NOTE TO USERS

The original manuscript received by UMI contains pages with print exceeding margin guidelines. Pages were microfilmed as received.

This reproduction is the best copy available

UMI

Neoarchean Coastal Sedimentation in the Shebandowan Group, Northwestern Ontario

by

Christa F. Koebernick ©

A Thesis Submitted in Partial
Fulfilment of the Requirements
for the Degree of Master of Science

Lakehead University, Thunder Bay, Ontario

November, 1996

0-612-33400-7

ABSTRACT

The study interpreted depositional environments from sedimentological data present in metasedimentary rocks of the Neoarchean Shebandowan Group of the Wawa Suprovince. Outcrops in the study area contained sedimentary structures and bed sequences consistent with shallow water, coastal sedimentation, and represents an important record of Archean depostional processes. Three depositional environments are represented in the rock record; tidal strandline, the shoreface, and the offshore. The tidal strandline was further divided into the tidal flat and tidal channel sub-environments. The presence of these three environments provides unequivocal evidence for the existence of shallow-water shelves in the Archean; a period during which sedimentation was dominated by deposition in alluvial fan, fluvial environments and deep water settings.

The three environments and associated sub-environments record processes reflective of differing current activity which controlled and influenced deposition. The tidal environment was dominated by bidirectional tidal currents. Deposition in the shoreface was predominated by unidirectional wave-produced currents which overprinted prevailing tidal current activity. In the distal portions of the shoreface environment though, deposition was once again controlled by tidal currents. In the offshore, deposition was controlled by storm currents which generated distinctive beds of hummocky cross-stratification.

The tidal environment is composed of many sedimentary structures similar to those present in Phanerozoic and present-day tidal sequences. In the tidal flat sub-environment, vertical sequences of flaser, lenticular, wavy and coarsely interlayered bedding reflect current velocity fluctuations intimately tied to spring - neap tidal cycles. The tidal channel sub-environment lacks many of the features characteristic of tidal channels described in the literature; such as extensive point bar development. Instead the tidal channels of the study area appear to represent sequences deposited in relatively straight channels.

Migration of sandwaves and dune fields deposited the cross-stratified lithofacies of the shoreface environment. Similar to a high-energy non-barred coastline, the proximal portion of the shoreface lacks any evidence of beach development. Instead, the shoreface records a rapid and discontinuous transition from the tidal strandline environment.

Hummocky cross-stratification (HCS), parallel laminated and massive sandstone beds as well as siltstone and mudstone beds typify the offshore environment. The HCS differs greatly in thickness and internal structure from HCS described in the literature. The HCS in the study area reflects restricted and/or variable sediment supply and flow conditions.

A paleotidal range was determined from the sediments of the tidal environment. The range indicated a mesotidal environment and is comparable to Precambrian tidal ranges reported in the literature. Tidal rhythmites, present on the tidal flats, suggest a length of 26 days for the NeoArchean lunar month. Currents which deposited the tidal rhythmites produced both semidiurnal and diurnal sediment sequences.

ACKNOWLEDGEMENTS

Many thanks to Dr. Fralick for his guidance, encouragment and support while writing this thesis. Thanks to all the professors in the Geology Department at Lakehead for their gudiance throughout the years. Thank you to Anne Hammond and Reino Viitala for slabbing rocks for me and making the occasional thin section; and Sam Spivak for occassional use of his computer and advice. Much appreciation to Wendy Bourke who always had the key ready whenever I needed to use the computer.

To my family; Mom, Dad, and the other four who were always there on the other end of the line, full of encouragement and love; and who were not above telling me to get it in gear and get the thesis done. Thanks to all my friends, who were also there with support and words of experience.

And finally to Peir, who was there when I needed the most encouragement, whose patience and understanding; even when pushed to the limits, was always there for me.

TABLE OF CONTENTS

PAGE

TABLE OF FIGURES

CHAPTER ONE -- INTRODUCTION

Shallow/marginal marine facies are present in the Archean shield areas of Australia and South Africa, yet their presence is notably under-represented in the Canadian Shield (Eriksson, 1979; Ojakangas, 1985). Instead, sedimentation in the Canadian Shield appears to be dominated by two distinctive facies associations. The most common is the Resedimented (Turbidite) Facies Association; the second is the Alluvial Fan - Fluvial Facies Association (Eriksson, 1979; Ojakangas, 1985).

It is apparent, that the most proximal and distal clastic depositional environments are abundantly developed in the Archean, but with no evidence of intermediate or marginal (shallow) marine settings (Eriksson, 1979). Ojakangas (1985) states that the interpreted lateral gradations of alluvial fan - fluvial sequences to turbidite sequences emphasizes the notable lack of shelf deposits, and there is apparently a direct transition from subaerial to slope environments. Studies by Parker (1980) and Rezka (1987) though have established the presence of shallow/marginal marine or shelf facies in the Archean of the Canadian Shield. These obsèrvations, in addition to those by Dimroth *et. al.* (1982) of a microtidal deposit; and Archer *et. al.* (1982) of storm dominated shelf deposition indicates the presence of shelf deposits in the Canadian Shield. Ojakangas (1985) interprets these deposits as local short-lived areas of temporary stability on volcanic terranes.

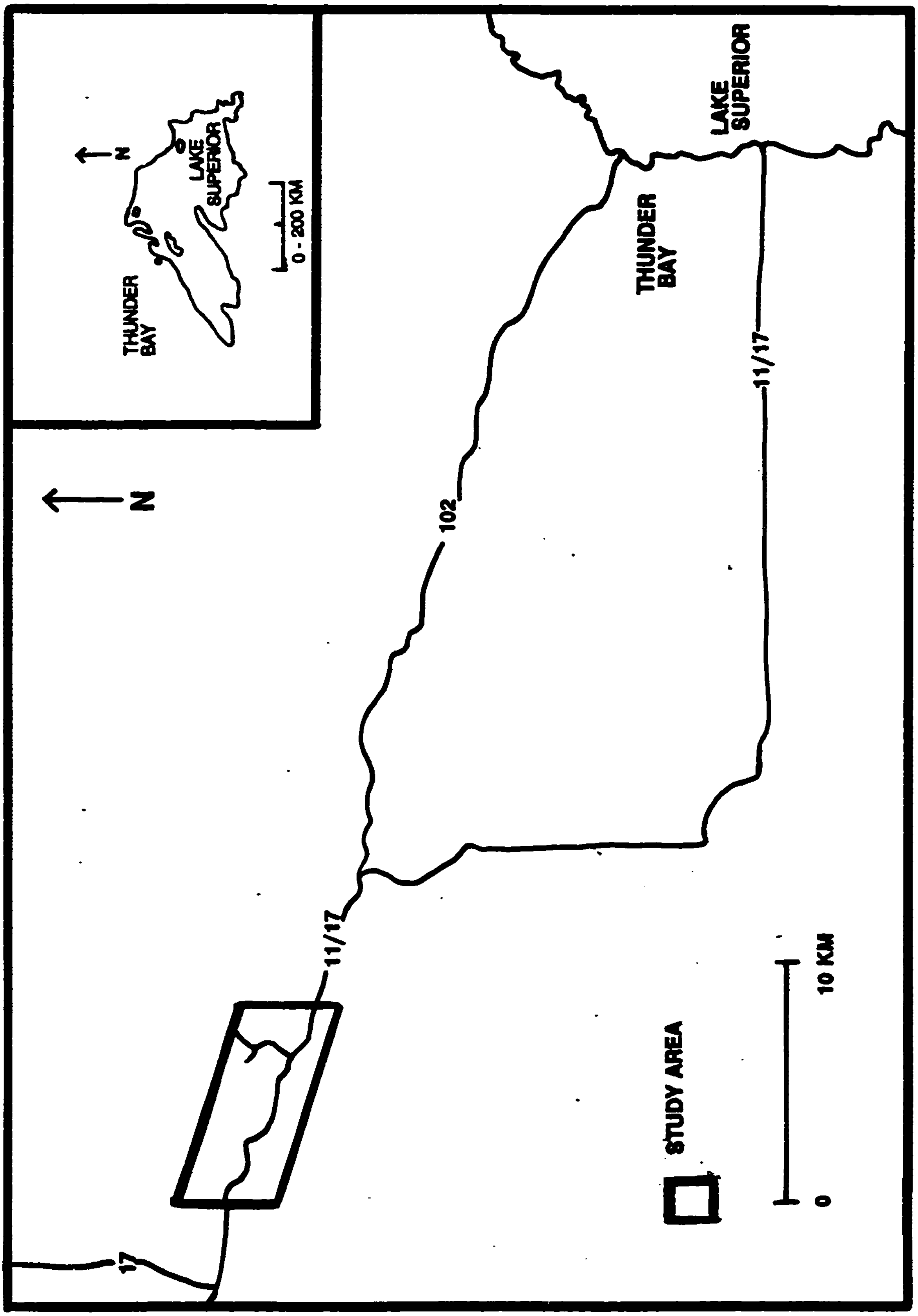
The present study looks at an example of a shallow/marginal marine setting in the Archean of the Canadian Shield. It follows the transition from a foreshore area dominated by intertidal flats cut by tidal channels into the shoreface, and eventually storm-dominated offshore environments. The absence of bioturbation and the lack of extreme deformation provides a clear picture of the depositional processes that were in action at the time.

