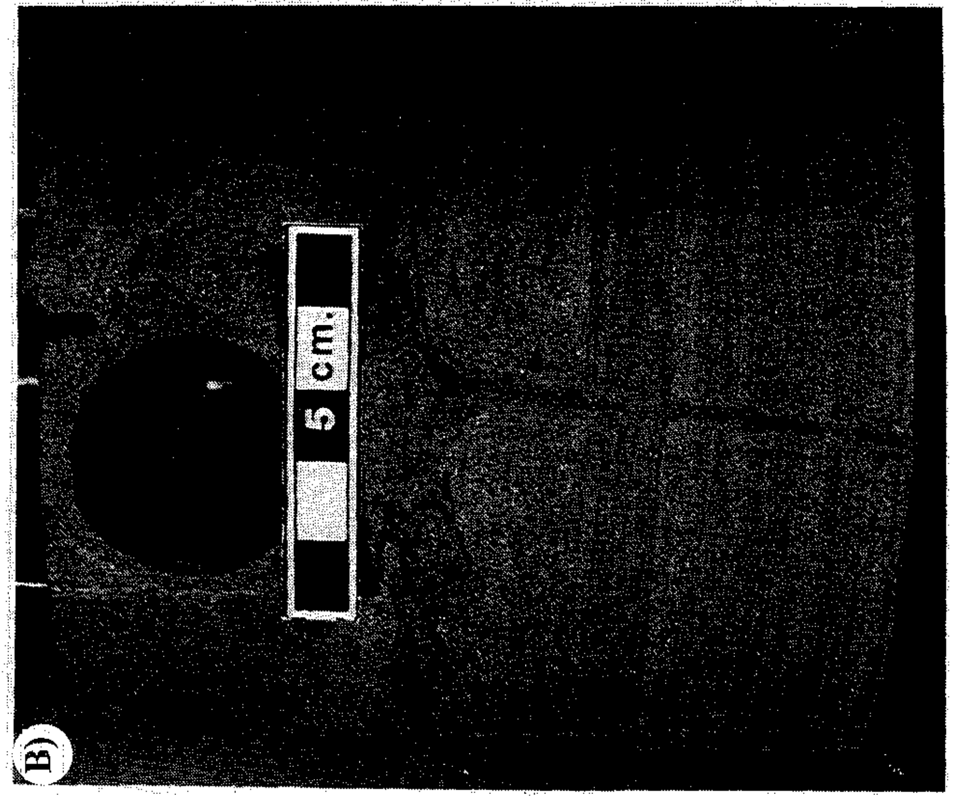
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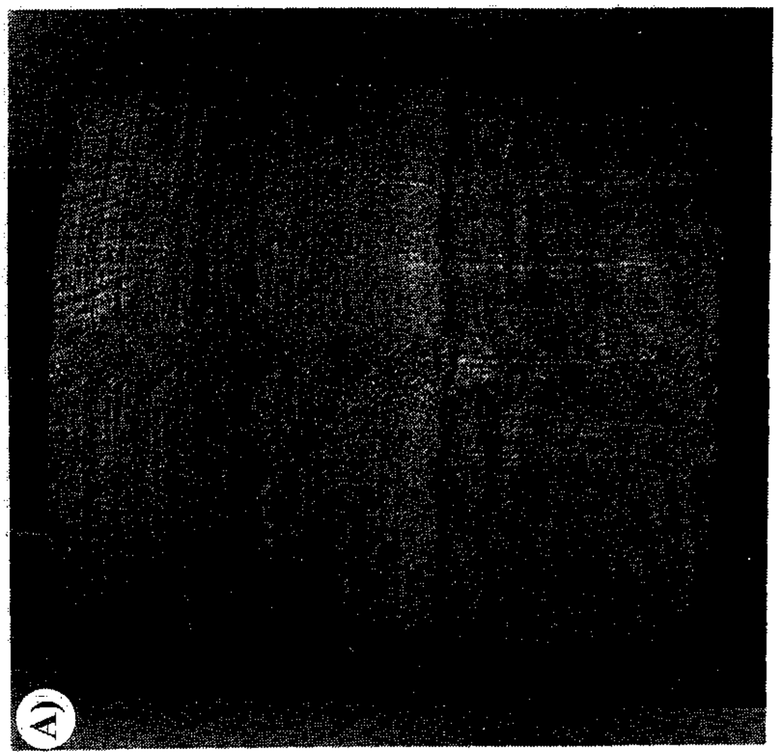

A)

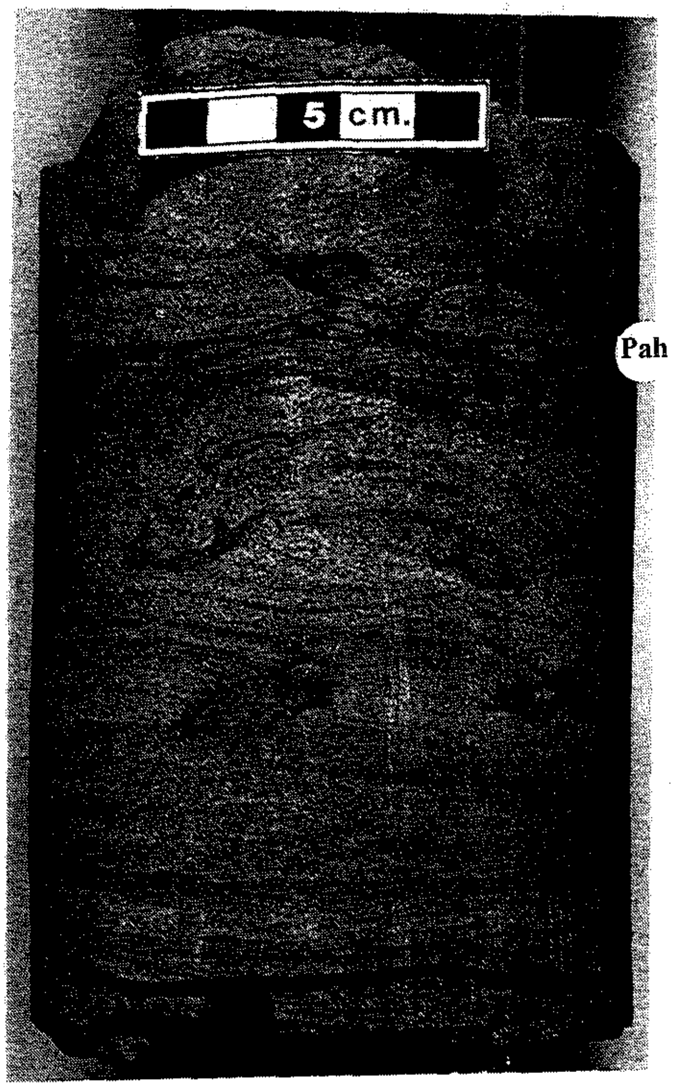


Figure 4.14 The horizontal tunnels of *Ophiomorpha* occur in other cores, but this photograph from 11-1-41-7W5 (9.70-9.84 m) shows several intersections of both *O. nodosa* and *O. irregulaire*. *Palaeophycus heberti* (Pah) also occurs in this wave-rippled sandstone.

fugichnia (escape traces), *Monocraterion* and *Skolithos* shafts. Mud drapes only contain the horizontal burrows of *Planolites* and *Palaeophycus* (Figure 4.13). *Ophiomorpha* is a common ichnofossil in the Viking sediments. Figure 4.14 shows the systematic difference between *Ophiomorpha nodosa* and *Ophiomorpha irregulaire.*

7-10-41-7W5 Core Description

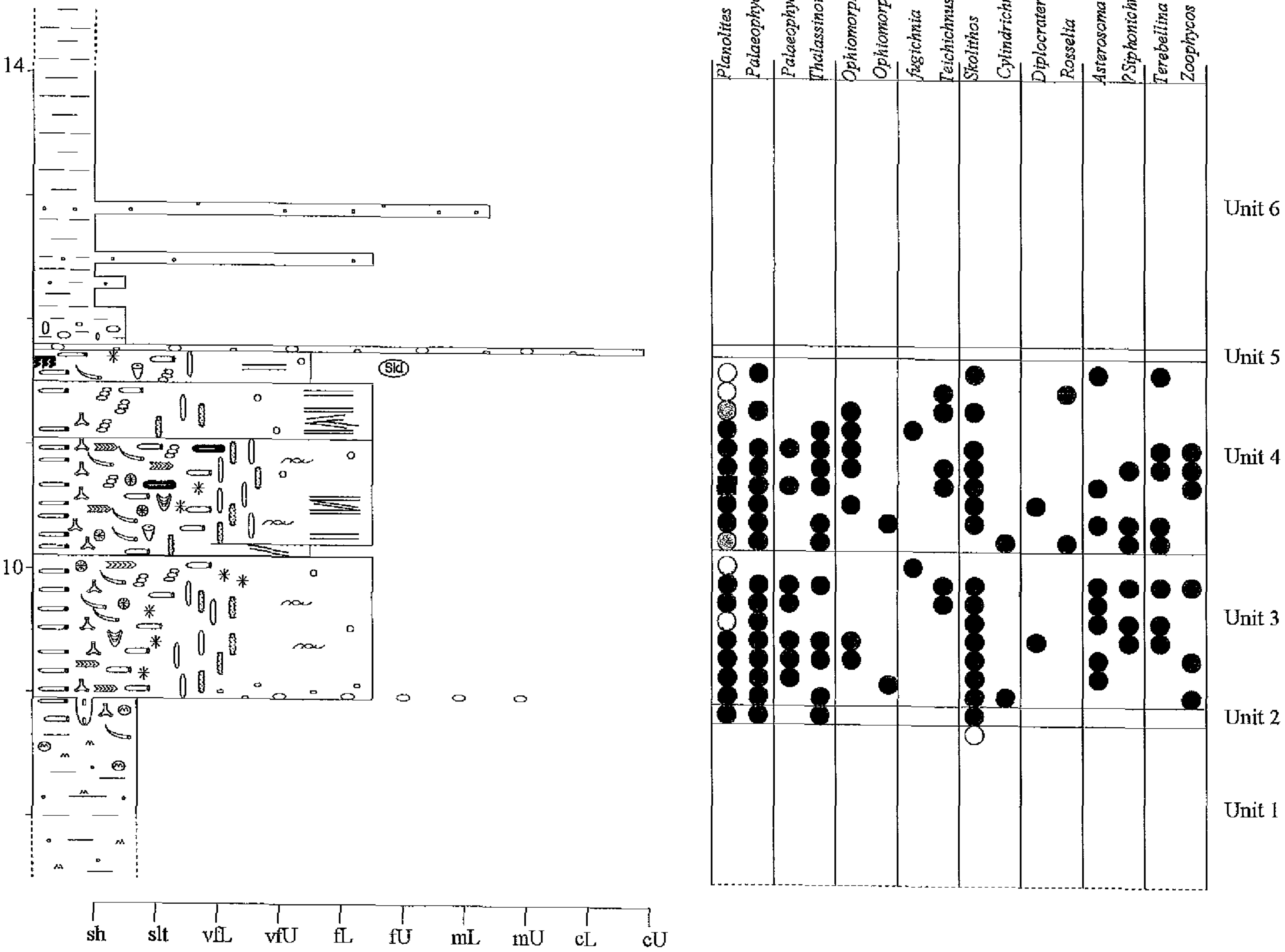
Of the 18.07 m cored in this location, only seven meters are shown in the lithology and the core box photograph (Figure 4.15). Five units are distinguished by physical structures and the diversity and relative abundances of the preserved biogenic assemblages.

Unit 1 (0-8.91 m) consists of intensely bioturbated siltstones (Facies 7) which have a "shredded" texture. *Helminthopsis* and *Anconichnus* are the most abundant traces, but *Chondrites*, *Schaubcylindrichnus* and *Terebellina* are also present. In the basal siltstones (0-2.25 m) pyrite is present. The upper contact of Unit 1 is sharp and erosive. Pebble-filled *Skolithos* burrows (4.18 i.p.s.a.) penetrate down into the siltstones.

Unit 2 (8.91-10.21 m) consists of poorly-sorted, pebbly, fine-grained sandstones (Facies 8K, Figure 4.16) that overlie the knife-sharp contact with Unit 1. The remainder of Unit 2 comprises parallel- to low-angle cross-rippled laminated-to-pervasively burrowed sandstones (Facies 8B). The trace assemblage is diverse (15 ichnospecies) and contains ethological patterns of both deposit- and suspension-feeders. These traces identified in this unit are: *Asterosoma*, *Cylindrichnus*, *Diplocraterion*, *fugichnia*, *Ophiomorpha irregulaire*, *Ophiomorpha nodosa*, *Palaeophycus heberti*, *Palaeophycus tubularis*, *Planolites*, *?Siphonichnus*, *Skolithos*, *Teichichnus*, *Terebellina*, *Thalassinoides* and *Zoophycos*. All standardized burrow intersections are fewer than 5.01 i.p.s.a., and most are fewer than 1.00 i.p.s.a. The upper Unit 2 boundary is sharp with a change in grain size from very-fine- to fine-grained sand (Unit 3) above this erosion surface.

A)

7-10-41-7W5
(18.07 m)



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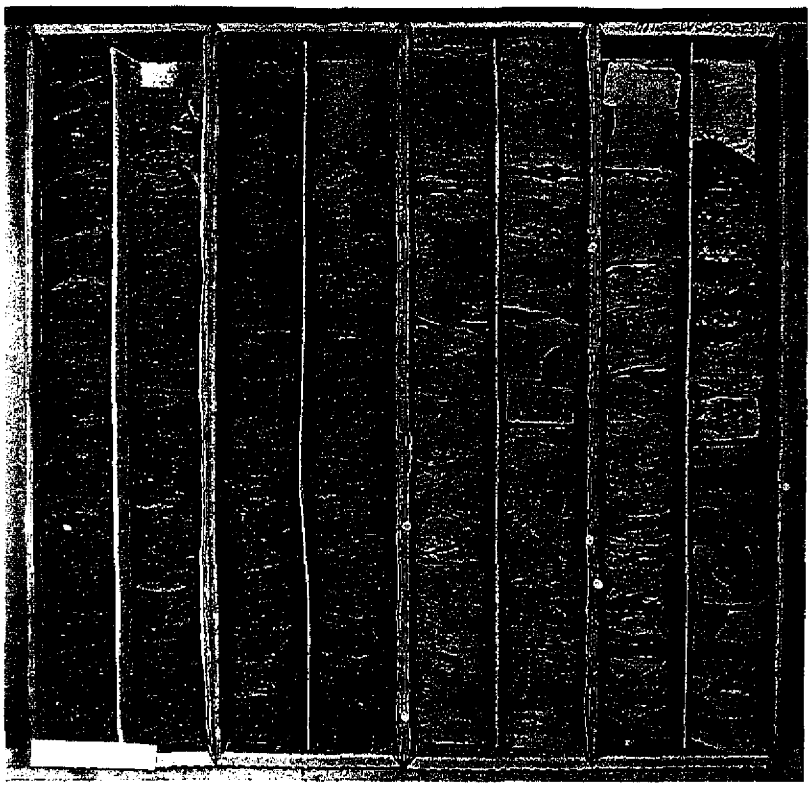

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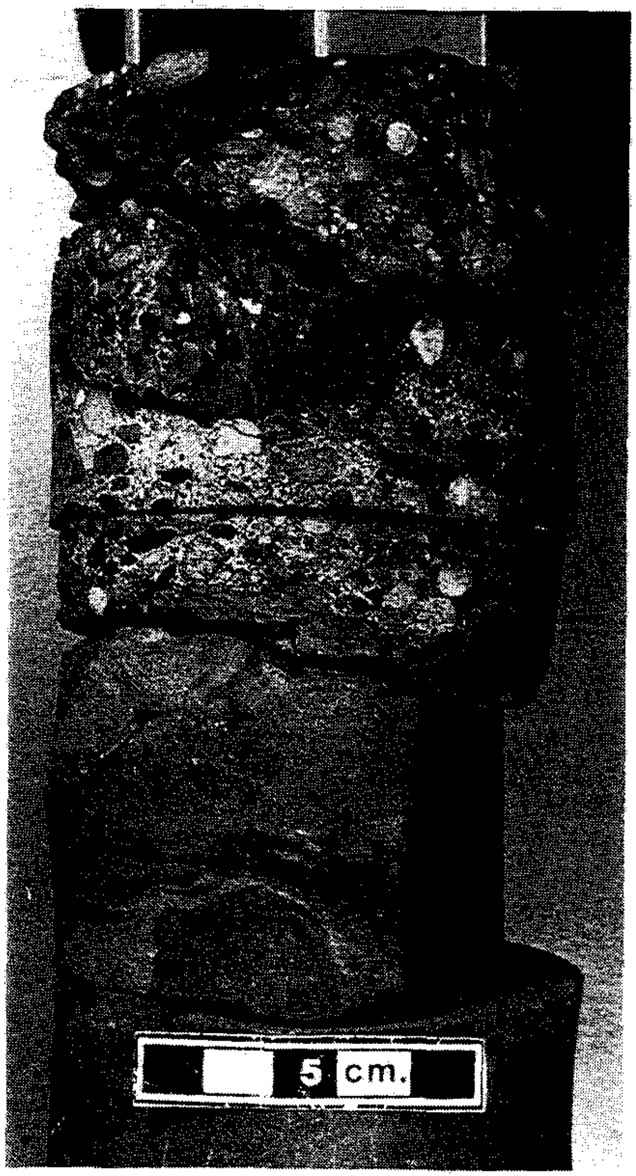


Figure 4.16 The contact between Unit 1 and Unit 2 is sharp and erosive (7-10-41-7W5, 8.98-9.18 m). In Unit 1, animals made the small *Ophiomorpha irregulaire* burrows before the siderization of the mud. Pebbly sandstones (Facies 8K) containing chert pebbles rest on the nonburrowed erosion surface. Intensely bioturbated siltstones occur above this erosion surface.