Bioturbation has destroyed many of the depositional features present in Phanerozoic examples of coastal environments. Thus, looking at a Archean example allows a glimpse into an unseen world. The undisturbed nature of the rocks permits a few fundamental questions to be addressed. Do the depositional processes resemble those of the Phanerozoic and present-day? What do the sediments tell us about the earth - moon system, and the length of a lunar month during the Archean? What is the nature of the transitions between the various depositional environments? And finally, was there frequent storm activity during the Archean? This study will look at these questions, and try to find answers for all of them.

LOCATION

The outcrops that comprise the study area are located along a five kilometre stretch of Highway 11/17 approximately 55 kilometres northwest of Thunder Bay, near Finmark Ontario (Figure 1-1). The majority of outcrops are well exposed, and vary between ten to a hundred metres in length. Highway 11/17 provides excellent access to all outcrops in the study area.

FIGURE 1-1 Map showing location of study area.


THUNDER BAY
LAKE SUPERIOR
N
0 - 200 KM
THUNDER BAY
LAKE SUPERIOR
N
102
11/17
11/17
17
STUDY AREA
0
10 KM

GEOLOGY OF THE FINMARK AREA

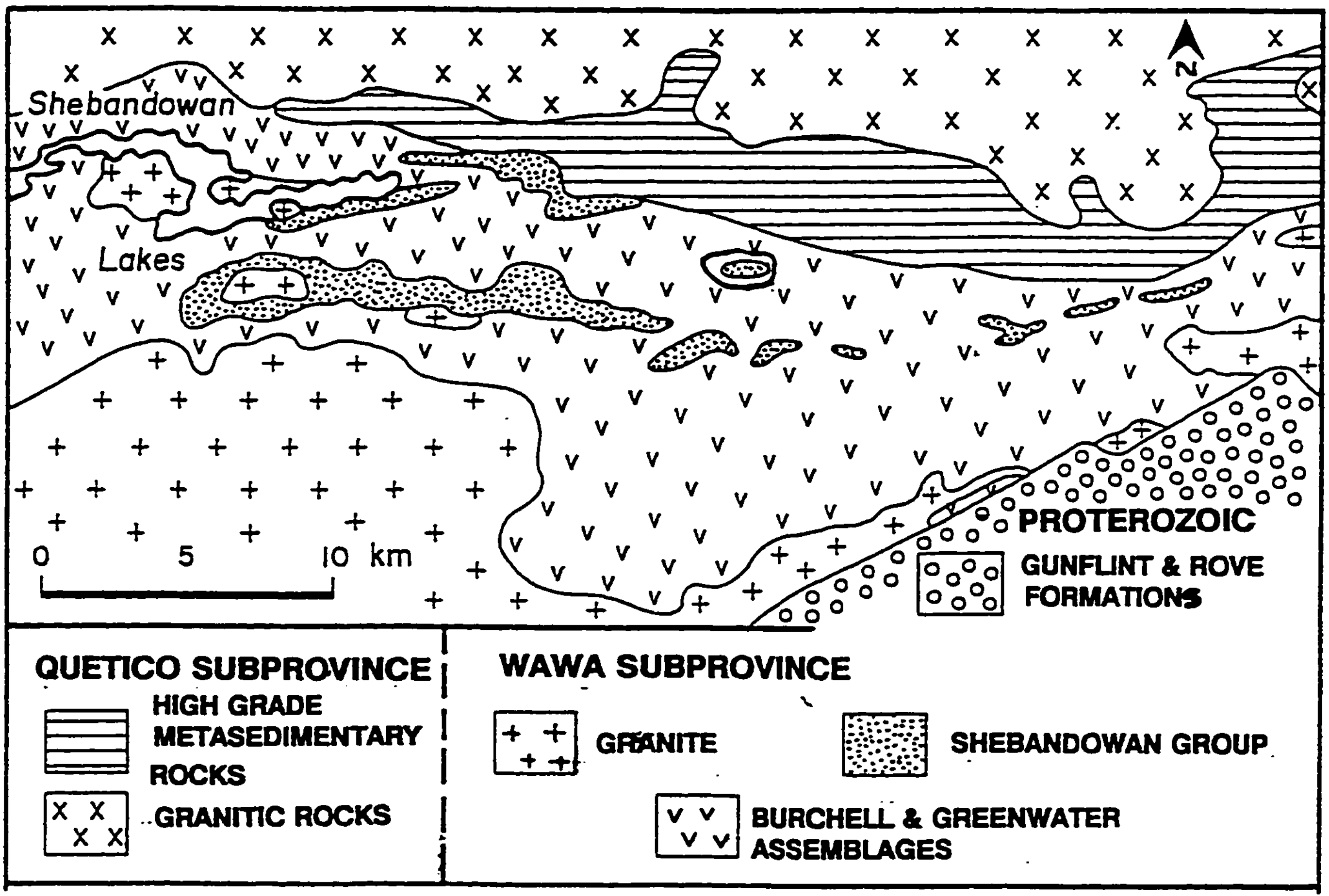
The study area is located within the Shebandowan greenstone belt. This belt forms a portion of the western Wawa Subprovince of the Canadian Shield (Figure 1-2). Within this greenstone belt, the supracrustal rocks are divisible into two main groups; an older metavolcanic sequence, and younger metasedimentary and metavolcanic successions which comprise the Shebandowan Group. The Shebandowan Group occurs as lenticular pods of rock scattered throughout the older metavolcanic sequence (Williams *et. al.*, 1991).

Older Metavolcanics

In earlier literature, the older metavolcanic sequence was referred to as Keewatin-type metavolcanics (Shegelski, 1980; Carter, 1984; Brown, 1985a; Carter, 1985; Borradaile and Brown, 1987; Rezka, 1987). Recently though, these metavolcanic rocks have been subdivided into two separate assemblages; the Burchell assemblage, and the Greenwater assemblage (Williams *et. al.*, 1991). The two assemblages are composed of a series of volcanic cycles which young in opposite directions (Williams *et. al.*, 1991).

The cycles, whose presence has also been noted by Carter (1984,1985), consist of massive and pillowed mafic, intermediate, and felsic flow rocks. Williams *et. al.* (1991) state that typically the lower part of the cycle is comprised of tholeiitic basalts, while the upper part consists of calc-alkalic andesite, dacite, and rhyolite. In many areas, the older metavolcanic rocks have been intruded by gabbroic bodies and

FIGURE 1-2 Geology of the region surrounding Finmark.



Shebandowan
Lakes
0
5
10 km
N
PROTEROZOIC
GUNFLINT & ROVE FORMATIONS
QUETICO SUBPROVINCE
HIGH GRADE METASEDIMENTARY ROCKS
GRANITIC ROCKS
WAWA SUBPROVINCE
GRANITE
SHEBANDOWAN GROUP
BURCHELL & GREENWATER ASSEMBLAGES

porphyritic dikes and sills (Corfu and Stott, 1986).

Interlayered with the older metavolcanic assemblages are thin layers of metasedimentary rocks. The metasedimentary rocks include both clastic and chemical sediments represented by sandstones to mudstones and iron formation and chert, respectively (Carter, 1985).

Shebandowan Group

Regional mapping projects by Tanton (1938), and Pye and Fenwick (1965) recognized the rocks of the Shebandowan Group as distinct volcanic and sedimentary rock units. These rock units are located as pod-like bodies within east-west trending exposures of the Shebandowan greenstone belt. The units were first termed the Shebandowan Group by Borradaile and Brown (1987), but have also been referred to as the Shebandowan assemblage (Williams *et. al.*, 1991). In this paper the term Shebandowan Group will be utilized. A U-Pb zircon age of approximately 2692 million years (Corfu & Stott, 1986) was determined for an alkalic volcanic rock belonging to the Shebandowan Group. Rocks of the Group unconformably overlie the older Burchell and Greenwater assemblages (Williams *et. al.*, 1991). Brown (1985a) supports the view that the Group is younger in age, and unconformably overlies the older metavolcanic assemblages. The Shebandowan Group consists of laterally interfingering volcanic and sedimentary rocks. Noting the interfingering of the volcanics and the sediments, Corfu and Stott (1986) have concluded that volcanism and sedimentation were concurrent; and as a result the age of 2692 Ma reflects the timing of sedimentation, as well as active volcanism. An identical U-Pb age of $\leq$ 2692 million years was obtained from a breccia in the vicinity of the study area (Corfu and Stott, 1995). Recently a U-Pb age of 2692 million years (Corfu, pers. comm.) was determined from a sandstone sample containing sphene, taken directly from the study area.

In much of the older literature, the rocks of the Shebandowan Group have been referred to as Timiskaming-type metasediments and metavolcanics (Shegelski, 1980; Carter, 1984, 1985, 1988; Corfu and Stott, 1986;) due to their similarity to the Timiskaming assemblage described by Cooke and Moorhouse (1969). The Shebandowan Group metavolcanics closely resemble, both chemically and physically, the Timiskaming metavolcanics. The metasediments of the Shebandowan Group also resemble the sediments found in the Timiskaming assemblage.

The volcanic portion of the Shebandowan Group is composed of interlayered calc-alkalic to shoshonitic volcanic rocks (Shegelski, 1980; Carter, 1988; Williams *et. al.*, 1991). Both Shegelski (1980) and Carter (1988) have suggested that the calc-alkalic and shoshonitic rocks represent material shed from proximal volcanic centres. Further evidence for proximal volcanism lies in the abundance of pyroclastic debris flows and the presence of subangular fragments found in flow breccia in the Shebandowan metavolcanics.

The material that was shed from these proximal volcanic centres is the source for the Shebandowan metasediments that comprise the rocks of the study area (Rezka, 1987; Eriksson *et. al.*, 1994). In essence, the metasediments of the study area represent volcaniclastic debris which was reworked in a number of sedimentary depositional environments, two of which are the topic of this study.

A variety of clastic sedimentary rocks comprise the sedimentary portion of the Shebandowan Group. Rock types include; conglomerates, sandstones, and lesser amounts of siltstones and mudstones. Carter (1985) describes the presence of wackes, siltstones and gritty siltstones along Highway 11-17, in the vicinity of the study area. Iron formation units which include magnetite-jasper and graphite-hematite-black chert (Williams *et. al.*, 1991) are also present at some locations, and are found interlayered with the clastic sediments. Carter (1985) describes the iron formation units as an early sequence of chemical metasediments comprising magnetite-jasper and magnetite-chert ironstone units.

Shegelski (1980) who also recognized the existence of distinctive volcanic and sedimentary units in the Shebandowan Group, studied them in detail in the Lake Shebandowan region. Within the sedimentary units, Shegelski (1980) observed the presence of mudcracks, debris flows, sheet flood and traction deposits. Shegelski (1980) has also described the presence of primary sedimentary structures such as cross-stratification, ripple cross-lamination, and planar lamination in this area and has commented on the presence of these sedimentary structures in other sections of the Shebandowan Group. In the Lake Shebandowan area Shegelski (1980) interpreted the sediments as having been deposited in an alluvial-fluvial environment following regional emergence and subsequent erosion.

To the east of the Lake Shebandowan region near Finmark, Parker (1980) studied an interlayered sandstone-siltstone-mudstone sequence which alternates with a cross-stratified sandstone sequence. Parker (1980) stated that the interlayered sandstone-siltstone-mudstone sequence represents deposition in a tidal flat environment, and the cross-stratified sandstone sequence represents deposition in the tidal channels that were draining the tidal flats. Parker's (1980) observations and conclusions are important as they represent the first description of a tidally-influenced environment in Neoarchean rocks of the Canadian Shield.

Rezka (1987) described the presence of small-scale hummocky cross-stratification in the Shebandowan Group. The hummocky cross-stratification was interpreted by Rezka (1987) to represent deposition on a shallow marine, storm dominated shelf. This observation, in conjunction with the presence of the nearby tidally-influenced environment described by Parker (1980) provides evidence for the development and existence of shallow water shelves in the Archean of the Canadian Shield.

Mapping projects by Carter (1984, 1985, 1990) have focussed on the Shebandowan greenstone belt, and the Shebandowan Group in particular. These mapping projects have looked at the mineralogy, petrology, and distribution of rock types; as well as structural geology. Carter (1988) has also studied the calc-alkalic and shoshonitic rocks of the Shebandowan Group. Regional investigations (Chorlton and Brown, 1984; Brown 1985b) have centred on mineralization within the Shebandowan greenstone belt, especially in the region containing the study area. More recently, mapping projects in townships immediately east of the study area have been carried out by Brown (1992) and Brown and Fogal (1993).