Unit 3 (10.21-11.70 m) is similar to Unit 2, parallel- and cross-rippled laminated sandstones with burrowed tops (Facies 8B). This fining upward unit is sharply truncated and overlain by conglomerates. It contains the same ichnospecies as Unit 2, and *Rosselia*. However, abundances are greater for each ichnospecies in Unit 3 than Unit 2.

Unit 4 (11.70-11.76 m) contains a clast-supported conglomerate that rests the basal erosion surface. This deposit contains well-rounded, poorly sorted chert pebbles. No trace fossils occur in this unit.

Unit 5 (11.76-18.07 m) consists of fissile black shale interstratified with medium-grained lenticular sandstones. Physical nor biogenic structures are discernable in this unit.

4.3 SUBSTRATE CHARACTERISTICS AND ICHNOFOSSIL ASSEMBLAGES

4.3.1 SUBSTRATE CHARACTERISTICS AND ICHNOFOSSIL ASSEMBLAGES: RESULTS

The lithologies documented in the South Willesden Green Channel are quantitatively classified into eight substrate groups based on the light reflected off the core surface, as described in Section 2.3.3. Although the Viking Alloformation substrate classification is similar to that of the Dunvegan, Substrate 2-Substrate 6 represent most of the Viking lithologies (Table 4.1). This suggests that the finer-grained Waskahigan sediments display more heterogeneity than the South Willesden Green sediments. Differences in sediment reflectivity result from the colour of the sediments. The "salt-and-pepper" Viking sandstones comprise grey and black chert grains that decrease sediment reflectivity. In comparison, the Dunvegan sandstones comprise beige sand grains and sideritic fragments, increasing sediment reflectivity.

Core surfaces representing the two most common substrate groups were suitably photographed to quantify the pale (sand) and dark (mud, silt and black chert) grains visually. Representative close-up photographs, using an extension tube, were taken of Substrate 4 and Substrate 6. Suitable photographs

South Willesden Green Channel
Substrate Types and Associated Facies and Ichnofossils

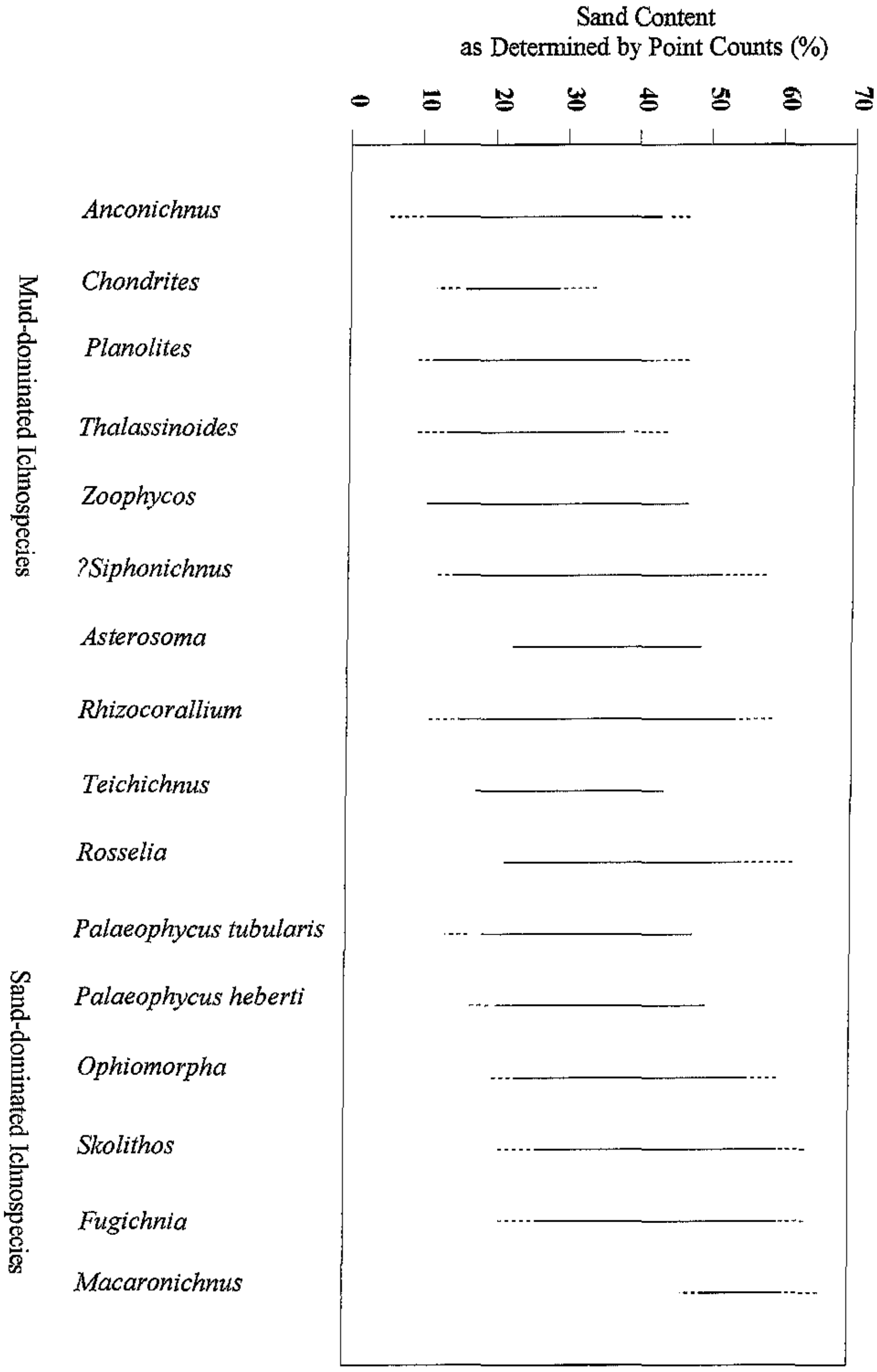
Substrate Type	% Dark Grain	% Pale Grain	Facies	Ichnofossils
Substrate 1			1C, 2, 7B	*Anconichnus, Asterosoma, Bergaueria, Chondrites, Helminthopsis, Palaeophycus heberti, Palaeophycus tubularis, Planolites, Schaubcylindrichnus, ?Siphonichnus, Teichichnus, Terebellina, Thalassinoides, Zoophycos*
Substrate 2			5, 6, 7A, 7B, 8B, 8K	*Anconichnus, Arenicolites, Asterosoma, Bergaueria, Chondrites, Cylindrichnus, fugichnia, Helminthopsis, Ophiomorpha, Palaeophycus heberti, Palaeophycus tubularis, Planolites, Rhizocorallium, Rosselia, Schaubcylindrichnus, ?Siphonichnus, Skolithos, Teichichnus, Terebellina, Thalassinoides, Zoophycos*
Substrate 3			8J, 9	*Anconichnus, Arenicolites, Asterosoma, Bergaueria, Chondrites, Cylindrichnus, Diplocraterion, Helminthopsis, Ophiomorpha, Palaeophycus heberti, Palaeophycus tubularis, Planolites, Rhizocorallium, Schaubcylindrichnus ?Siphonichnus, Skolithos Subphyllochorda, Teichichnus, Terebellina, Thalassinoides, Zoophycos*
Substrate 4	56	44	3C, 8D, 8E, 8F, 8G	*Anconichnus, Arenicolites, Asterosoma, Bergaueria, Chondrites, Cylindrichnus, fugichnia, Helminthopsis, Macaronichnus, Ophiomorpha, Palaeophycus heberti, Palaeophycus tubularis, Planolites, Rhizocorallium, Rosselia, Schaubcylindrichnus, ?Siphonichnus, Skolithos, Teichichnus, Terebellina, Thalassinoides, Zoophycos*
Substrate 5			8, 9	*Macaronichnus, Ophiomorpha, Palaeophycus heberti, Palaeophycus tubularis, Planolites, Skolithos*
Substrate 6	52	48	8A, 8B, 8D, 8E, 8F, 8G, 8I, 8J,	1) Rare traces or 2) *Asterosoma, Cylindrichnus, Macaronichnus, Ophiomorpha, Palaeophycus heberti, Palaeophycus tubularis, Planolites, Skolithos*
Substrate 7			8B, 8D, 8F	*Arenicolites, Asterosoma, Cylindrichnus, fugichnia, Macaronichnus, Ophiomorpha, Palaeophycus heberti, Palaeophycus tubularis, Planolites, Rhizocorallium, Rosselia, Skolithos, Teichichnus*
Substrate 8			8D, 8F	*Arenicolites, Asterosoma, Cylindrichnus, fugichnia, Macaronichnus, Ophiomorpha, Palaeophycus heberti, Palaeophycus tubularis, Planolites, Rosselia, Skolithos, Teichichnus*

were not taken of the other substrate groups during the summer of 1992. I made the assumption that Substrates 1-3 contain a higher percentage of dark grains (mud and silt) than Substrate 4. I assumed that Substrates 7-10 contain greater percentages of sand grains (white, light grey and reflective black chert). For example, Substrate 5 sediments would contain more pale grains than those associated with Substrate 4 (44%) but less than Substrate 6 (48%). This assumption worked well with the Dunvegan sediments. However, dark grey sandstones are more prominent in the coarser Viking sediments. The objective of these point counts (by number) of dark grains (mud, silt and dark grey-black chert) and pale (white, light grey sand) grains is to make generalizations pertaining to animal-sediment relationships in this incised channel. These generalizations will be compared to those recognized in the Waskahigan Bottleneck incised channel to determine if any similarities exist. Thin sections should have been sampled for a more accurate substrate analysis; however, these samples were not taken. This should be a future consideration in determining the usefulness of substrate groups as an analytical tool for biological aspect of ecological reconstructions.

The facies and trace fossils common to these substrate groups enabled generalizations to be made with regards to animal-sediment relationships (Tables 4.1-4.2).

Substrate 1 comprises carbonaceous shales (Facies 1C), blockstones (Facies 2) and sandy siltstones (Facies 7B). This substrate was not quantified but approximations can be inferred from the quantified Waskahigan substrate example (10% pale grains and 90% dark grains). Based on the facies characterized in the Viking Substrate 1, this sediment content is an acceptable assumption because the shale, mud and silt are dark brown to black in both substrate groups. The percentage of dark grains is not affected by dark chert grains.

The traces identified in these facies are: *Anconichnus*, *Asterosoma*, *Bergaueria*, *Chondrites*, *Helminthopsis*, *Palaeophycus heberti*, *Palaeophycus tubularis*, *Planolites*, *Schaubcylindrichnus*, *?Siphonichnus*, *Teichichnus*, *Terebellina*, *Thalassinoides* and *Zoophycos*. Most animals producing



Sand Content and Common Trace Fossils in the South Willesden Green Channel

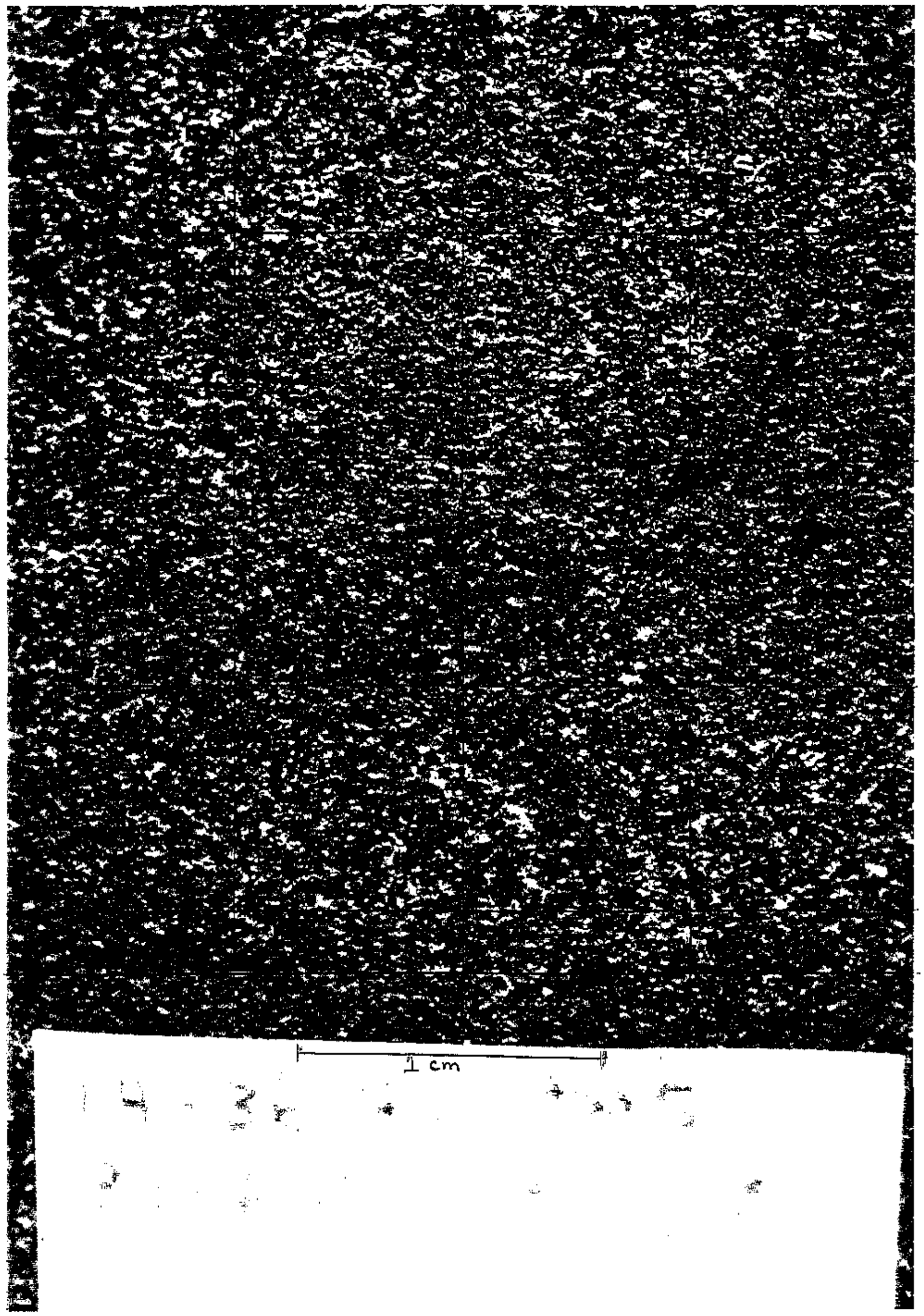
these ichnofossils dwell in muddy substrates but some burrow through sand beds.