Structural Geology of the Shebandowan Group

Although it is believed that the Shebandowan Group has experienced at least one episode of deformation(Brown, 1985a; Corfu and Stott, 1986; and Borradaile and Brown, 1987), viewpoints vary on the number of deformational events that have affected the Shebandowan greenstone belt. Stott and Schnieders (1983) and Corfu and Stott (1986) identify two separate phases of deformation present within this greenstone belt. The first phase records a regional D1 deformation, attributable to a period of vertical tectonism (Stott and Schnieders, 1983; Corfu and Stott, 1986). The second phase, D2 which dominates in the northern half of the greenstone belt is the result of shortening and shearing. Corfu and Stott (1986) state that the Shebandowan Group was deposited after the initial regional D1 deformational event and therefore was unaffected by D1 deformation, but was then subsequently deformed by a later D2 deformational event. The volcanic and sedimentary rocks of the Shebandowan Group have undergone greenschist facies regional metamorphism.

Brown (1985a), and Borradaile and Brown (1987) have shown that only one episode of deformation has affected the Shebandowan greenstone belt. In a study by Borradaile and Brown (1987) of structural elements within the Shebandowan Group, they concluded that it had been folded in a single tectonic episode. Their work has also unequivocally indicated that an unconformity does exist between the older Burchell and Greenwater assemblages, and the overlying Shebandowan Group.

Tectonic Setting

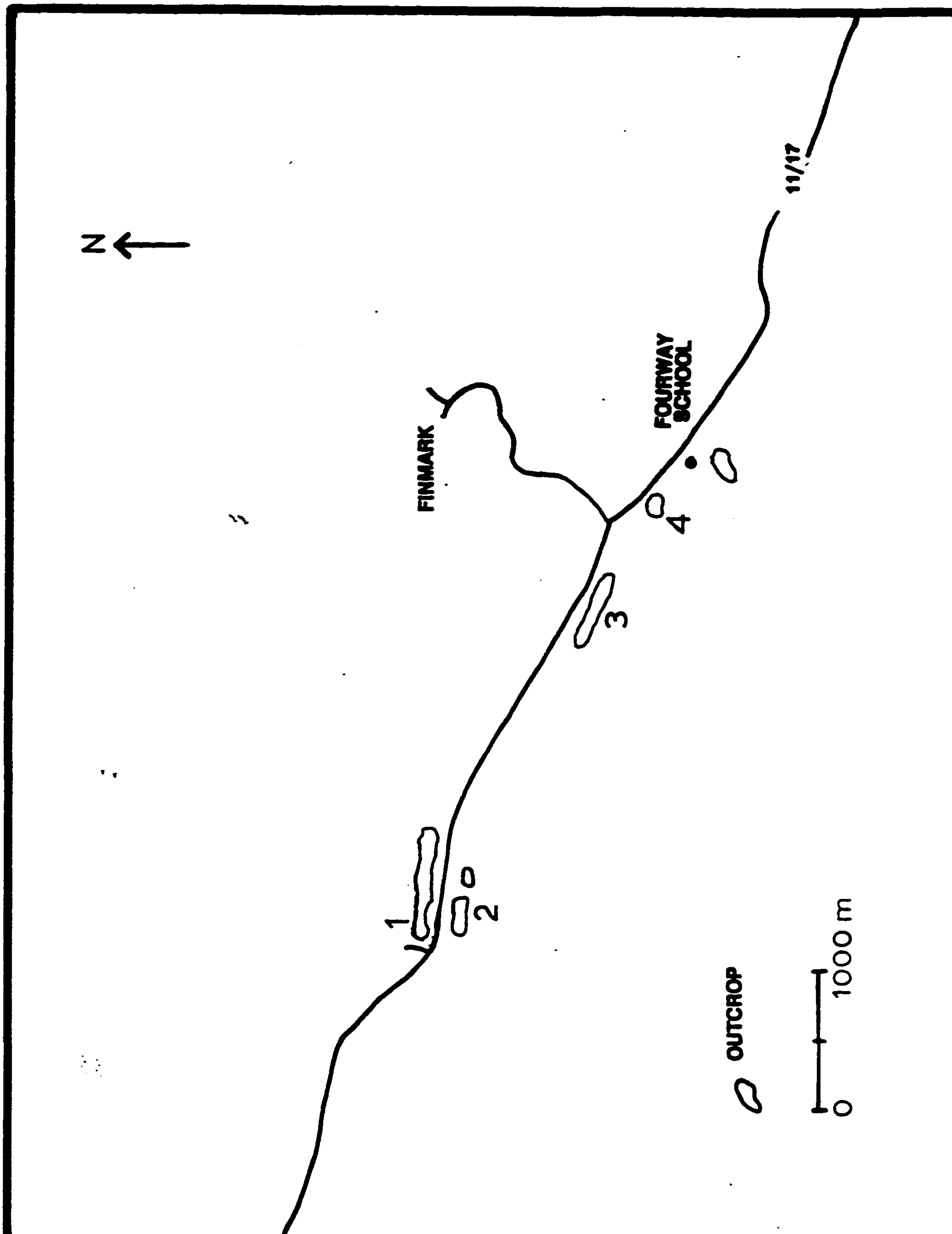
The calc-alkalic - shoshonitic suite of rocks is very similar both chemically and petrographically to Timiskaming volcanic rocks examined by Corfu *et. al.* (1991). The Timiskaming volcanic rocks have been interpreted as representing the products of magmatism and tectonism related to the final stages of subduction during and following collision and amalgamation of arcs (Corfu *et. al.*, 1991). Chemical and petrographic similarities between the two groups of volcanic rocks, and lithological similarities between associated sedimentary rocks indicate that the rocks of the Shebandowan Group are also products related to arc magmatism and tectonism in the final stages of subduction. Eriksson *et. al.* (1994, in press) favour this tectonic environment for the Shebandowan Group. Their paper states that the sediments of the Shebandowan Group were deposited in a forearc or rifted interarc basin of a mature volcanic arc immediately prior to a major collisional event (Eriksson *et. al.*, 1994).

METHODOLOGY

Detailed logging of all outcrops containing facies associations formed in shallow water environments was carried out in the fall of 1994 and the summer of 1995. Logging involved measuring and describing all beds on a centimetre to decimetre scale, and construction of stratigraphic sections. During the mapping process samples were taken from numerous locations in the outcrop, and their exact positions recorded. These samples were subsequently slabbed, and further logging was done on a millimetre and centimetre scale with the aid of a binocular microscope. Stratigraphic sections were constructed from these slabbed samples which provide further insight into the minute variations and transitions found both in and between individual beds and laminae. Both the outcrops present in the study area and the slabbed samples were examined for the existence of tidal bundles or rhythmites.

All outcrops in the study area were logged and sampled. Photographs of sedimentary structures were also taken. Locations of all outcrops are shown on Figure 1-3. The only outcrop not extensively logged was behind Fourway School, as it was heavily covered with lichens, and no sedimentary structures were discernable.

FIGURE 1-3 Location of outcrops within the study area.


N
11/17
FOURWAY SCHOOL
FINMARK
1
2
3
4
OUTCROP
0
1000 m

CHAPTER TWO -- TIDAL ENVIRONMENT

Work by Parker (1980) has identified the existence of at least one main depositional environment within the current study area. This environment, which he interprets to be tidally-influenced (Parker, 1980), was broken down into the tidal flat and tidal channel sub-environments. Since environmental interpretations have already been made, the terms tidal flat and tidal channel sub-environments will be used to aid in the description of the sedimentary structures and features that are present in these two sub-environments.

Sedimentary structures and features that are characteristic of a tidal environment are present in all outcrops of the study area. The tidal environment can be subdivided into the tidal flat and tidal channel sub-environments; both of these sub-environments are strongly represented. Within the outcrops a lack of bioturbation has allowed the superb preservation of sedimentary structures and features. Many of the observed physical features closely resemble those that are present in Phanerozoic and present-day tidal environments.