Substrate 2 contains a wider variety of facies than Substrate 1, including blockstones, banded mudstones (Facies 5), pebbly mudstones (Facies 6), muddy and sandy siltstones (Facies 7A, 7B), laminated-to-burrowed sandstones (Facies 8B) and pebbly sandstones (Facies 8K). The Waskahigan substrate group consists of approximately 21% pale grains and 79% dark grains. However, the Viking substrate group contains more sand based on the facies and trace fossils. Enough mud and grey-black sand are present in the substrate for the core surface reflectivity to be low. The Viking sandstone facies (Facies 8K) is classified in this category because the black chert grains lower the reflectivity of the core surface. Twenty-one ichnospecies are identified: *Anconichnus*, *Arenicolites*, *Asterosoma*, *Bergaueria*, *Chondrites*, *Cylindrichnus*, *fugichnia*, *Helminthopsis*, *Ophiomorpha*, *Palaeophycus heberti*, *Palaeophycus tubularis*, *Planolites*, *Rhizocorallium*, *Rosselia*, *Schaubcylindrichnus*, *?Siphonichnus*, *Skolithos*, *Teichichnus*, *Terebellina*, *Thalassinoides* and *Zoophycos*. Trace fossils are not found in the pebbly mudstones and sandstones associated with this substrate group.

Substrate 3 contains fewer facies than the previous substrate groups. It comprises muddy siltstones, pervasively bioturbated sandstones (Facies 8J), pebbly sandstones and conglomerates (Facies 9). These facies reflect more light than Substrate 2 facies (more pale grains), but contain fewer pale grains (by number) than Substrate 4 (44%).

Most trace fossils occur in the pervasively bioturbated sandstones with some present in the muddy siltstones and the pebbly sandstones. Ichnofossils are absent in the conglomerates. The Substrate 3 trace assemblage is the same as Substrate 2, but also includes *Diplocraterion* and *Subphyllochorda*.

Substrate 4 represents most facies in the South Willesden Green channel: gritty mudstones (Facies 3C), siltstones, laminated-to-burrowed sandstones, parallel-laminated sandstones (Facies 8D), wave- and current-rippled sandstones (Facies 8E, 8F), cross-bedded sandstones (Facies 8G),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structureless sandstones (Facies 8I) and pervasively bioturbated sandstones. Figure 4.17 shows the core surface that was photographed (14-36-40-7W5) and counted. It suggests that the percentage of sand grains to mud and silt in Substrate 4 are 44% and 56%, respectively. These values are comparable to the Dunvegan Substrate 4 41% and 59%.

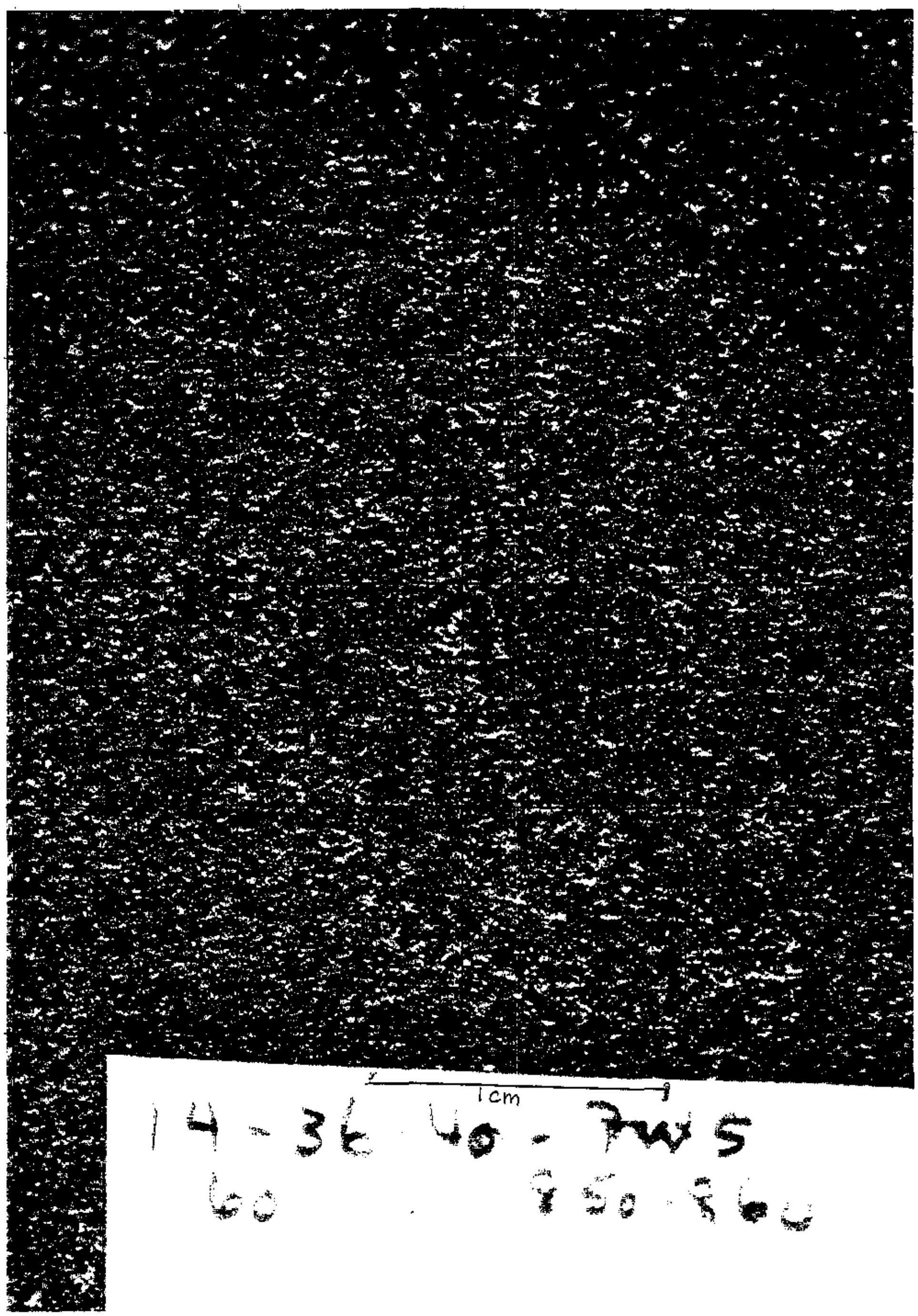
The vertical and horizontal traces present in the sediments of this substrate group are the same as those in Substrate 2: *Anconichnus*, *Arenicolites*, *Asterosoma*, *Bergaueria*, *Chondrites*, *Cylindrichnus*, *Helminthopsis*, *fugichnia*, *Macaronichnus*, *Ophiomorpha*, *Palaeophycus heberti*, *Palaeophycus tubularis*, *Planolites*, *Rhizocorallium*, *Rosselia*, *Schaubcylindrichnus*, *?Siphonichnus*, *Skolithos*, *Teichichnus*, *Terebellina*, *Thalassinoides* and *Zoophycos*. The facies common to this substrate group contain both mud-dwelling and sand-dwelling animals with the behavioural patterns of the latter preserved in sandier sediments.

Substrate 5 consists of sandstones and conglomerates. Most deposits are laminated-to-burrowed, parallel-laminated and pervasively bioturbated sandstones. Structureless and pebbly sandstones are also included in this substrate group.

The trace fossils present in the sandstones include *Macaronichnus*, *Ophiomorpha*, *Palaeophycus heberti*, *Palaeophycus tubularis*, and *Skolithos*. *Planolites* burrows dominate the traces preserved in mud drapes. The other traces listed in Table 4.1 rarely occur and have few i.p.s.a.s.

Substrate 6 contains muddy sandstones (Facies 8A), laminated-to-burrowed sandstones, parallel-laminated sandstones, current-rippled sandstones, structureless sandstones, cross-bedded sandstones and pervasively bioturbated sandstones. The quantified sample core surface (14-36-40-7W5, Figure 4.18) has 48% pale grains and 52% dark grains. Viking sandstones have fewer pale grains than those sandstones associated with Substrate 6 of the Waskahigan Channel (54% pale and 46% dark grains).

Most traces in Substrate 6 occur in the laminated-to-burrowed, parallel-laminated and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pervasively bioturbated sandstones. Few traces, if any, are present in the muddy sandstones (eg., *Cylindrichnus*, *Palaeophycus heberti* and *Planolites*). Discernable traces are absent in the current-rippled sandstones. *Cylindrichnus*, *Macaronichnus*, *Palaeophycus tubularis* are found in some cross-bedded sandstones. *Planolites*, *Skolithos* and *Ophiomorpha* occur in the structureless and pebbly sandstones. *Asterosoma* and *Palaeophycus* occur in the pebbly sandstones.

Substrate 7 represents three sandstones found in Substrate 6: laminated-to-burrowed, parallel-laminated and current-rippled sandstones. However, these sandstones contain a greater sand content based on higher reflectivities. The laminated-to-burrowed sandstones contain most traces associated with this substrate group. The following are trace fossils associated with Substrate 7: *Arenicolites*, *Asterosoma*, *Cylindrichnus*, *fugichnia*, *Macaronichnus*, *Ophiomorpha*, *Palaeophycus heberti*, *Palaeophycus tubularis*, *Planolites*, *Rhizocorallium*, *Rosselia*, *Skolithos* and *Teichichnus*.

Substrate 8 characterizes the cleanest sandstones in the South Willesden Green area: parallel-laminated (Facies 8D) and current-rippled sandstones (Facies 8F). These sandstones consist of pale to medium grey sand grains with few black grains. The pale sand content is greater than 48%, but less than 65%, based on the comparison with the Waskahigan Substrate 10. Eleven ichnofossils common in these sandstones: *Asterosoma*, *Arenicolites*, *Cylindrichnus*, *fugichnia*, *Macaronichnus*, *Ophiomorpha*, *Palaeophycus heberti*, *Palaeophycus tubularis*, *Rosselia*, *Skolithos* and *Teichichnus*. *Planolites* and *Thalassinoides* occur in mud drapes.

The point counts suggest that the Viking substrates contain more dark grains. The sediments are coarser (medium- to coarse-grained, grey to black sand and cobbles) than the Dunvegan sediments. Trace fossils common in Viking sediments are ethological patterns made by sand-dwelling animals in coarser-grained sediments (eg. *Macaronichnus*, *Ophiomorpha*, *Rosselia* and *Skolithos*).

4.3.2 SUBSTRATE CHARACTERISTICS AND ASSOCIATED ICHNOFOSSILS: IMPLICATIONS

The sediments measured in the Willesden Green channel were grouped into eight substrate groups, as described in Section 4.3.1. These substrate groups suggest this semi-quantitative substrate analysis has potential to predict the types of benthic animals that burrowed through the sediments and provide additional information regarding the ecology of the benthic environment. However, the current method of quantification must compare environments with similar sedimentology.

Trace fossils are not exclusive to one substrate group nor facies. Ichnofossil abundances vary according to the proportion of reflective grains (sand) and non-reflective grains (mud and silt). The repetition of facies suggests that the mode of deposition be the key factor for determining if a benthic animal will burrow through the sediment.

Ecological Implications

Substrate 1 has a sand content of approximately 10%. The sediments characterizing this substrate group include carbonaceous shales, blockstones and sandy siltstones. The animals that burrowed through these sediments were marine, based on the discernable biogenic structures: *Anconichnus*, *Chondrites*, *Helminthopsis*, *Planolites*, *Schaubcylindrichnus*, *Terebellina* and *Zoophycos*. These traces represent the *Cruziana* Ichnofacies (Seilacher, 1967; Carney, 1981; Ekdale, 1985, 1988; Pemberton *et al.*, 1992a, 1992b, 1992c). This ichnofacies supports Boreen's (1989) interpretation of a marine environment. The conditions of deposition maintained a steady rain of organic material and fine grain sediment to enable these deposit feeding animals to inhabit the sediment-water interface. In fine-grained sediments, *Planolites* animals can burrow without constructing horizontal feeding tubes. In other situations the mud and silt were loosely packed requiring the marine animals to construct agglutinated tubes. Substrate 1 represents the "Regional Viking" sediments (Allomembers A and B).

Substrate 2 comprises mudstones (Facies 5, 6), blockstones (Facies 2), siltstones (Facies 7) and sandstones (Facies 8B and 8K). Discernable traces are absent in the banded and pebbly mudstones and the pebbly sandstones. However, trace fossils are present in the other facies. *Anconichnus, Chondrites, Helminthopsis, Planolites, Rosselia, Schaubcylindrichnus, Terebellina* and *Zoophycos* are traces common to the *Cruziana* Ichnofacies and characteristic of the offshore/lower shoreface transition zone (Seilacher, 1967; Ekdale, 1985; Pemberton *et al.*, 1992a, 1992c). Sand-adapted animals produced *Arenicolites, Cylindrichnus, fugichnia, Macaronichnus, Ophiomorpha, Rhizocorallium* and *Skolithos* ethological patterns. Assemblages dominated by these traces characterize the *Skolithos* Ichnofacies (Seilacher, 1967; Ekdale, 1985; Pemberton *et al.*, 1992a, 1992c).

These marine traces are found in several depositional environments, but most are characteristic of the shoreface and intertidal zones. For example, *Macaronichnus segregatis* is diagnostic of high energy intertidal and subtidal environments (Clifton and Thompson, 1978). The combination of *Cruziana* and *Skolithos* Ichnofacies suggests that sediments were deposited under stressed conditions (Pemberton and Wightman, 1992; Ranger and Pemberton, 1992).

Substrate 3 comprises muddy siltstones, pervasively bioturbated and pebbly sandstones, and conglomerates. Most trace fossils occur in the pervasively bioturbated sandstones with some present in the muddy siltstones and the pebbly sandstones. Trace fossils are absent in the conglomerates. The Substrate 3 trace assemblage contains horizontal and vertical biogenic structures. *Diplocraterion* and *Subphyllochorda* suggest probable depositional environments in which these facies were deposited.

Diplocraterion shows the sediment-water interface changed because of sediment erosion and deposition, as reflected by the suspension-feeder's spreite (Bjerstedt and Erickson, 1989). This animal is common in moderate to high wave energy environments, sandy tidal flats and estuarine channel deposits (Ekdale, 1988; Bjerstedt and Erickson, 1989; Pemberton *et al.*, 1992c). Bjerstedt and Erickson (1989) suggest that *Diplocraterion* is a "tidalphile" and a useful indicator of intertidal and shallow subtidal environments. The *Skolithos* Ichnofacies comprises *Diplocraterion* and other vertical traces present in Substrate 3 facies. *Cruziana* Ichnofacies is also present in this substrate group, comprising the locomotion trace *Subphyllochorda* and other horizontal traces.

Substrate 4 comprises gritty mudstones, siltstones and several sandstones (Facies 8B, 8D, 8E, 8F, 8G, 8I, 8J). The trace assemblages present in these facies include behavioural patterns made by mud-dwelling and sand-dwelling animals; ethological patterns of the latter are present in the sandier facies.

The *Cruziana* Ichnofacies is characteristic of the muddier sediments of Substrate 4. Trace fossils representing this ichnofacies include: *Anconichnus*, *Chondrites*, *Helminthopsis*, *Planolites*, *Rosselia*, *?Siphonichnus*, *Terebellina* and *Zoophycos*. The *Cruziana* Ichnofacies is characteristic of quiet marine conditions of the offshore/lower shoreface transition (Ekdale, 1985, 1988; Frey and Howard, 1985, 1990; Pemberton *et al.*, 1992c).

The *Skolithos* Ichnofacies is characteristic of the sandier sediments grouped in Substrate 4. Vertical trace fossils representing this ichnofacies include: *Arenicolites*, *Cylindrichnus*, *Diplocraterion*, *fugichnia*, *Macaronichnus*, *Ophiomorpha*, *Rhizocorallium* and *Skolithos*. The *Skolithos* Ichnofacies characterizes moderate to high wave energy environments (Alpert, 1974; Clifton and Thompson, 1978; Frey *et al.*, 1978; Ekdale, 1985, 1988; Frey and Howard, 1985, 1990; Pemberton *et al.*, 1992c).

The different depositional environments suggest that the facies in Substrate 4 are not deposited by the same conditions but that they contain the same proportions of pale and dark grains.

Substrate 5 consists of sandstones (Facies 8B, 8D, 8I, 8J, 8K) and conglomerates. The trace assemblages in the sandstones are dominated by robust burrows made by animals adapted to the moderate to high wave energy environments (eg., *Macaronichnus*, *Ophiomorpha*, *Palaeophycus heberti*, *Palaeophycus tubularis* and *Skolithos*). *Planolites* is the dominant trace in the mud drapes. Sandstones contain: *Arenicolites*, *Asterosoma*, *Cylindrichnus*, *Diplocraterion*, *fugichnia*, *Rhizocorallium*, *Rosselia*, *?Siphonichnus*, *Subphyllochorda*, *Teichichnus*, *Thalassinoides* and *Zoophycos*. The trace fossil assemblages common in the facies of Substrate 5 represent a mixed *Skolithos* and *Cruziana* Ichnofacies.