Both upward-fining and coarsening trends are present in the outcrops. On a large scale, the outcrops exhibit overall coarsening trends toward the offshore environment, or towards the centre of a tidal channel. Occasionally, a fining trend exists superimposed on the overall coarsening trend, such as when moving out of the tidal channel sub-environment, and back into the tidal flat sub-environment.

A wide range of sedimentary structures are present in all of the outcrops (see Figures 2-1 & 2-2). These structures have been divided into a number of different bed types. The characteristics of all bed types present in the tidal environment are discussed in the following sections. An additional section discusses those features that do not easily fall under one of the various bed types.

WAVY - LENTICULAR - FLASER BEDDED LITHOFACIES

Reineck and Wunderlich (1968) present both a classification scheme and define wavy, lenticular and flaser bedding. The classification scheme, which is illustrated in Figure 2-3 is divided into three main bedding types, as well as a number of subdivisions. The nature of the subdivisions is determined by the nature of either the sand lenses, or the mud flasers. This classification scheme was utilized in the following descriptions of wavy, lenticular and flaser bedding.

Flaser, and especially lenticular bedding is ubiquitous throughout the outcrops of the study area and in addition to wavy bedding, are characteristic of the tidal environment (Figures 2-1 & 2-2). A variety of grainsizes are represented in the wavy, lenticular and flaser beds. These grainsizes range from coarse-grained sandstones to fine-grained siltstones and mudstones.

Lenticular and Flaser Bedding

Lenticular and flaser bedding are very common in the study area. Both types of

FIGURES 2-1 &2-2 Sedimentary structures typical of the tidal environment. Wavy, lenticular, flaser and coarsely interlayered bedding are all present in the photograph. Parallel laminated and massive beds can also be seen.

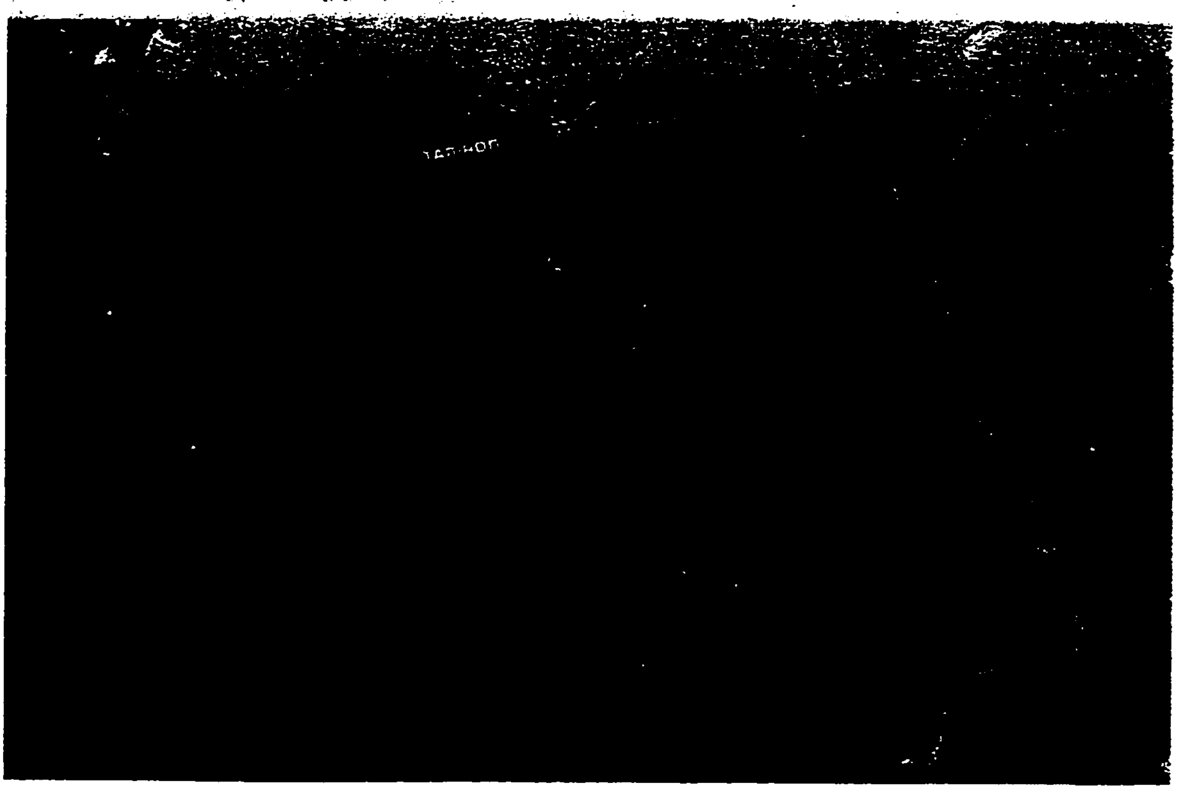
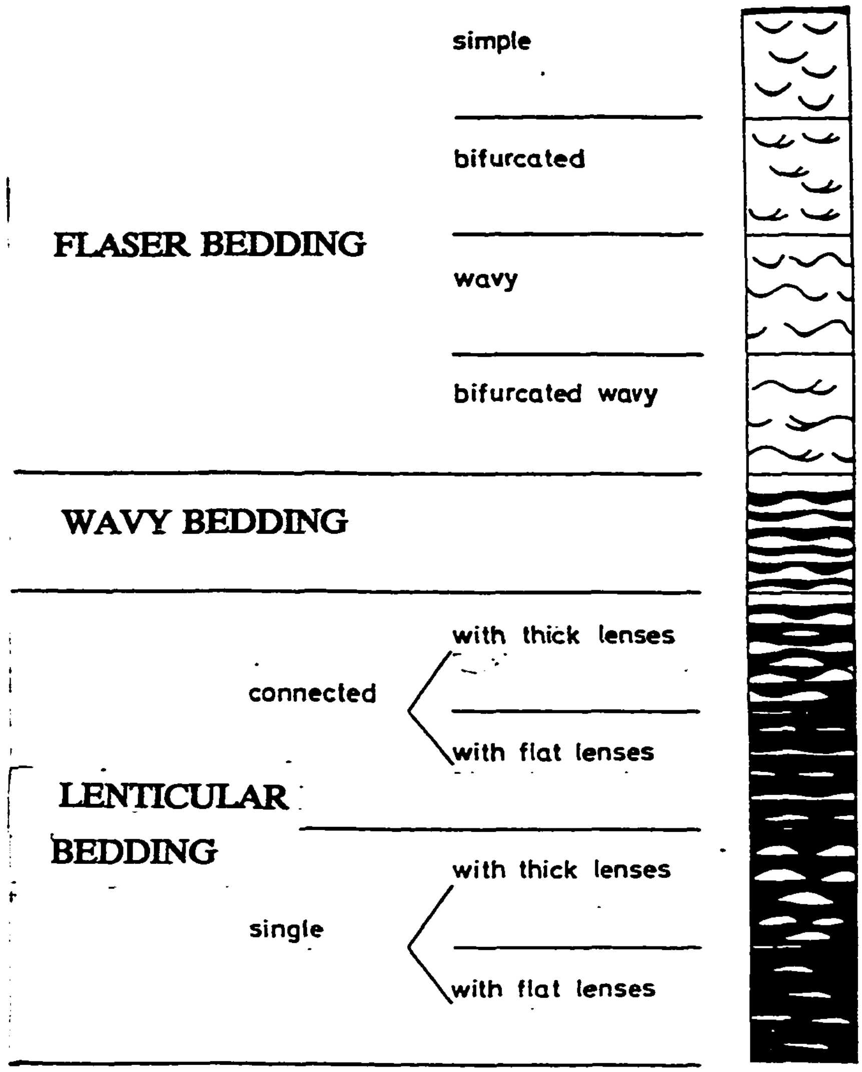


FIGURE 2-3 Scheme from Reineck and Wunderlich (1968) for the classification of flaser, lenticular, and wavy bedding.



simple
bifurcated
FLASER BEDDING
wavy
bifurcated wavy
WAVY BEDDING
with thick lenses
connected
with flat lenses
LENTICULAR BEDDING
with thick lenses
single
with flat lenses

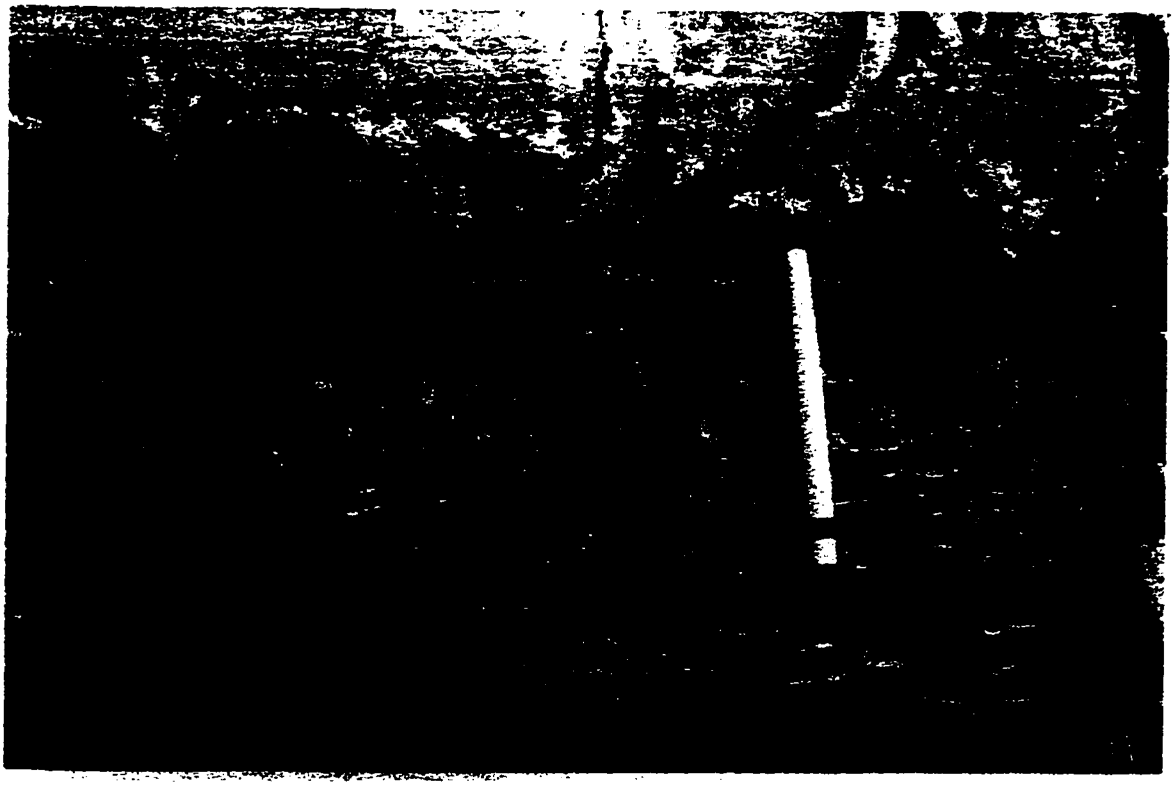
bedding are closely spatially associated with each other. Beds range in maximum thickness from 2.3 to 80.0 centimetres, with an average bed thickness of 14.0 centimetres. The characteristics of each bedding type will be discussed separately, but they will be treated together in discussions of the other types of bedding that they are commonly associated with.

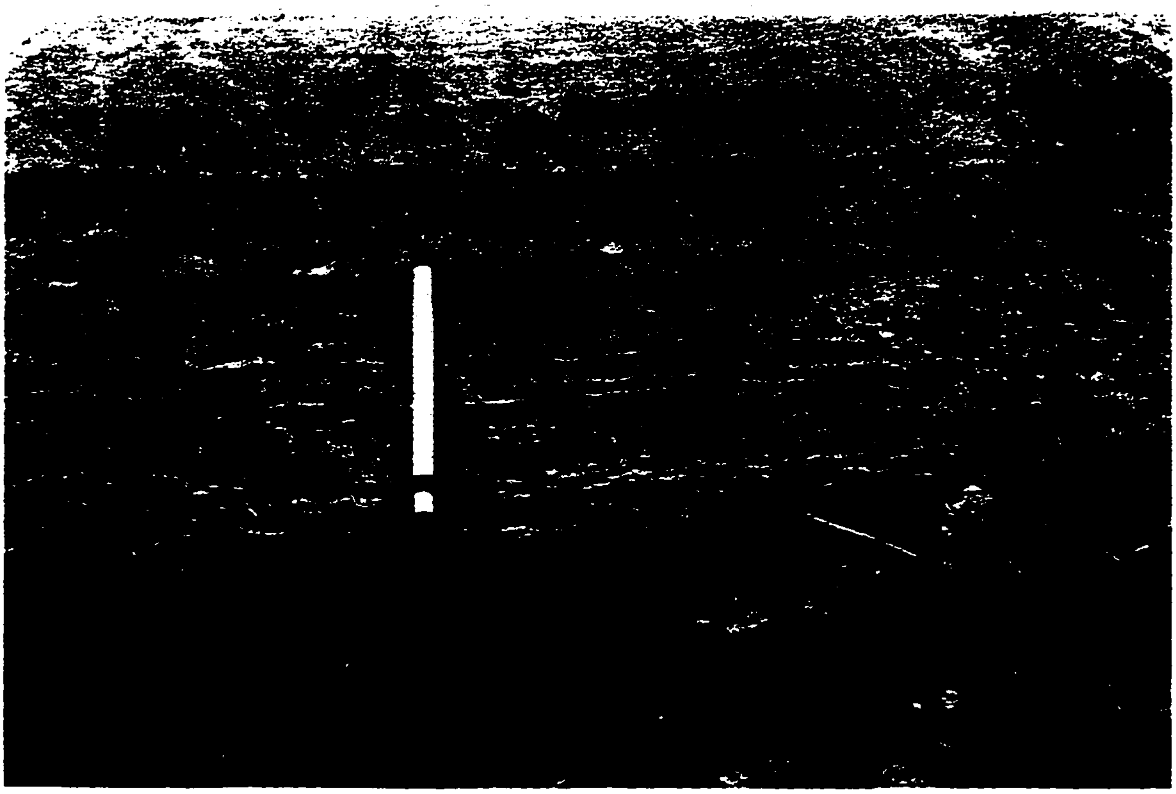
Lenticular bedding refers to the presence of isolated or connected sand lenses in a series of muddy layers (after Reineck and Wunderlich, 1969). This type of bedding is common in many of the outcrops in the study area (Figures 2-4 and 2-5). The lenses are usually composed of fine-, medium- or coarse-grained sand. They appear to be suspended in layers of very fine-grained siltstone to mudstone. Based on the nature of the sand lenses (see Figure 2-3), lenticular bedding can be subdivided into two different types (Reineck and Wunderlich, 1969). The first type is lenticular bedding in which the lenses are connected. The second type is lenticular bedding with single lenses.