Substrate 6 consists of muddy sandstones (Facies 8A), laminated-to-burrowed sandstones (Facies 8B), parallel-laminated (Facies 8D), current-rippled sandstones (Facies 8F), cross-bedded sandstones (Facies 8G), structureless sandstones (Facies 8I), pervasively bioturbated sandstones (Facies 8J) and pebbly sandstones. Most trace fossils are present in Facies 8B, 8D and 8J: *Arenicolites*, *Asterosoma*, *Cylindrichnus*, *Diplocraterion*, *fugichnia*, *Macaronichnus* (Facies 8G only), *Ophiomorpha*, *Palaeophycus heberti*, *Palaeophycus tubularis*, *Planolites*, *Rhizocorallium*, *Rosselia*, *?Siphonichnus*, *Skolithos*, *Subphyllochorda*, *Teichichnus*, *Thalassinoides* and *Zoophycos*. These biogenic structures represent the *Skolithos* Ichnofacies with a few traces representing the *Cruziana* Ichnofacies. Most deposit-feeders cannot adapt to moderate to high wave energy and sedimentation (rates and grain size) in probable intertidal and subtidal environments (Ekdale, 1985, Pemberton *et al.*, 1992a, 1992b, 1992c).

Substrate 7 represents three cleaner sandstone facies present in Substrate 6 (Facies 8B, 8D, 8F). The laminated-to-burrowed sandstones (Facies 8B) contain most traces associated with these sandstones in the other substrate groups. The trace fossils present are robust structures (eg., *Ophiomorpha*) and the animals are adapted to swift currents and shifting substrates (eg., *Skolithos* and *Macaronichnus*) (Pemberton *et al.*, 1992c, Howard and Frey, 1984). These ichnofossils characterize the *Skolithos* Ichnofacies.

Substrate 8 typifies the cleanest sandstones in the South Willesden Green area: parallel-laminated (Facies 8D) and current-rippled sandstones (Facies 8F). Parallel-laminated sandstones contain thirteen ichnospecies: *Asterosoma*, *Arenicolites*, *Cylindrichnus*, *fugichnia*, *Macaronichnus*, *Ophiomorpha*, *Palaeophycus heberti*, *Palaeophycus tubularis*, *Planolites*, *Rosselia*, *Skolithos*, *Teichichnus* and *Thalassinoides*. The current-rippled sands are deposited under conditions too stressful for benthic animals. *Macaronichnus* preservation is rare because sand beds are thinner than one metre (Clifton and Thompson, 1978). *Fugichnia* support these bed thicknesses because the traces suggest that sand beds were deposited in thicknesses less than 30 cm (Nichols *et al.*, 1978). These traces represent the *Skolithos* Ichnofacies in moderate to high energy environments that are marine or marginal-marine (Ekdale, 1985, Pemberton *et al.*, 1992a, 1992b, 1992c).

Generalizations can still be made regarding these sandstones based on the trace fossils present in the deposit. The grain size, composition and consistency of sediment limit the type of invertebrates, and consequently biogenic structures, that can exist in the sediment. For example, the trace assemblages in laminated-to-burrowed sandstones (Facies 8B), characterized by Substrate 2, differ from those in Substrate 7 based on the quantity of dark grains, particularly mud particles. The thickness of individual sand layers will also influence the substrate group. If a facies is common to many substrate groups, the thickness of the individual beds governs the substrate group. For example, laminated-to-burrowed sandstones in Substrate 7 are thicker and contain more sand-adapted traces than those in Substrate 2. This facies in Substrate 2 is thinner and contains more organic debris and mud. The traces occurring in this facies can be used to imply changes in pale/dark grain percentages.

Ichnospecies Predictability

With substrate analysis, one can sort facies by pale and dark grain percentages. Most benthic structures are not exclusive to one facies or substrate group, as shown in Table 4.1. Trace fossils occur in sediments comprising specific properties and resulting from specific depositional conditions. In the South Willesden Green incised valley, the presence or absence of eight ichnospecies is predictable in certain sediments. This section addresses the predictability of these trace fossils: *Planolites*, *Rhizocorallium*, *Teichichnus*, *Palaeophycus heberti*, *Skolithos*, *Macaronichnus*, *Ophiomorpha* and *Rosselia*.

Planolites

These simple, unlined burrows are preserved in most facies measured in the cores, but are concentrated in mud drapes deposited from suspension during waning flow stages. Mud drapes (Facies 1C) are associated with Substrates 1 and 2 in the South Willesden Green channel. This facies is characteristic of Substrate 2 in the Waskahigan channel.

Rhizocorallium

These horizontal U-shaped burrows occur in sediments with an approximate ratio of 50% pale grain (sand) and 50% dark grain (mud and silt) (eg., muddy siltstones, laminated-to-burrowed sandstones and pervasively bioturbated sandstones). These facies are present in Substrate 4 and Substrate 6 and contain 56% and 52% dark grains, respectively. Observations show that the sediment comprises of mud and sand. The percentage of dark grains is higher than cited for the Waskahigan Channel (46%) because some sand grains are black chert.

Teichichnus

The vertically stacked horizontal tubes characteristic of *Teichichnus* are present in Substrates 1-8 (as are *Palaeophycus heberti* burrows), but it is most common in Substrates 4 and 6. The following facies contain *Teichichnus* burrows: carbonaceous shales (Facies 1C), blockstones (Facies 2), laminated-to-burrowed sandstones (Facies 8B), parallel-laminated sandstones (Facies 8D) and pervasively bioturbated sandstones (Facies 8J). This trace fossil occurs in the sand layers in shales and sand deposits with a pale grain (sand) percentage of 44-48%. The corresponding value in the Waskahigan sediment is 54% pale grains. The difference in percentage is related to the black chert common in South Willesden Green sandstones.

Palaeophycus heberti

This horizontal, lined burrow resembles *Palaeophycus tubularis* but has a thicker, granular burrow wall. This trace fossil commonly occurs in fine- to medium-grained laminated-to-burrowed sandstones (Facies 8B), parallel-laminated sandstones (Facies 8D) and pervasively bioturbated sandstones (Facies 8J) and less frequently in the gritty mudstone (Facies 3C). In the South Willesden Green Channel, *Palaeophycus heberti* is characteristic of Substrates 2-8, whereas in the Waskahigan Channel it is characteristic of Substrates 7 and 8, consisting of sand with no dark sand grains (eg., chert). Substrate 4 in the South Willesden Green has 44% sand grains as compared with 62% in Substrate 8 of the Waskahigan Channel. *Palaeophycus heberti* is more common in Viking sandstones than Dunvegan sandstones (wave-rippled and pervasively bioturbated sandstones) due to the coarser sandstone deposits (fine- to medium-grained sand).

Skolithos

Viking facies containing *Skolithos* shafts are as predictable as those containing *Planolites* burrows: event beds in siltstones (Facies 7A), gritty mudstones (Facies 3C), laminated-to-burrowed sandstones (Facies 8B), parallel-laminated sandstones (Facies 8D), structureless sandstones (Facies 8I), pervasively bioturbated sandstones (Facies 8J) and pebbly sandstones (Facies 8K). These facies are characteristic of Substrates 1-8, but *Skolithos* shafts are concentrated in sandstones containing few clay particles. These observations are comparable to the Waskahigan facies. The pale grain range in which *Skolithos* shafts are common is 48-65%, corresponding to Substrate 6 of the South Willesden Green Channel and Substrate 10 of the Waskahigan Channel, respectively. The variation in pale grain content relates to the dark chert grains present in the Viking sandstones.

Macaronichnus, *Ophiomorpha* and *Rosselia* are three trace fossils that are absent from the Waskahigan Channel deposits. However, they are predictable in Willesden Green Channel deposits.

These traces are present because the Viking sediments in which they occur are coarser-grained than the Dunvegan deposits.

Macaronichnus

The horizontal burrows found in clean sand have a heavy mineral boundary that separates the burrow fill and the surrounding matrix (Clifton and Thompson, 1978). *Macaronichnus segregatis* intersections are present in laminated-to-burrowed (Facies 8B), parallel-laminated (Facies 8D) and cross-bedded sandstones (8G). These facies are common to Substrates 4-8, but *Macaronichnus* is more common in sediments associated with Substrate 8. This suggests that the animal producing this trace preferred sediment with a pale grain (sand) percentage greater than 48% (Substrate 6).

Ophiomorpha

These robust burrows, lined with faecal pellets, occur in various sandy facies (Facies 3C, 8B, 8D, 8I, 8K and 8J). These facies are characteristic of several substrate groups. Substrate 5 contains these facies except the gritty mudstones (Facies 3C). *Ophiomorpha* is most common in laminated-to-burrowed sandstones (Facies 8B). The pale grain percentage is between 44% and 48% based on point counts. These grey, fine- to medium-grained sandstones contain black faecal pellets and some clay particles.

Rosselia

This vertical to oblique bulbous biogenic structure has concentric laminae surrounding its shaft. *Rosselia* is common in laminated-to-burrowed (Facies 8B), parallel-laminated (Facies 8D) and pervasively bioturbated sandstones (Facies 8J). These sandstones are common to Substrates 3-8. The dark grain (mud and silt) content is approximately 52%, using Substrate 6 as the approximate percentage because *Rosselia* occurs more frequently in this substrate group. A sediment that contains *Rosselia* may have *Asterosoma* as a member of its trace assemblage.

The preservation of *in situ* biogenic structures is dependent on erosion and biogenic reworking. Trace fossil predictability in certain deposits is beneficial when reconstructing the palaeoecology of a benthic community. If one could predict trace fossil assemblages, probable ecological parameters could be suggested.

4.4 STATISTICAL ANALYSIS

4.4.1 STATISTICAL ANALYSIS: RESULTS

As in the Waskahigan Bottleneck Channel (Dunvegan Alloformation), cores in the South Willesden Green Channel (Viking Alloformation) have certain traces that frequently occur together in sediment intervals. Correlations were done on seventeen trace pairs to detect if they represent true relationships between animals and the substrate or are the result of preservation biases. The number of trace intersections per standard area is the only quantified parameter available in the Viking channel.

These correlations suggest most trace fossil pairs and the synaeresis crack associations in the South Willesden Green Channel are not statistically significant. The size of the sample populations used are too small to be statistically significant, fewer than 30 intervals were used. This suggests that more parameters (eg., sediment, time and noncontemporaneous populations) control these trace pairs. Trace associations involving *Skolithos* shafts correlated well for core intervals containing *Thalassinoides* and *Teichichnus* burrows. The *Skolithos-Thalassinoides* association correlated better in the South Willesden Green Channel than in the Waskahigan Bottleneck Channel.

These trace fossil associations are useful in determining if an ichnospecies had the potential for preservation in certain facies. For example, deposit-feeding burrows generally correlate poorly with suspension-feeding traces. However, two different deposit-feeding traces or two different suspension-feeding traces correlate well. In the South Willesden Green Channel, the suspension-feeding/ dwelling shaft *Skolithos* correlates well with the deposit-feeding/ dwelling structures *Thalassinoides* and

Teichichnus. Ichnospecies correlations show that ichnofossils with similar ethological patterns or trophic function correlate.

Skolithos-Thalassinoides Association

Statistically, *Skolithos* shafts and *Thalassinoides* burrows are the best trace association in the Viking channel. These intersections are preserved together in twenty-eight intervals. This association is most common in laminated-to-burrowed sandstones (Facies 8B) and pervasively bioturbated sandstones (Facies 8J). It can also occur in siltstones (Facies 7) below transgressively modified regression surfaces of erosion that define the base of the incised valley. *Thalassinoides* burrows are found in thick muds draping sand beds.

Skolithos-Teichichnus Association

Skolithos and *Teichichnus* burrows are preserved together in fourteen intervals. This association occurs in laminated-to-burrowed sandstones (Facies 8B), wave- and current-rippled sandstones (Facies 8E -8F) and pervasively bioturbated sandstones (Facies 8J).

Synaeresis Crack Associations

*Thalassinoides*and *Planolites* burrow intersections occur in mud drapes containing synaeresis cracks. Sediments containing these shrinkage cracks were subject to salinity fluctuations (Plummer and Gostin, 1981). The association with *Thalassinoides* is correlates well, whereas that with *Planolites does* not. This association is common in banded mudstones, laminated-to-burrowed sandstones, wave- and current-rippled sandstones, parallel-laminated sandstones and pervasively bioturbated sandstones.

4.4.2 STATISTICAL ANALYSIS: A DISCUSSION

Most trace fossil pairs tested were not statistically significant. This suggests that preservation in a particular sediment rely on more factors than ethological patterns. However,correlation answered a key question; could animals, producing these ethological patterns, have been members of a contemporaneous benthic population? Statistically significant trace fossil associations, based on small sample populations, suggest that the animals could have belonged to the same benthic population, but this must be corroborated with physical evidence such as the absence of crosscutting relationships (Bromley, 1990).

Overall, vertical dwelling structures did not correlate with horizontal feeding traces. This reflects environmental parameters, such as wave-energy, turbidity and grain movement, acting on the sediment-water interfaces during colonization. Suspension-feeders occurring in sandy substrates require moderate to high energy waves to bring nutrients and low to no turbidity so that filter-feeding apparatus do not clog. Horizontal deposit-feeders found in muddy substrates require low wave energy or waning flows. Turbidity affects the organisms by supplying nutrients to the sediment-water interface.

Skolithos-Thalassinoides Association

This association of vertical and horizontal biogenic structures reflect similar trophic functions (eg., feeding and dwelling). *Skolithos* shafts are typical of clean sand deposited under moderate to high current energies (Alpert, 1974; Pemberton and MacEachern, 1994). *Thalassinoides* burrows are characteristically preserved in firm, potentially dewatered mud and thick mud drapes that are overlain by coarser sediments (Pemberton and Frey, 1982, 1990). *Skolithos* is a domicile shaft produced by annelids, brachiopods or phoronids (Alpert, 1974; Häntzschel, 1975). It is also suggested that vermiform suspension-feeders or passive carnivores make this simple vertical shaft (Frey and Howard, 1990; Pemberton *et al.*, 1992c). *Thalassinoides* burrows represent nonreinforced, box-like structures of animals analogous to the intertidal *Callianassa* shrimp (Häntzschel, 1975; Pemberton and Frey, 1982; Ekdale, 1985; Frey and Howard, 1985). These burrows act as dwelling structures for these animals. These biogenic structures are most common in interbedded mudstones and sandstones (Facies 3B, 8B).

Skolithos-Teichichnus Association

Intervals containing *Skolithos* and *Teichichnus* correlated well because both traces are made by animals adapted to sandy environments. However, the trophic functions of these animals differ. *Skolithos* is a vertical dwelling for a suspension-feeding or a feeding-dwelling structure of a deposit-feeding vermiform (Häntzschel, 1975; Frey and Howard, 1985, 1990). The trace *Teichichnus* consists of simple, vertically stacked horizontal burrows created by retrusive spreiten (Häntzschel, 1975; Frey and Howard, 1985, 1990). It is interpreted as a feeding or combined feeding-dwelling structure of a vermiform animal (Frey and Howard, 1990). The retrusive spreiten reflect its vertical movement through the sediment and the active or passive filling of the horizontal burrow (Frey and Howard, 1985, 1990). In pervasively bioturbated sandstones these trace fossils can coexist but they may not be contemporaneous (Bromley, 1990).

Synaeresis Crack Associations

Synaeresis cracks and *Thalassinoides* burrows correlate well. The ecological generalizations regarding these deposit-feeders and shrinkage cracks suggest that as salinities fluctuated at the sediment-water interface, the abundance of preserved *Thalassinoides* burrows changed (increased or decreased) in successive intervals next to mud containing synaeresis cracks. These observations must be tested further with greater sample sizes because this correlation is based on four intervals containing both burrows and cracks. The analyses of this association did not correlate in the larger Dunvegan sample (n=7).

Most South Willesden Green trace fossil relationships are not statistically significant because more than one dependent factor (eg., salinity, hydraulic circulation, substrate and/or sedimentary processes) caused a physical bias in trace fossil preservation (Scott, 1978; Frey and Seilacher, 1980; Carney, 1981; Birks, 1985; Allison and Briggs, 1991). Nonquantified variables bias the linear regression results because a trace is tested against another trace and not a physical parameter such as wave energy. Regression outputs show most tracemakers are dependent on parameters other than a specific tracemaker. Another difficulty in this analysis is the lack of time constraints in core sediments. Crosscutting relationships are absent, thus making it difficult to distinguishing successions within specific biogenic assemblages.