The majority of the lenticular bedding in the study area contains connected lenses. Laterally, in many of the beds, the connected lenses will pass into isolated lenses and then back into a series of connected lenses. In other beds, the layer of connected lenses can be traced out for the entire length of the bed. Many of the lenses are thick compared to their length, (2 - 3 cm in length: 1.5 - 4 cm in thickness) although others appear somewhat elongated and flattened (6 - 8 cm in length; 1 - 2 cm in thickness).

FIGURE 2-4 Lenticular bedding with both connected and single lenses. Wavy bedding and parallel lamination is also present in the top part of the picture.

FIGURE 2-5 Lenticular bedding.





Lenticular bedding with isolated or single lenses is much rarer. In this type, theisolated lenses appear to float in the very fine-grained siltstone or mudstone layer. These lenses are isolated in both the horizontal and vertical directions. The lenses may be thick or flattened in appearance.

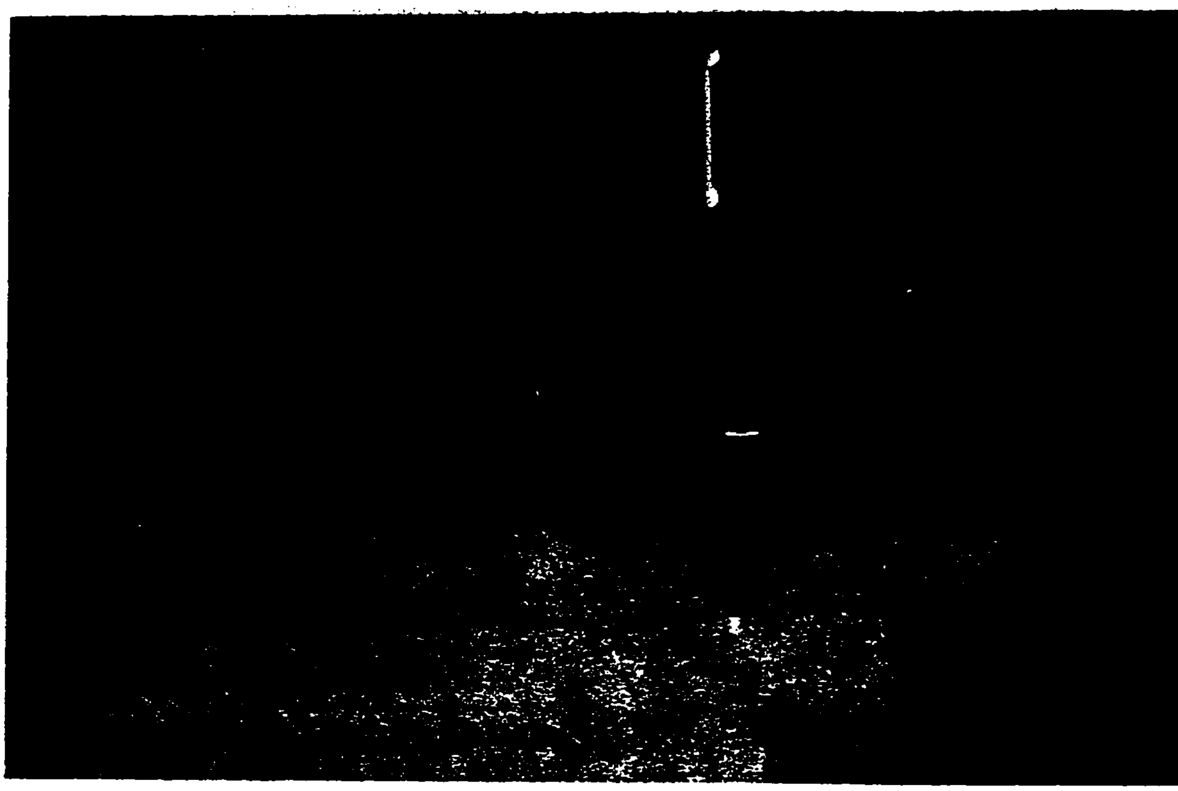
In flaser bedding, mud flasers are present in layers of fine- to coarse-grained sandstone. Flasers are simply incomplete mud laminae. Flaser bedding can be divided into a number of different types (Figure 2-3), based on the nature of the mud flasers. The different types of flaser bedding that are present in the outcrops of the study area include; simple flaser bedding, wavy flaser bedding, and bifurcated wavy flaser bedding.

Simple flaser bedding contains isolated mud flasers that have no contact between each other in both horizontal or vertical directions. The ends of the individual flaser curve upwards, resulting in a concave appearance to the flasers.

Wavy flaser bedding is common throughout the study area. As the name implies, the flasers are wavy in appearance, and show both concavity and convexity. It often appears as if a number of flasers are connected in a horizontal direction (Figure 2-6). This apparent layer of mud flasers though, is laterally discontinuous and represents overlapping flasers.

Bifurcated wavy flaser bedding is also present in a number of the outcrops,

FIGURE 2-6 Laterally discontinuous layer of wavy flaser bedding.