The substrate is a key factor for the apparent trace pairs in the South Willesden Green Channel. Certain tracemakers prefer specific substrate textures (eg., grain size and mud-to-sand ratios) and wave energies. Of these trace pairs, some traces are predictable concerning facies or type of sediment. *Planolites* occurs primarily in mud drapes and shales interbedded with sand. These sediments have a dark grain percentage of approximately 90%. Other horizontal traces are associated with this trace fossil; whereas *Skolithos* and other vertical traces are infrequent expect in pervasively bioturbated sediment. *Rhizocorallium* is a trace that is found in sediments having ≈50% dark grains (mud and silt). Traces, such as *Macronichnus*, *Ophiomorpha* and *Palaeophycus heberti*, are more abundant in the Viking cores than Dunvegan cores. This relates to grain size and environmental conditions (eg., wave energy, sediment stability) at the sediment-water interface. The medium-grained sand also contains little mud and organic debris. These traces, excluding *Macronichnus*, have burrow walls that support the structure from collapse. The association of substrates and trace fossils permits sediment-water interface colonization to be better understood.

4.5 ENVIRONMENTAL CORE INTERPRETATIONS

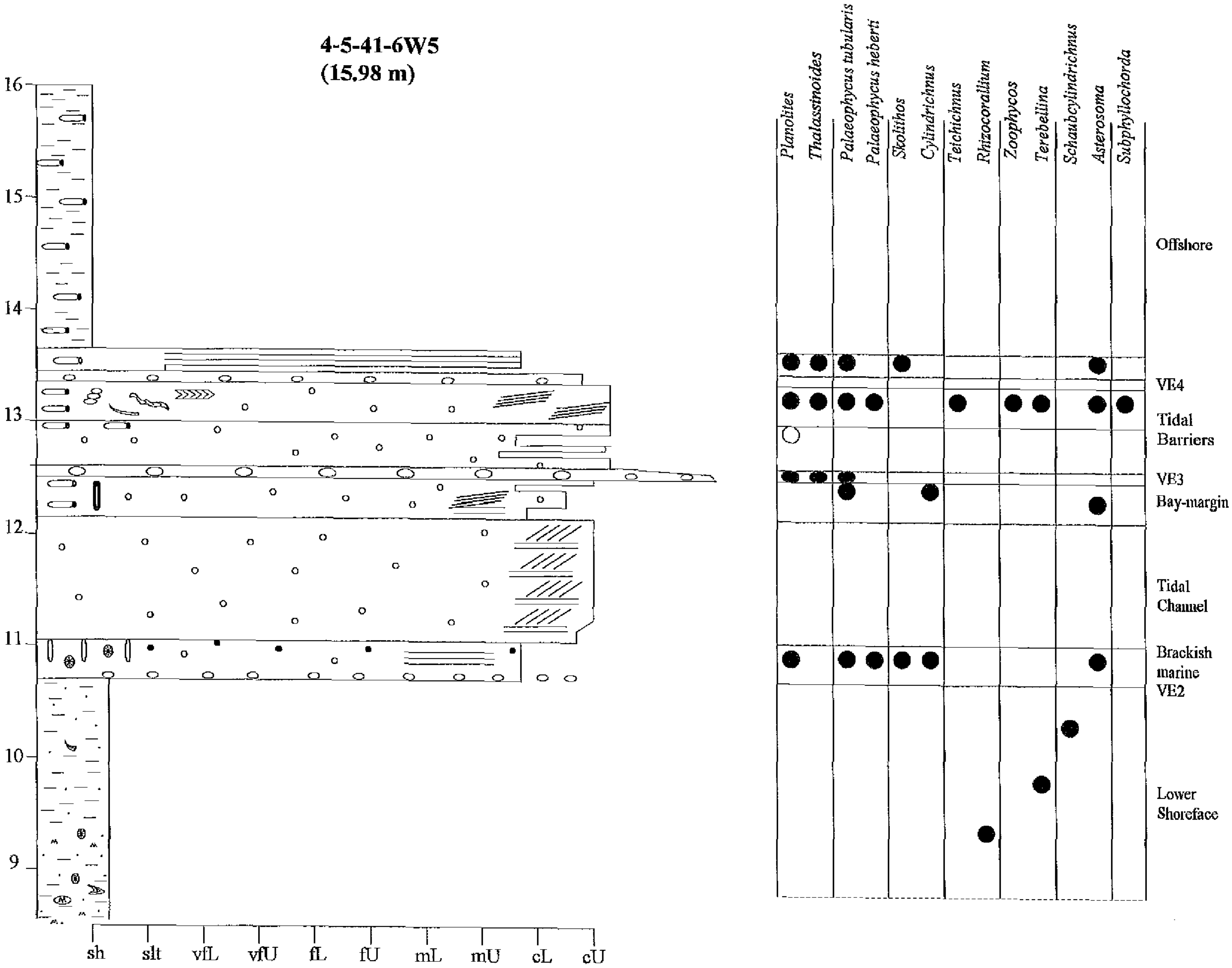
The Viking cores are interpreted in the same order as described: from the most seaward core (4-5-41-6W5) to the most landward core (7-10-41-7W5). These interpretations depend on the quantification of trace fossils to distinguish between different units containing comparable physical sedimentary structures. These environmental interpretations are based sedimentary facies, trace fossil assemblages (see Section 4.2) and the succession of depositional environments in each core. The core figures in Section 4.2 are modified to display depositional environments instead of unit numbers.

The trace fossil assemblages are characteristic of the *Skolithos* and *Cruziana* Ichnofacies. These ichnofacies suggest potential environmental conditions (eg., sediment stability and consistency, and salinity fluctuations) that existed as the South Willesden Green channel infilled and benthic communities colonized the sediments. These ecological conditions affected the diversity and abundances of the individual traces in these assemblages. These variations support the following environmental interpretations and enable generalizations to be made concerning the palaeoecology and palaeogeography of the South Willesden Green incised valley (Section 4.6).

4-5-41-6W5 Core Interpretation

The ten depositional units in this 15.98 m core contain a variety of medium- to coarse-grained facies (Figure 4.19). Bioturbation is rare, with burrow intersections ranging from 0.07 i.p.s.a. to 4.70 i.p.s.a.

4-5-41-6W5
(15.98 m)



Unit 1 (0-10.72 m) is interpreted as offshore marine deposits associated with "Regional Viking" silty mudstones. The traces present in this unit are characteristic of marine organisms associated with the *Cruziana* Ichnofacies. Few pebbles mantle the contact between Unit 1 and Unit 2. Passively-filled vertical dwelling structures are absent (i.e., no *Glossifungites* Ichnofacies). The absence of these burrows suggests that the channel erosion surface (VE2) subaqueously truncated the marine sediments of Allomember A.

Unit 2 (10.72-11.06 m) contains horizontally oriented sand- and mud-adapted ichnospecies (e.g., *Asterosoma*, *Palaeophycus heberti*, *Palaeophycus tubularis* and *Planolites*). This unit is interpreted as a brackish water environment due to their abundance and restricted diversity in the mudstones and fine-grained siltstones. Few animals can survive the upper-flow regime as showed by the presence of parallel-laminated sandstones. These sandstones are frequent neither enough nor thick enough to support the burrowing activity of suspension-feeders. The assemblage is dominated by non-suspension-feeders due to the turbidity during mud deposition. The pebbles scattered at the unit's upper contact suggest two apparent stages of the fill (Boreen, 1989). The trace fossil assemblage supports this as reflected in the change of trace fossil assemblages.

Unit 3 (11.06-12.18 m) consists of a nonburrowed, coarsening upwards unit of parallel-laminated, medium-grained sandstones interbedded with planar-trough, cross-bedded sandstones. This unit is interpreted as a tidal channel deposit in the estuarine mouth of this tripartite estuarine system based on the physical sedimentology. This unit is the base of the Stage 2 containing coarser-grained deposits than those of Stage 1, and consists of winnowed marine sediments (Boreen, 1989).

Unit 4 (12.18-12.49 m) contains parallel-laminated sandstones with rarely to pervasively bioturbated tops interbedded with cross-bedded sandstones. This unit is interpreted as a subtidal bar or bay-margin deposit (Pemberton *et al.*, 1992b). Biogenic structures are rare, but sideritized and shale rip-up clasts are very abundant, thus suggesting physical processes were stronger than biological processes.

Unit 5 (12.49-12.59 m) comprises a poorly-sorted conglomerate lag that defines the knife-sharp, nonburrowed VE3 erosion surface. This lag separates the estuarine deposits of the incised valley-fill (Allomember C) from the coarsening upward regressive facies of Allomember D.

Unit 6 (12.59-12.90 m) contains the sediments associated with Allomember D. This unit consists of fine-grained sandstones interbedded with medium-grained sand layers. Bioturbation is rare but in some intervals in which few *Planolites* burrows are present.

Unit 7 (12.90-13.38 m) consists of medium-grained, ripple-cross-laminated sandstones with burrowed mud drapes that separate the laminated sets. The benthic community was influenced by more marine conditions because the deposit-feeding and locomotion traces are characteristic of the *Cruziana* Ichnofacies.

Unit 8 (13.38-13.46 m) consists of a muddy conglomerate interpreted as the VE4 lag. This conglomerate sits on the knife-sharp erosion surface truncates the regressive deposits (Allomember D). It separates them from the overlying transgressive deposits (Allomember E).

Unit 9 (13.46-13.63 m) consists of muddy siltstone layers interbedded with shales. This unit contains a trace assemblage of *Asterosoma*, *Palaeophycus*, *Planolites*, *Skolithos* and *Thalassinoides*. This assemblage suggests that the palaeoenvironment was stressed. *Thalassinoides* burrows suggest this environment was the intertidal zone. This trace assemblage is characteristic of the *Cruziana* Ichnofacies.

The sediments associated with Allomember C (10.72-12.53 m) are interpreted as distal marine sandstones deposited in the estuary mouth, the seaward end of Dalrymple *et al.*'s (1992) tripartite model. Two stages of deposition were interpreted by Boreen (1989). The trace fossils identified in this core suggest that condition became brackish or marine conditions became more prominent in the second stage of deposition. These deposits and ichnofossil assemblages suggest the presence of tidal barriers in this part of the estuary, therefore a restricted exchange of marine and brackish water.

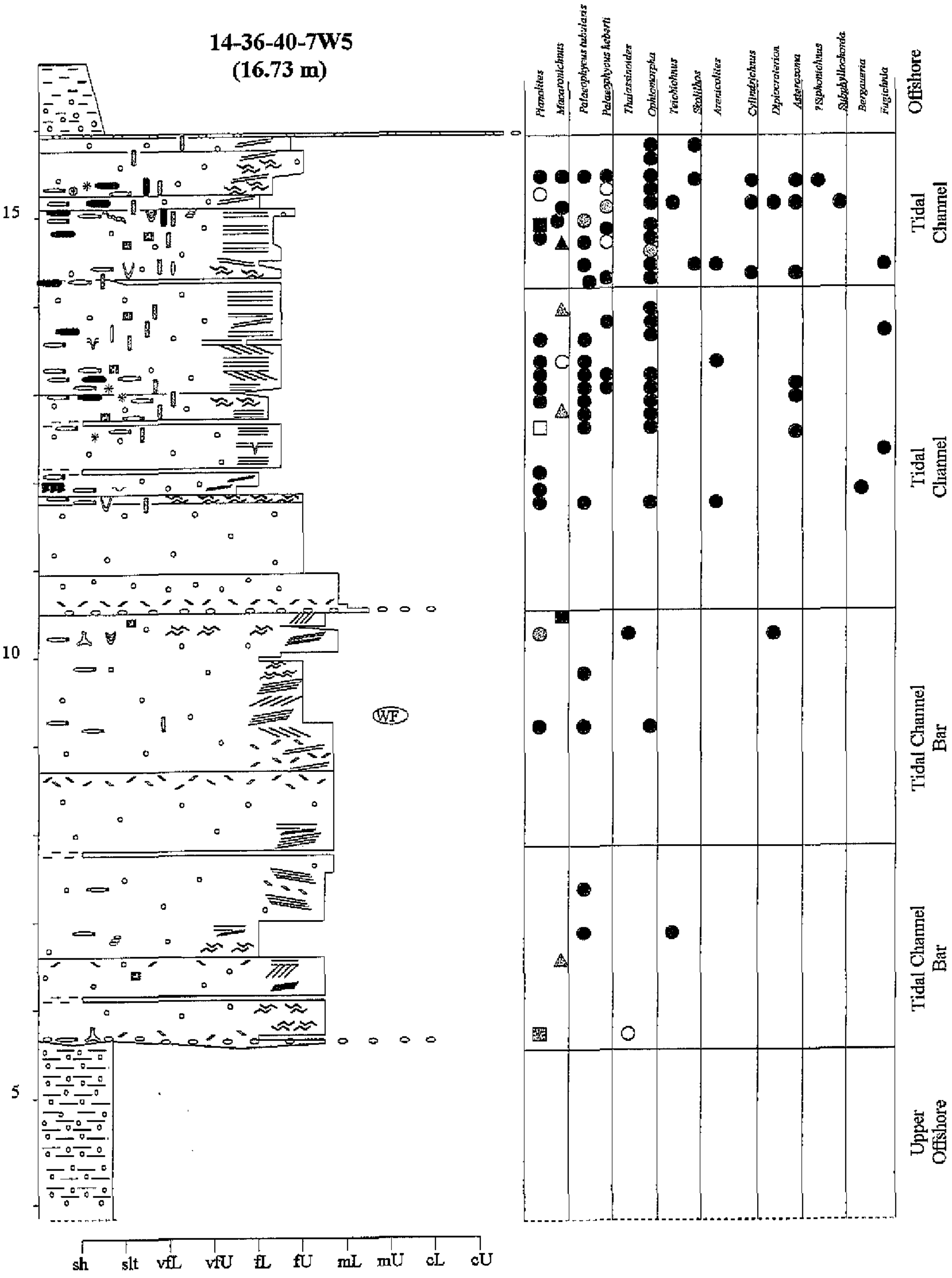
Unit 10 (13.63-15.98 m) comprises black shale and mudstones associated with an offshore environment. Bioturbation is undiscernable due to the lack of coarser-grained material to contrast biogenic structures. This unit has been informally called the Colorado Shales or the unnamed shales of the Colorado Group. Bloch *et al.* (1993) formally named these shales the Westgate Formation.

14-36-40-7W5 Core Interpretation

The sediments in the seven units are marine in origin and reworked by currents and waves (Boreen, 1989) (Figure 4.20).

Unit 1 siltstones (0-5.69 m) were deposited in the upper offshore as suggested by the grain size and reworking of the sediments by marine animals who produced *Helminthopsis*, *Anconichnus* and *Terebellina* ichnofossils. Subaerial erosion of these sediments during channel incision produced a firm semiconsolidated substrate for dwelling structures (e.g,. *Planolites* and *Thalassinoides* burrows). These burrows contain pebbles and sand from the overlying unit, and are characteristic of the *Glossifungites* Ichnofacies (Frey and Seilacher, 1980; Pemberton and Frey, 1985; Boreen, 1989; MacEachern *et al.*, 1992; Pemberton *et al.*, 1992a, 1992b). This ichnofacies is characteristic of the transgressively modified Viking erosion surface VE2, and is associated with channel incision.

Unit 2 - Unit 4 (2.59-11.75 m) contain sediment interpreted as part of a high wave energy environment, as suggested by the presence of *Macaronichnus segregatis* burrows and few other biogenic structures (*Palaeophycus tubularis* and *Teichichnus*). Cross-beds and rip-up clasts are observed within the fine- to medium-grained sandstones. These physical structures are common in subtidal to intertidal areas as tidal channel bars (Clifton and Thompson, 1978; Frey and Howard, 1986). These units are considered to represent the first stage of channel infill (Stage 1) (Boreen, 1989). The



14-36-40-7W5
(16.73 m)

pebble lag, separating these sandstones and the overlying sandstone units (Unit 5 - Unit 6), is winnowed from marine sand (Boreen, 1989).

Unit 5 (11.79-14.30 m) and **Unit 6** (14.30-15.89 m) are more marine in character based on the diversity of the ichnofauna. In Unit 5 and Unit 6 there are 9-14 ichnospecies as compared with 5-6 ichnospecies in Unit 2 - Unit 4. *Macaronichnus* burrows are the most abundant (187.45 i.p.s.a.) in these units. The presence of a *Skolithos* Ichnofacies suggests current activity was moderate to high. *Fugichnia* preservation and parallel-laminated sand deposits, less than 30 cm thick, support this current velocity. Tidal influences are confirmed by *Arenicolites*, *Diplocraterion* and *Ophiomorpha* burrows constructed by animals that inhabit tidal flats and tidal channel deposits (Weimer and Hoyt, 1964; Howard, 1971a; Häntzschel, 1975; Frey *et al.*, 1978; Pieńkowski, 1985; Ekdale, 1988; Bjerstedt and Erickson, 1989; Frey and Howard, 1990; Pemberton *et al.*, 1992). Based on these observations Unit 5 - Unit 6 are interpreted as tidal channel deposits.

Unit 7 (15.89-16.73 m) consists of black shales overlying the VE4 erosion surface. Sand stringers are observed in this unit. The sand was transported into the basin by frequent storm events. These marine shales have been interpreted as the Colorado Shales.

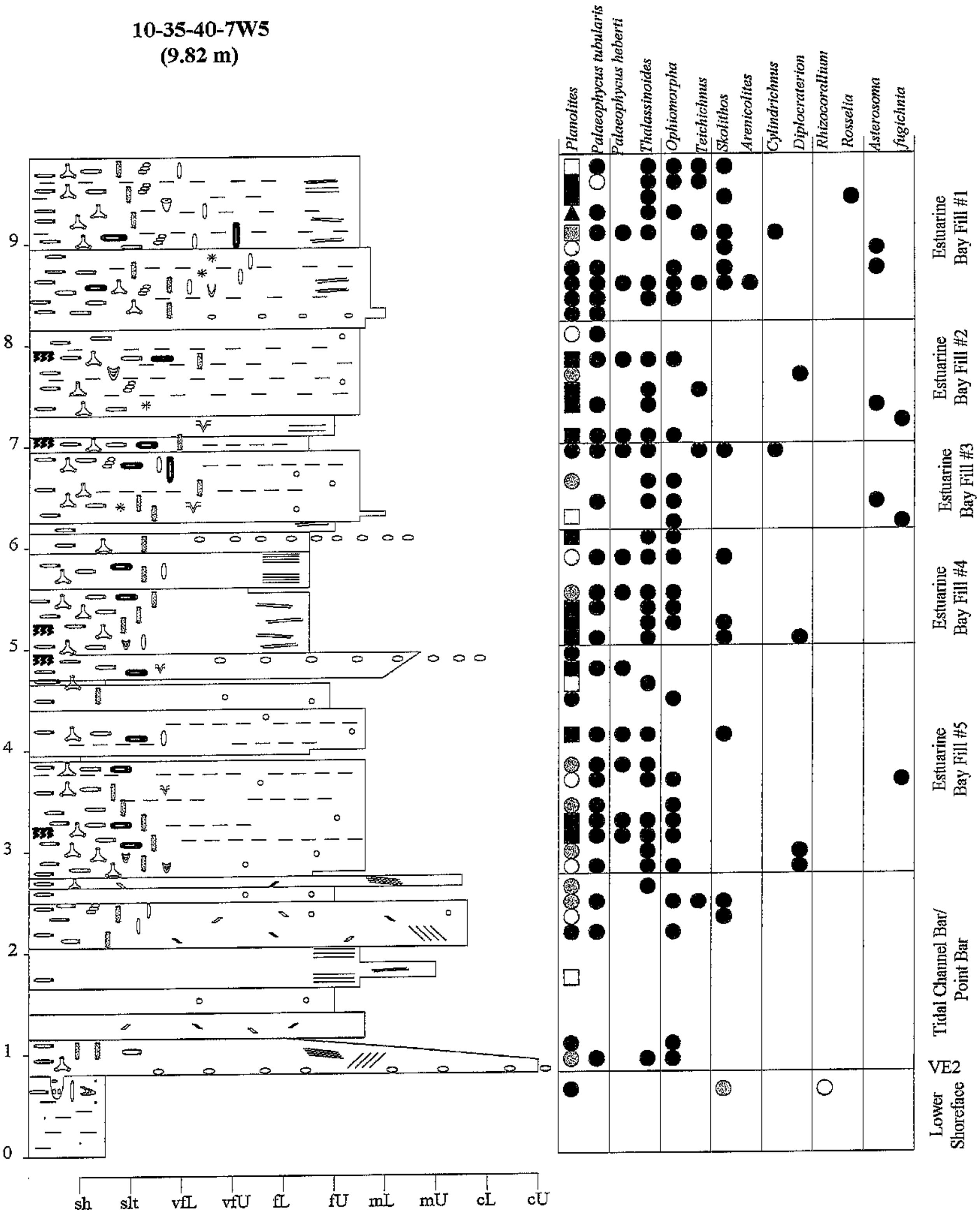
By reference to the tripartite estuarine model as recently reviewed by Dalrymple *et al.* (1992), these sediments in 14-36-40-7W5 were deposited in the estuary mouth.

10-35-40-7W5 Core Interpretation

This core has been interpreted by Boreen (1989) and MacEachern *et al.* (1992). My interpretation confirms their interpretations of depositional environments, but I have subdivided their estuarine bay fill into five pulses using trace abundances (i.p.s.a.) (Figure 4.21).

Unit 1 muddy siltstones (0-.70 m) were deposited in the offshore/lower shoreface. Because HCS beds are absent, the beds were probably deposited below storm wave base. This is consistent with

10-35-40-7W5
(9.82 m)



intense biogenic reworking by marine deposit-feeders, as showed by *Helminthopsis*. This unit consists of Regional Viking sediments of Allomember A. Pebble-filled *Planolites, Skolithos,* and *Rhizocorallium* burrows characterize the marine *Glossifungites* Ichnofacies (Frey and Seilacher, 1980; Pemberton and Frey, 1985; Boreen, 1989; MacEachern, 1992; Pemberton *et al.*, 1992a, 1992b). This ichnofacies suggests that the firm, dewatered muddy siltstones were subaerially eroded and burrowed by domicile constructing animals at this VE2 omission surface (Pemberton and Frey, 1985). This surface represents the incision of the Willesden Green channel (Boreen, 1989).

Unit 2 (0.70-2.75 m) contains cross-bedded sandstones interpreted as a tidal channel bar (Boreen, 1989; MacEachern *et al.*, 1992). The robust *Ophiomorpha* and *Skolithos* burrows suggest the sand was deposited in a marine environment influenced by currents that produced 10-25° cross-beds. The trace assemblage is characteristic of *Skolithos* Ichnofacies. This tidal channel bar occurs in the estuary mouth of the Willesden Green channel.

Unit 3 - **Unit** 7 (2.75-9.82 m) have been previously interpreted as the muddy interbedded facies deposited in the central basin of the estuary (Boreen, 1989) and in a subtidal estuarine bay (MacEachern *et al.*, 1992). I argue that, based on quantified abundances, distinctions can be made in these middle estuary deposits, particularly in increasing marine conditions upward in the core (Units 3-7). Each unit contains biogenic characteristics of the *Skolithos* Ichnofacies. Unit 7 contains the most ichnospecies, and is characteristic of a mixed *Skolithos-Cruziana* Ichnofacies. *Arenicolites* burrows are absent from Unit 1- Unit 6, but they occur in Unit 7 and support the interpretation of a brackish water environment. The presence of *Rosselia* and *Asterosoma* suggest that Unit 7 was deposited in more marine conditions than Unit 3 - Unit 6 because together they are good indicators of the offshore/ lower shoreface transition zone (Pemberton *et al.*, 1992c).

This increase in marine conditions is an important interpretation, because neither VE3 (Allomember C) nor the sediments of Allomember D and E were cored in this location.

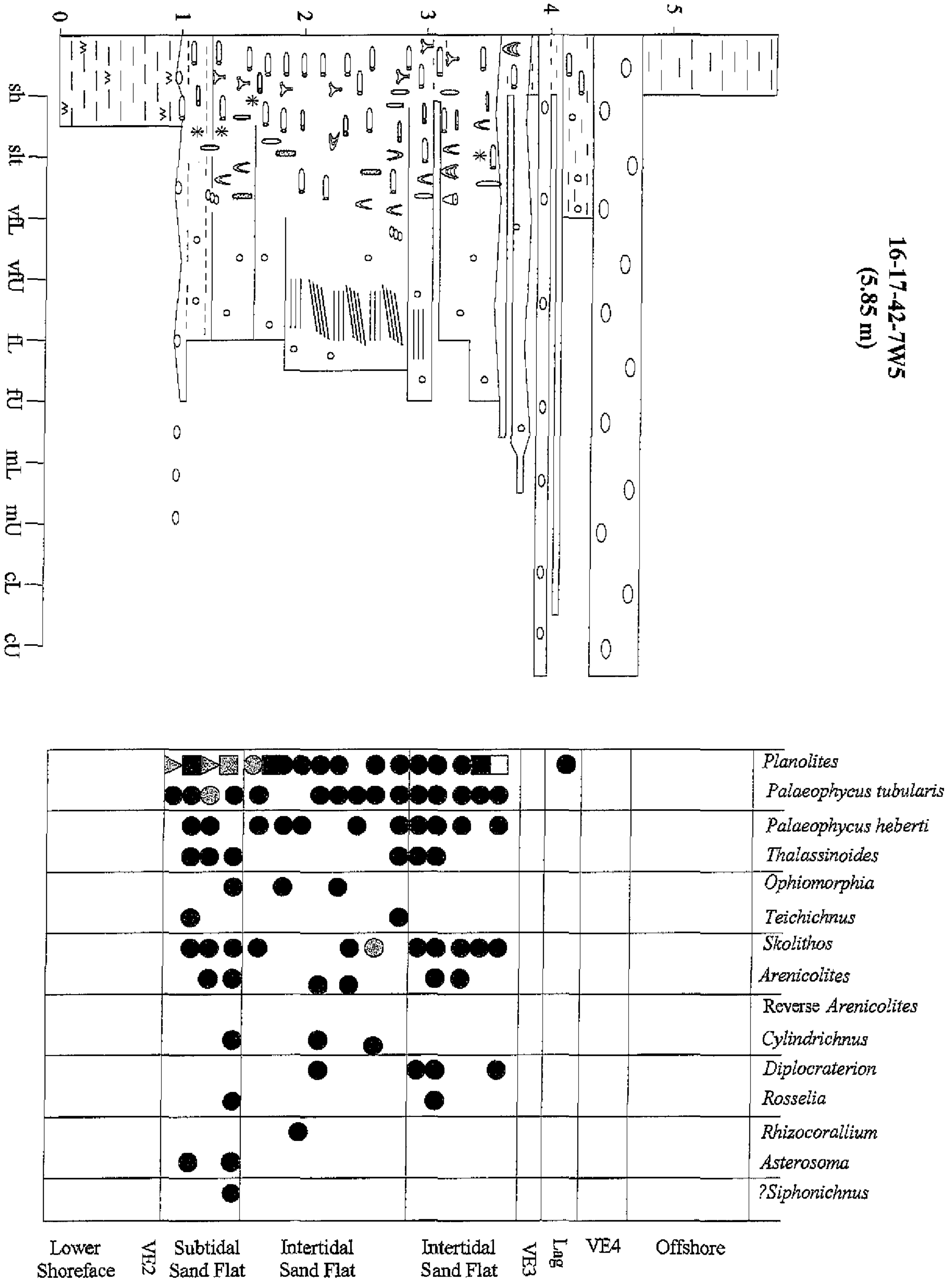
16-17-42-7W5 Core Interpretation

The sediment packages in this 5.85 m core belong to Allomembers B-E (Figure 4.22). The sediments are interpreted by Boreen (1989) to have been deposited in an estuarine sand flat environment within the middle reaches of the estuary. Ichnological data confirm this interpretation and suggest that the North and South Willesden Green Channels infilled together.

Unit 1 (0-1.02 m) contains muddy siltstones that are characteristic of other cores in which only *Helminthopsis* is the discernable ichnospecies. This monospecific population results in an intensely bioturbated substrate. The Unit 1 upper contact is erosive and sharp. Vertical dwelling structures do not extend downward from the sharp into the underlying lower offshore sediments, but occur above this surface (VE2) in Unit 2. The lack of a *Glossifungites* Ichnofacies suggests that colonization occurred after or was removed by subaerial erosion (Pemberton and Frey, 1985; Pemberton, MacEachern and Frey, 1992).

Unit 2 (1.02-1.62 m) deposits support colonization after a subaerial erosion in this location. Laminated-to-burrowed mudstones are interpreted as a probable subtidal estuarine sand flat based on the physical structures and the trace fossil assemblage. This assemblage contains *Rosselia* and *Asterosoma* that Pemberton *et al.* (1992c) consider good lower shoreface indicators. These traces show a mixed *Cruziana-Skolithos* Ichnofacies; however deposit-feeder burrows are more common than the vertical dwelling structures.

Unit 3 (1.62-3.07 m) has physical and biogenic structures comparable to Unit 2, but this unit is based on grain size changes in the parallel- to low-angle-laminated sandstones with burrowed tops. *Thalassinoides*, *Ophiomorpha* and *Diplocraterion* are good indicators that the salinity range is 25-30‰ in an intertidal sand flat environment (Frey *et al.*, 1978; Pemberton and Frey, 1986; Bjerstedt and Erickson, 1989; Howard and Frey, 1990; E.G. Kauffman, pers. comm., 1993). This trace assemblage is characteristic of a *Skolithos* Ichnofacies because dwelling structures are more common than feeding


16-17-42-7W5
(5.85 m)
0
1
2
3
4
5
sh
slt
vfL
vfU
fL
fU
mL
mU
cL
cU
Planolites
Palaeophycus tubularis
Palaeophycus heberti
Thalassinoides
Ophiomorphia
Teichichnus
Skolithos
Arenicolites
Reverse Arenicolites
Cylindrichnus
Diplocraterion
Rosselia
Rhizocorallium
Asterosoma
?Siphonichnus
Lower Shoreface
VE2
Subtidal Sand Flat
Intertidal Sand Flat
Intertidal Sand Flat
VE3
Lag
VE4
Offshore

structures.

Unit 4 (3.07-3.84 m) is comparable to Unit 3, but fewer trace fossils exist in this coarsening upward succession. Marine influences have increased because the traces are characteristic of a mixed *Cruziana-Skolithos* Ichnofacies. This intertidal deposit contains *Diplocraterion*, *Rosselia*, *Arenicolites* and *Cylindrichnus*, and those typically observed in these sediments (e.g., *Planolites* and *Palaeophycus*). This unit is eroded and capped by the VE erosion surface. This surface marks the end of Allomember C deposition (Boreen, 1989).

Unit 5 (3.84-4.06 m) represents the basal lag of Allomember D. The conglomerates, interbedded with mudstones, rest on the VE erosion surface, and consist of well-rounded, poorly sorted-pebbles and granules. This suggests that the pebbles are winnowed marine sediments (Boreen, 1989). This unit fines upward into the muddy sediments of Unit 6.

Unit 6 (4.06-4.32 m) contains the muddy sediment that overlies the coarse-grained material of Unit 5 and the VE surface (Boreen, 1989). Bioturbation is not observed in this unit.

Unit 7 (4.32-4.74 m) comprises the basal conglomerate lag of Allomember E that rests on the VE4 erosion surface. This transgressive surface is not underlain by a *Glossifungites* Ichnofacies.

Unit 8 (4.74-5.85 m) contains black shales of Allomember E. The absence of HCS beds suggests little storm activity. Bioturbation is undiscernable due to the lack of textural contrasts in the sediment.

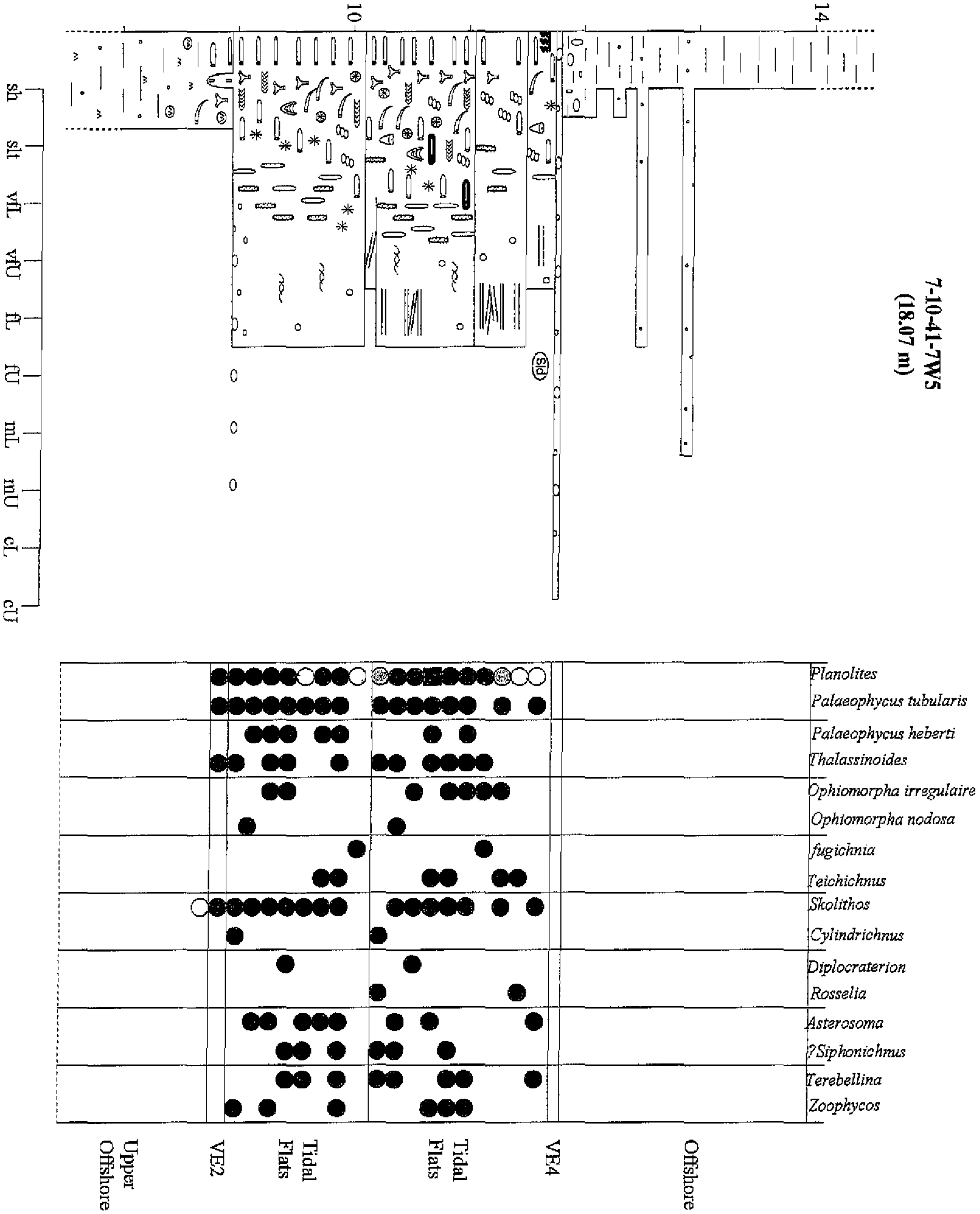
Without trace fossil quantification, the estuarine sand flat could not have been differentiated into three stacked estuarine sand flats in core 16-17-42-7W5. These stacked flats were influenced by different marine parameters (eg., salinity) as determined by subtle changes in the ichnofossil assemblages. This core is comparable to core 11-1-41-7W5 in the South channel. However, in the subtle differences cannot be assessed because the ichnological data is not available.

7-10-41-7W5 Core Interpretation

Boreen (1989) interpreted this 18.07 m core to contain estuarine sediments (Allomember C) deposited above marine siltstones (Allomember B) and below marine shales (Allomember E) (Figure 4.23). The depositional environment as inferred by the muddy estuarine very-fine- to fine-grained sediments is a mud flat. The quantification of trace fossils confirms Boreen's (1989) interpretation. However, I argue that this mud flat can be divided into a lower mud flat and an upper mud flat because of quantification, with the latter having more abundant i.p.s.a. and influenced by more marine conditions.

Unit 1 (0-8.91 m) comprises muddy siltstones deposited in the upper offshore, and associated with Allomember B. The preserved traces, particularly *Helminthopsis* and *Anconichnus*, suggest the environment was well-oxygenated and intensely bioturbated as reflected by the "shredded" texture (Häntzschel, 1975; Bromley, 1990). Other discernable traces include *Chondrites*, *Terebellina* and *Schaubcylindrichnus*. These five traces are characteristic of the *Cruziana* Ichnofacies. The preservation of *Chondrites* is due to tracemakers burrowing through anaerobic to anoxic sediments. Few animals can subsequently reburrow and destroy this biogenic structure due to the reduced or absent oxygen present in the interstitial spaces. *Terebellina* and *Schaubcylindrichnus* burrows are constructed by animals secreting a mucus substance that acts as a glue to agglutinate sand grains together to create the burrow lining (Bromley, 1990). These cemented burrows withstand biodegradation, unlike the reinforced burrow walls of other deposit-feeding/ dwelling structures (Bromley, 1990).

The contact between Allomembers B and C is a knife-sharp and is penetrated by *Thalassinoides* and *Planolites* burrows, which characterize the *Glossifungites* Ichnofacies (Frey and Seilacher, 1980; Pemberton and Frey, 1985; Boreen, 1989; MacEachern *et al.*, 1992; Pemberton *et al.*, 1992a, 1992b). Colonization by dwelling/feeding animals occurred before the deposition of the pebbly sand and conglomerate that rest on this omission surface. This surface marks the channel incision (VE2) and defines the base of Allomember C (estuarine sediments and marine conglomerates) (Boreen, 1989).


7-10-41-7W5
(18.07 m)
10
14
sh
slt
vfL
vfU
fL
fU
mL
mU
cL
cU
sid
Planolites
Palaeophycus tubularis
Palaeophycus heberti
Thalassinoides
Ophiomorpha irregulaire
Ophiomorpha nodosa
Fugichnia
Teichichnus
Skolithos
Cylindrichnus
Diplocraterion
Rosselia
Asterosoma
?Siphonichnus
Terebellina
Zoophycos
Upper Offshore
VE2
Tidal Flats
Tidal Flats
VE4
Offshore

Unit 2 (8.91-10.21 m) and **Unit 3** (10.21-11.70 m) have similar facies preserved in the laminated-to-burrowed sandstones. The parallel- to ripple cross-laminated beds suggest that upper flow regime currents deposited the sand in this location. The deposit was subsequently subjected to long periods of waning flow in which mud was deposited from suspension. The benthic animals that colonized these sediments were adapted to short periods of rapid sedimentation followed by longer periods of waning flows. During waning flows burrowing activity was reestablished and the tops of the laminated sands were intensely bioturbated by deposit- and suspension-feeders. The sand layers, deposited by the tidal currents, are thin (less than 30 cm) because escape structures are present. The biogenic assemblages in both units are characteristic of the mixed *Skolithos-Cruziana* Ichnofacies and are commonly found in estuarine deposits (Frey and Howard, 1986; Pemberton and Wightman, 1992; Pemberton *et al.*, 1992c; Ranger and Pemberton, 1992). In Unit 2 the ichnofacies consists of more *Cruziana* type ichnospecies (eg, *Rosselia*). Based on the modern analogues of *Diplocraterion*, *Ophiomorpha* and *Thalassinoides*, Unit 3 is inferred as tidal flats in an intertidal environment (Weimer and Hoyt, 1964; Frey *et al.*, 1978; Frey and Howard, 1985, 1990; Ekdale, 1988; Bjerstedt and Erickson, 1989; Pemberton *et al.*, 1992c).

Unit 4 (11.70-11.76 m) comprises the sediment lying on Viking erosion surface VE4. The absence of the VE3 and Allomember D regressive facies suggest they were eroded during the transgression and deposition of the conglomerates that rest on this VE4 surface. Bioturbation is not discernable in the conglomerates.

Unit 5 (11.76-18.07 m) consists of fissile black shales interbedded with thin structureless or wave-rippled sand layers (Allomember E). These sediments were deposited in an offshore environment. Sand deposition was influenced by storm surges which transported sand into the offshore environment. Bioturbation is not discernable.

Allomember C was deposited in a mud flat environment in the middle reaches of the South

Willesden incised channel (Boreen, 1989; Dalrymple *et al.*, 1992).

4.6 PALAEOGEOGRAPHY OF THE SOUTH WILLESDEN GREEN CHANNEL, VIKING ALLOFORMATION

The Willesden Green Channel is a major incised channel in the Viking Alloformation (Allomember C). This channel is characteristically estuarine based on the physical and biogenic sedimentology. The underlying gradually coarsening upwards succession of mudstones, siltstones and fine-grained sandstones (Allomembers A and B) are intensely bioturbated by marine invertebrates. *Helminthopsis*, *Anconichnus*, *Terebellina* and *Schaubcylindrichnus* ichnofossils preserved in these underlying Regional Viking sediments support the interpretation of a marine environment. *Terebellina* and *Schaubcylindrichnus* are also found in the marginal-marine facies associated with the channel fill (Allomember C). The data show that burrow diameters and abundances decrease in a brackish (marginal-marine) sediments. In a marginal-marine environment, stressed physical factors limit the diversity of the *in situ* invertebrate communities. The data show that *Palaeophycus* and *Planolites* also follow this trend of diminished size in marginal-marine sediments compared with those found in marine sediments. This channel fill is truncated by sandstones consistent with the "Viking regressive facies" (Allomember D) (Boreen, 1989). Truncating the regressive facies are pebbly mudstones (Allomember E). Black shales known as the Colorado Shale blanket the last Viking Allomember in the Willesden Green area. These shales contain few discernable biogenic traces. *Planolites* burrows are evident near silt event beds suggesting that these tracemakers were transported into this marine environment.

Boreen (1989) interpreted that the Willesden Green Channel was a transgressive estuarine fill. The palaeogeography was organized by sediment facies associations such as interbedded facies associations and cross-bedded facies associations. Boreen (1989) interpreted these two facies associations, for example, as an estuarine sand flat and tidal channel. Biogenic structures are used as characteristics of the sedimentary fabric.

My study using the trace fossil assemblages, confirms Boreen's (1989) interpretations. The use of biogenic structures as the primary reconstruction tool has lead to a further division of environmental regions within this incised channel. Although salinity cannot be measured, due to insufficient shell material to analyze, subtle differences in the diversity and abundance of ichnofossils suggest that salinity became more marine, less brackish, as the channel infilled. At the base of the channel infill (Allomember C), the animals that lived in sediment and at the sediment water interface could tolerate a wide fluctuation in salinity levels. Near the top of the cores the biogenic structures suggest that the salinity was similar to seawater (35 ‰) because the fewer ichnospecies are present although the numbers are higher for individual ichnospecies. The relative size of these traces is more robust because fewer stresses are acting upon the animals.

The purpose is not to disprove Boreen's interpretation but enhance it by using ecology. The types of invertebrates that can live in a marine or impoverished-marine environments depend on the physical geology and ecology that existed in the Willesden Green area.

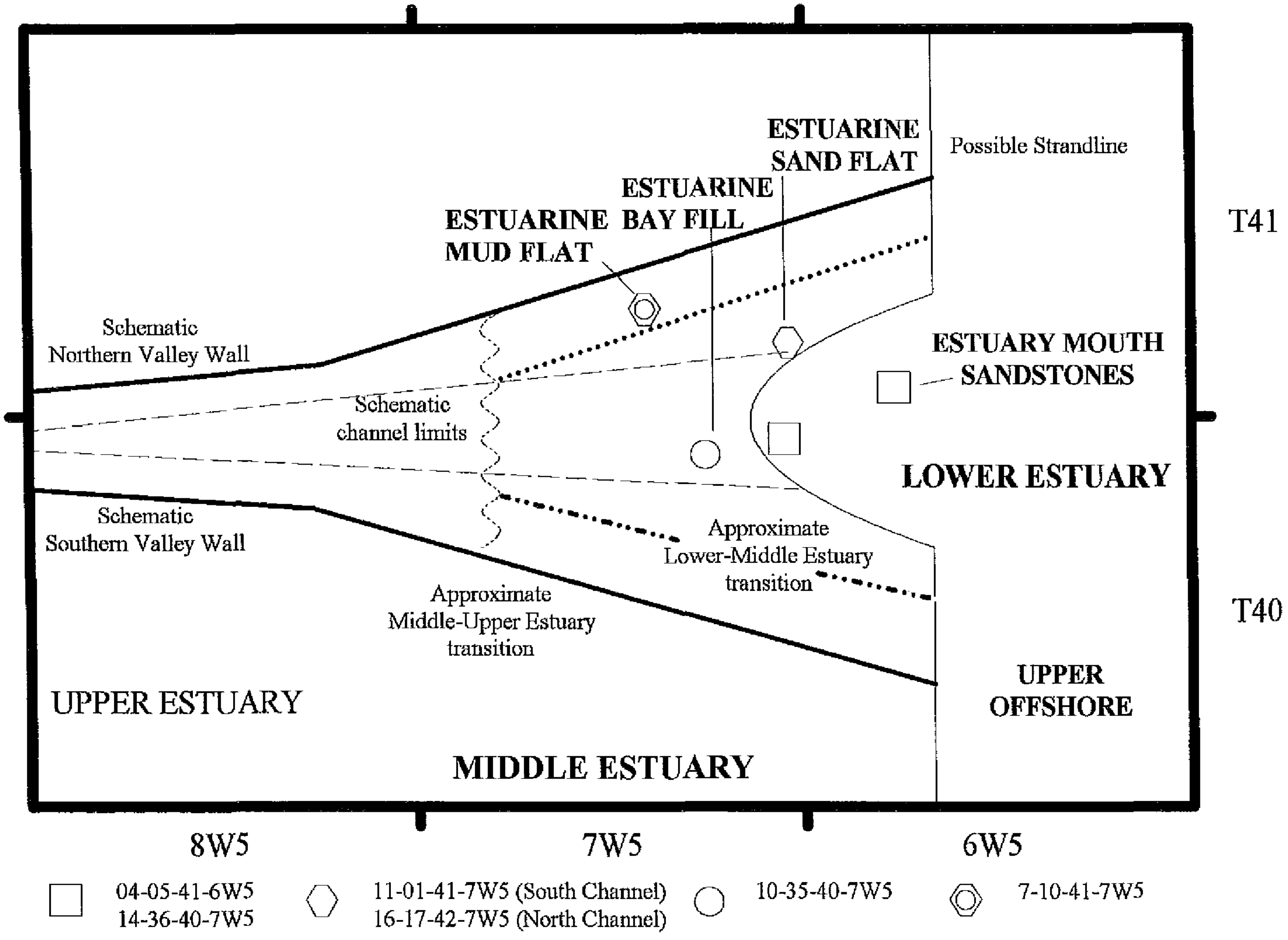
By examining the Willesden Green cores according to their relative positions from the most seaward (4-5-41-6W5) to the most landward location (7-10-41-6W5), trends emerge from the trace fossil assemblages as the channel was transgressed. Boreen (1989) proved that the Willesden Green Channel could be classified by tripartite zonation that is typical of incised valley fills (Dalrymple *et al.*, 1993). Trace fossil assemblages observed agree with this zonation. The physical sedimentology suggests what environmental conditions existed and ichnology supports these environmental interpretations.

Longitudinal variations in sedimentology exist along the channel axis. Coarse-grained sediments occur seaward, in the lower estuary zone (e.g., the estuary mouth) of the tripartite zonation of the South Willesden Green Channel. Fine-grained sediments are found in the middle estuary. The trace fossil assemblages found in this region belong to the *Skolithos* Ichnofacies. The middle estuary (e.g., an estuarine bay fill) consists of interbedded mudstones and sandstones. These deposits laterally progress from the bay fill, near the channel axis, to estuarine sand and mud flats toward the channel margins. The traces found in this zone are characteristic of the *Skolithos-Cruziana* Ichnofacies. The upper estuary is not cored; therefore, I will not make any specific generalizations concerning the most landward section of the tripartite zonation.

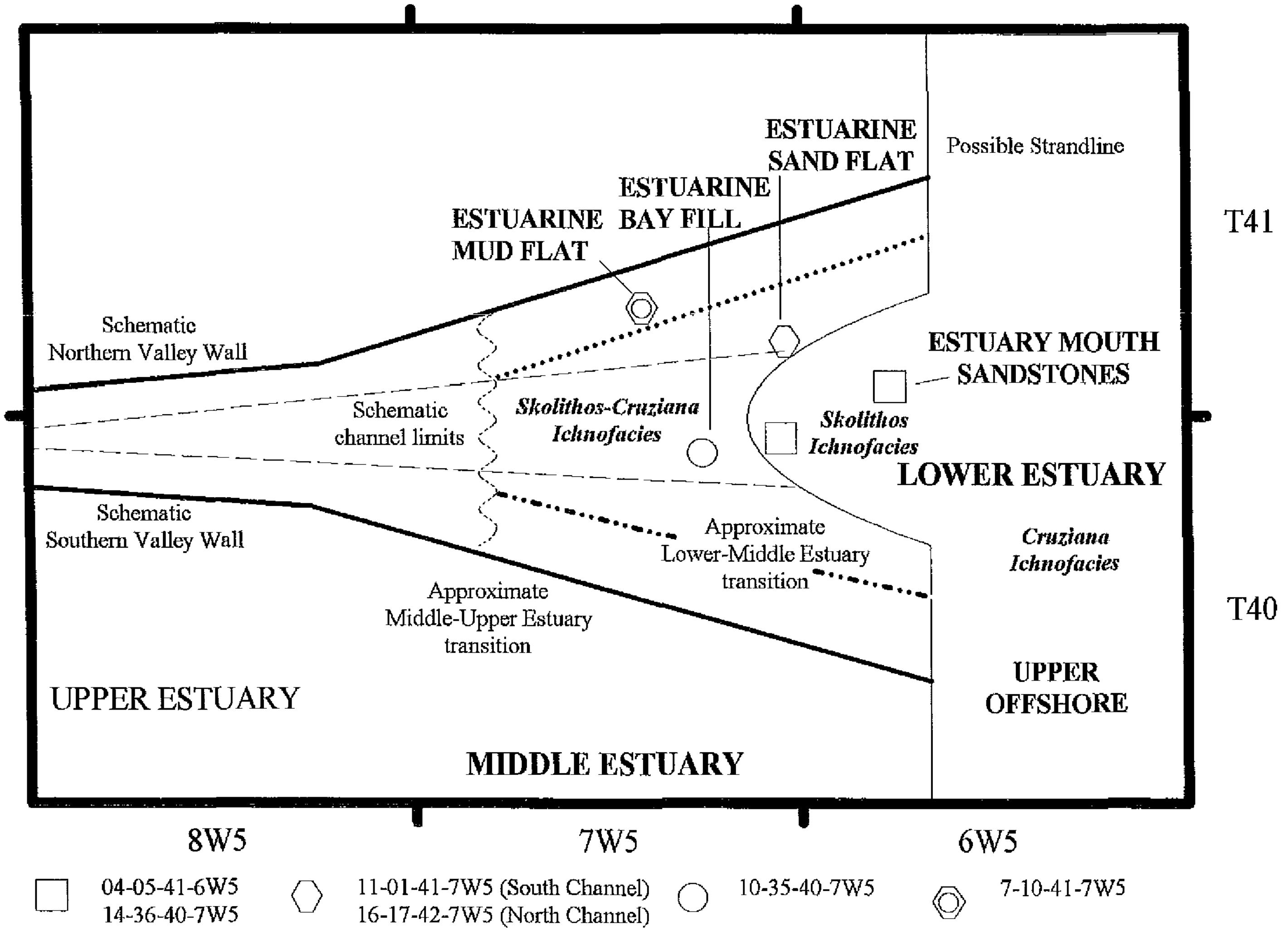
The core interpretations confirm Boreen's (1989) tripartite zonation in the South Willesden Green Channel. However, this study divides the middle estuary into environmental regions (i.e., estuarine bay fill, mud flats and sand flats) based on animal ecology and ethology preserved by burrows and traces (Figure 4.24). Each region has different depositional conditions and sediments that enable only specific animals to burrow. The more favourable the conditions, the more animals should burrow through the sediment. Favourable conditions depend on the physical sedimentology, wave conditions at the sediment-water interface and the abundance of ingestible organic material.

The ichnofacies are less diverse than the Waskahigan Bottleneck Channel because of the coarser sediment supply. This affects no only the preservation of ichnofossils but also the species cable of burrowing in the Viking benthos. However, the ichnofacies characteristically became more marine upwards as reflected by the *Cruziana* Ichnofacies replacing the *Skolithos* or *Skolithos-Cruziana* Ichnofacies (Figure 2.25). These ichnofacies change toward more diverse and abundant trace fossils of marine origin are observed from the mouth of the estuary westward toward the bay head delta of the upper estuary. This change was also documented in the individual cores. The Viking Alloformation is stratigraphically positioned between two marine sequences and understanding the ethology of the benthic community allows a more comprehensive understanding of the infilling of the Willesden Green Channel.

Palaeogeography of the South Willesden Green Channel, Viking Alloformation, Allomember C



Ichnofacies of the South Willesden Green Channel, Viking Alloformation, Allomember C



CHAPTER 5

A COMPARISON OF ICHNOLOGICAL GENERALIZATIONS FOR THE WASKAHIGAN BOTTLENECK AND THE SOUTH WILLESDEN GREEN INCISED VALLEY FILLS

In the body of this thesis, I have identified and analyzed trace fossil assemblages from selected cores in the Waskahigan Bottleneck (Dunvegan) and South Willesden Green (Viking) incised valley-fills. The quantification of these assemblages has suggested evolution of each Cretaceous valley-fill, both vertically and laterally. Subtle changes observed in abundance and diversity of the trace fossil assemblages reflect ecological variations in these systems.

5.1 A COMPARISON OF THE SEDIMENTOLOGICAL AND DEPOSITIONAL ENVIRONMENTS

The Dunvegan and Viking channels are sedimentologically different although they can be designated as tripartite estuaries. The Waskahigan sediments are finer and cleaner than the South Willesden Green sediments. These sedimentological differences reflect physical differences in the depositional environments. Shingle D of the Dunvegan Alloformation is deltaic, whereas Viking Allomember C is an incised valley with a *Glossifungites* firmground at the base. The trace fossils identified in these channel deposits support estuarine conditions existing during infilling. The individual trace fossils are varied within an assemblage and depositional environment; however, consistencies within ichnofossil assemblages and ichnofacies exist within the estuarine zonation. Based on stratigraphy, it is known that the deposits in these locations were transgressed. This study was conducted to understand how the benthic community reacted to these environmental changes. My interpretations are based on a very detailed ichnofossil data base. This data base has enabled me to interpret pulses or successions within a depositional environment

For example in core 14-4-64-23W5, interpreted as a distal delta of the Waskahigan Bottleneck Channel, two distinct distal delta fronts are interpreted from two different lobes: Shingle D2 and Shingle D1 (the Waskahigan Bottleneck Channel). The stratigraphically lower, distal delta front (Shingle D2) experienced more marine conditions than Shingle D1 as shown by the intensity of bioturbation. The abundances of burrow intersections are higher and *Anconichnus* and *Helminthopsis* are present. *Fugichnia* (escape traces) suggest that sand was deposited rapidly in one interval; this trace is not found in Shingle D1.

The data has enabled similar distinctions to be made in the South Willesden Green Channel, (Allomember C). In core 10-35-40-7W5, an estuarine bay fill deposit is subdivided into five successive fills. These distinctions are based on both the sedimentology and the quantified ichnofossils. The interpretations are largely based on the increase in burrow intersection abundances. The diversity of the trace fossil assemblage increased with *Rosselia* occurring during the last estuarine bay fill. It is also in this final fill that synaeresis cracks are not preserved suggesting that conditions are more marine.

Similarities occur in depositional environments that occur in both channels. Tidal channels have similar ichnospecies' abundances and diversities. *Planolites* and *Skolithos* are the dominant species. The depositing feeding trace occurs predominantly in mud drapes and mud layers. The abundances of burrow intersections suggest that these muds are organically rich. The suspension-feeding trace occurs in the sand intervals. *Skolithos* shafts are less abundant suggesting that the water is turbid and these filter-feeding organisms cannot tolerate this environment. The abundances also suggest that the period of strong currents or planar flow be limited and the waning flow and settling of particulate matter prevailed for long periods. The *in situ* mixes of *Skolithos* and *Cruziana* Ichnofacies, found in both channels, suggest that marine conditions extend up the channel and resulted in stressed depositional environments.

Measured burrow dimensions are also indicators of ecological conditions at the sediment-water interface. Optimal conditions (e.g., salinity, nutrients, substrate) enable benthic organisms to thrive, by growing and producing larger ethological patterns. Not only can the burrows be larger but the number of burrow intersections in the core interval will increase. In an estuarine environment, conditions will not be optimal. Salinity levels will decrease or fluctuate and the substrate may be less stable. Organic material may or may not be a concern because modern estuaries are considered nutrient-rich environments. The benthos in a brackish water environment will have smaller burrow diameters. These diameters were used along with diversities and abundances to detect if conditions became more marine as the sea transgressed at that specific location. Compaction, if evident, can provide clues to the substrate without locomotion traces like *Subphyllochorda*.

Differences also exist in these channels. Some ichnospecies are only found in one channel. For example, *Chondrites* occurs in the Waskahigan sediments and *Macronichnus* is found only in the Willesden Green sediments. Primary control of the occurrence of these ichnofossils is the depositional environment and hydraulic conditions. Waskahigan deposits are probably composed of river-borne sediment, not reworked marine sand and pebbles. Reworked marine sediments make up the Viking deposits.

The nature of the base of the channels suggests different infilling circumstances. In the Waskahigan channel (Shingle D1), the erosion surface is overlain by non-burrowed channel sandstones or brackish sediments. *In situ* trace fossil assemblages (*Skolithos* and *Cruziana* Ichnofacies) show depositional conditions, in this meandering deltaic channel were initially fluvial, and became brackish to marine because of river avulsion and lobe switching in the bottleneck area (Bhattacharya, 1989). The base of the Waskahigan Bottleneck does not contain a *Glossifungites* Ichnofacies. This suggests that the fluvial channel eroded the interdistributary bay sediment common at the base of many cores. During the transgression of this channel, infilling was continuous with several, up to five, depositional pulses. Massive sandstones at the base of many channels, remain unburrowed. Sideritized mud rip-clasts and wood fragments are observed in some of these deposits. Deposition and bioturbation occurred under low to moderate energy conditions, as suggested by sediment grain size and interbedded structures of the mud and sand deposits.

In the Viking channel, fluvial sediments were subaerially eroded during the initial phases of transgression then reworked by marine processes resulting in winnowed, marine sand, chert pebbles and conglomerates. These sediments were deposited under brackish to marine conditions, as suggested by the trace fossils (e.g., *Skolithos* and *Rhizocorallium*) that penetrate the erosion surface (VE2). This firmground, trace fossil assemblage is characteristic of the *Glossifungites* Ichnofacies. *Skolithos* Ichnofacies is more common than a mixed *Skolithos-Cruziana* Ichnofacies because hydraulic conditions were moderate to high as suggested by sand deposits greater than thirty centimetres and few escape traces (fugichnia). The mode of infilling occurred in two apparent stages. The second stage was influenced by more marine conditions and coarser sediments as the channel transgressed.

The qualitative-quantitative study provided trace associations based on grain size, physical environment and ethology. The results suggest that trace fossils can be assigned to a specific substrate based on the percentage of mud versus sand. Knowing the conditions of the sediment-water interface, one can predict what trace fossils should be observable. Those that are absent may not have been preserved or existed with the type of organisms the ethology suggests. For example, *Teichichnus* is more common in Viking sediments than Waskahigan sediments as a function of the grain size and the sand-mud ratio, approximately 50%-50%. *Rhizocorallium* is a very common ethological pattern in fine-grained sediments characteristic of the Waskahigan Substrate 6. This trace is rare in the medium-coarse grained facies of the Willesden Green Channel because not enough mud is present for this organism to feed and travel through. Conversely, *Ophiomorpha* tunnels are very common in the Viking deposits but rare in the Dunvegan deposits. *Macronichnus* and *Rosselia* only occur in the Willesden Green cores, suggesting that lower shoreface and estuarine mouth deposits are absent the Waskahigan Bottleneck cores.

5.2 CONCLUSIONS

This study may not be significant concerning stratigraphy and petroleum exploration. However concerning palaeobiology and ichnology, my interpretations suggest the ecological conditions that governed the *in situ* benthic communities in these Cretaceous estuaries in the Alberta Basin. This study is the first of its kind. This comparison dealt with trace fossil assemblages in two different estuarine environments. One limitation of the current study is the limited number of cores used in the environmental interpretations. More cores should support the current palaeoecology suggested in this thesis.

The examination of two Cretaceous estuarine fills can test the predictability of the analysis techniques than a direct comparison. Indirect comparisons result from the difference in morphologies of the incised-valley fills, grain size and composition. The physical and sedimentological parameters influence the organisms burrowing the sediment-water interface and the preservation potential of the trace fossils. For example, ichnospecies of vertical filter feeders (e.g., *Skolithos*) are characteristically found in sediments influenced by strong currents and less turbidity. These conditions existed in the South Willesden Green Channel (medium-to-coarse grain sandstone). The Waskahigan Channel typifies ichnospecies of horizontal burrowers that are commonly found in mud-dominated sediments (e.g., *Planolites*, *Terebellina*, *Zoophycos*). Quantitative analysis shows subtle changes in the evolution of Alberta Basin incised valley-fills of the Western Interior Seaway. Changes in ecological conditions at the sediment-water interface are reflected in the abundance and diversity of trace fossil assemblages. Increases in marine conditions are detected laterally and vertically by these ichnoassemblages and corresponding ichnofacies. Overall, as the overlying water became more marine, the ichnofossils became more diverse and more abundant. Channels. Besides enabling palaeobiologists the opportunity to study subtle environmental and ecological changes, this study provides measurements and descriptions of subsurface trace fossils that are not based on outcrops.

One interesting omission in both incised-valley fills is the absence of shells and shelly debris. Shells and shell fragments are observed in allomembers above and below these brackish, marginal marine channels. In such an environment, an abundance of shelly material should be present. There are four methods to produce this omission: 1) chemical dissolution, 2) physical weathering, 3) transportation toward the basin and 4) organism boring. Thus, omissions and inclusions provide a complete ecological and biological picture of the Waskahigan and South Willesden Green Channels.

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APPENDIX A-D

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COMPARATIVE CHART OF FACIES DESCRIBED IN THE VIKING AND DUNVEGAN ALLOFORMATIONS

FACIES	VIKING ALLOFM.	DUNVEGAN ALLOFM.
FACIES 1: SHALES		
1A (Laminated Shale)	yes	yes
1B (Bioturbated Shale)	yes	yes
1C (Carbonaceous Shale)	yes	yes
FACIES 2: BLOCKSTONES	no	yes
FACIES 3: BIOTURBATED MUDSTONES		
3A (Pervasively Bioturbated Mudstone)	no	yes
3B (Laminated-to-Burrowed Mudstone)	yes	yes
3C (Bioturbated Gritty Mudstone)	yes	no
FACIES 4: PINSTRIPED MUDSTONES	no	yes
FACIES 5: BANDED MUDSTONES	no	yes
FACIES 6: PEBBLY MUDSTONES	yes	no
FACIES 7: SILTSTONES		
7A (Muddy Siltstone)	yes	no
7B (Sandy Siltstone)	yes	no
FACIES 8: SANDSTONES		
8A (Muddy Sandstone)	yes	no
8B (Laminated-to-Burrowed Sandstone)	yes	no
8C (Hummocky-Cross-Stratified Sandstone)	yes	yes
8D (Parallel-Laminated Sandstone)	yes	yes
8E (Wave-Rippled Sandstone)	yes	yes
8F (Current-Rippled Sandstone)	yes	yes
8G (Cross-Bedded Sandstone)	yes	yes
8H (Sigmoidally-Cross-Bedded Sandstone)	no	yes
8I (Structureless Sandstone)	yes	yes
8J (Pervasively Bioturbated Sandstone)	no	yes
8K (Pebbly Sandstone)	yes	no
FACIES 9: CONGLOMERATES	yes	no
FACIES 10: LAGS		
10A (Shale and/or Sideritized Mud Rip-Up Clasts)	yes	yes
10B (Coarse Pebbly Lag)	yes	no

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Pocket 1

Colour Scheme for the Number of Burrow Intersections per Standard Area (i.p.s.a.)

▲	30.01 – >40.00
◬	20.01 – 30.00
■	18.01 – 20.00
▨	16.01 – 18.00
□	14.01 – 16.00
■	12.01 – 14.00
■	10.01 – 12.00
●	8.01 – 10.00
◍	6.01 – 8.00
○	4.01 – 6.00
●	2.01 – 4.00
●	1.01 – 2.00
●	0 – 1.00