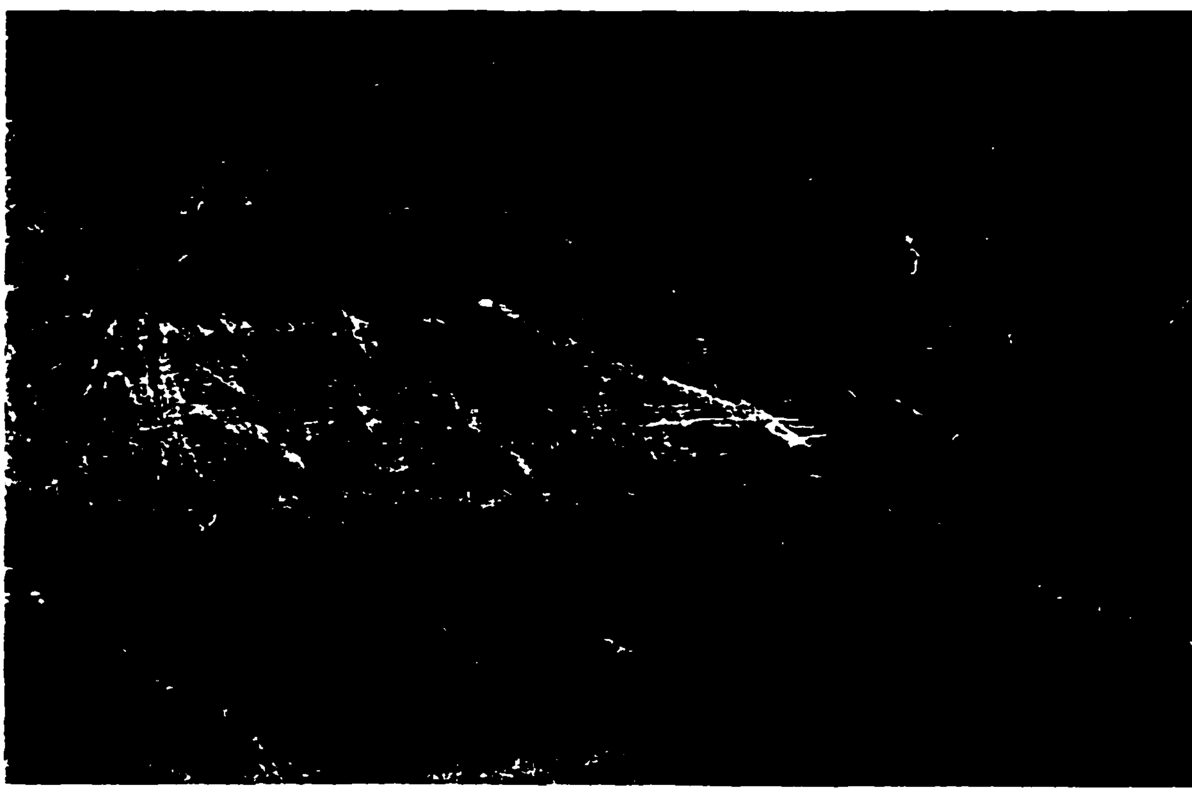


especially outcrops 1 and 2 (Figure 1-3). In this type of flaser bedding, the wavy mud flasers are bifurcated. In other words, the flasers divide into two separate parts. Once again, although a number of flasers may appear to be joined together in a single layer, these apparent layers are laterally discontinuous.

Lenticular and flaser beds are commonly overlain and underlain by either massive or parallel laminated sandstone beds (Figure 2-7). Very often, there are no sharp and distinct boundaries between these different bed types. Many of the sandstone beds gradationally pass upwards into overlying lenticular and flaser beds. Sometimes, there is load casting of the overlying sandstone beds into the top layers of lenticular and flaser bedding. On one occasion, the top layer of lenticular and flaser bedding which underlies a parallel laminated sandstone bed, is erosively cut by ripple laminated sandstones.

Wavy bedding is closely associated with flaser and lenticular bedding (see Figure 2-4). Contacts between the wavy beds, and the lenticular and flaser beds can be sharp or gradational and irregular or flat. The base of a wavy bed will often load down into underlying lenticular bedding. Coarsely interlayered bedding (described in a later section) is also found in association with flaser and lenticular bedding. Wherever a coarsely interlayered bed underlies flaser and lenticular bedding, the boundary between the two bed types is irregular and gradational. When a coarsely interlayered bed overlies lenticular and flaser bedding, the boundary is sharp and distinct.

FIGURE 2-7 Interbedded flaser, lenticular, wavy, parallel laminated sandstone beds, and massive siltstone beds.



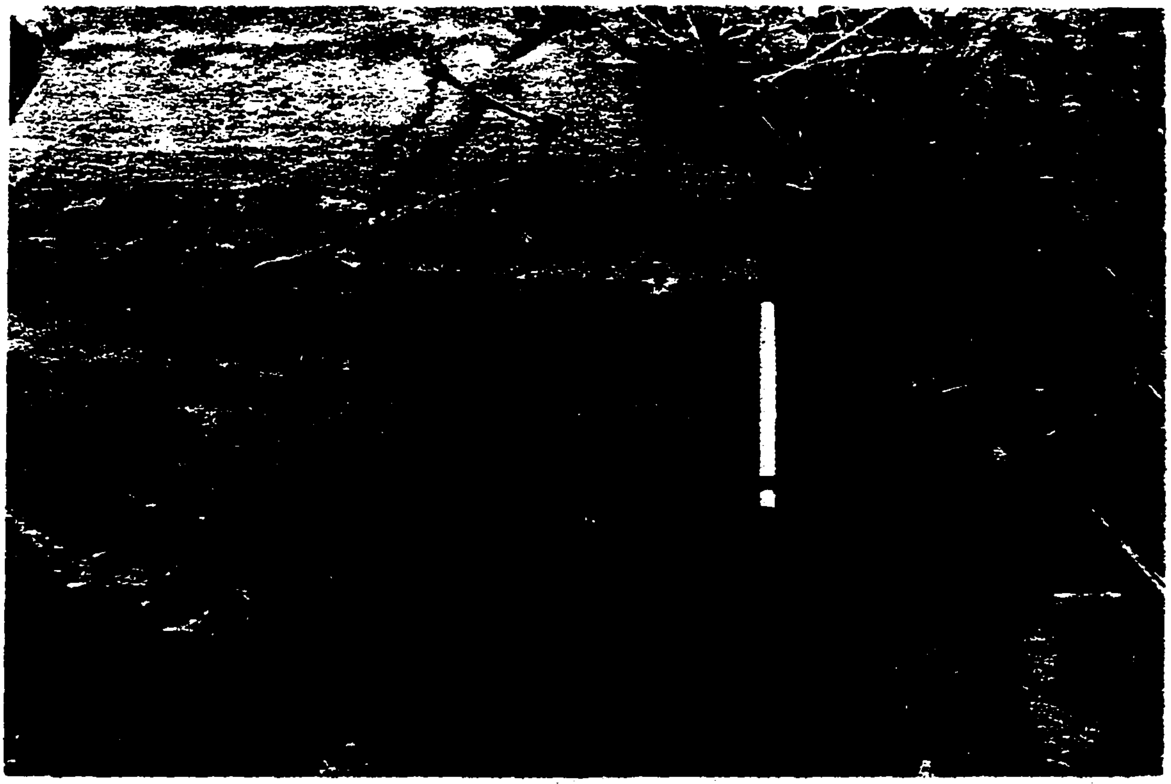
Two of the flaser beds are cut by sandstone lenses. The top of one 25.0 cm bed is cut by a sandstone lens, 30.0 x 5.0 centimetres in size. The lens is filled with coarse-grained sand-sized material which fines up into a fine-grained sandstone. The other bed contains a sandstone lens similar in size, which shows no grading within the lens.

Wavy Bedding

Throughout outcrops 1 and 2, there are beds with a fine- to medium-grained sandstone base which fines upwards into a fine-grained siltstone or mudstone top. The transition from the medium-grained base into the fine-grained top is marked by the presence of a single layer composed of a horizontal series of asymmetrical ripples (Figure 2-8). The ripples have heights of 2.0 centimetres or less, and wavelengths of 5.0 centimetres or less. The overlying silts and muds completely fill the ripple troughs and thinly cover the ripple crests. The medium-grained basal portion of the bed is always considerably thicker than the fine-grained top. The layer of silt and mud which comprises the top is generally 1.0 centimetre or less in thickness.

These beds range from 1.0 to 25.0 centimetres in thickness. The average thickness of a wavy bed is approximately 7.5 centimetres. Individual beds of this type tend to vertically stack in sequences 2 or 3 beds thick. The beds in a stacked sequence average 6.0 to 7.0 centimetres in thickness. All beds appear to be laterally extensive, although they do occasionally exhibit a slight pinching and swelling.

Figure 2-8 Wavy bedding - note the asymmetical ripples.



The fine- to medium-grained sandstone that comprise the basal portion of a wavy bed are typically parallel laminated (67 percent of the beds). The remaining 33 percent of the beds consist of a massive fine- to medium-grained base, which fines upwards. Within this parallel laminated basal portion, laminae thickness varies from 0.1 to 0.5 centimetres. The laminae are usually composed of fine-grained silt or mud. The silty and muddy tops are never parallel laminated.

In one section of outcrop 1, wavy bedding is present in a transition zone between a tidal channel sub-environment and an overlying tidal flat sub-environment. Two beds, with no parallel lamination overlie an infilled channel scour. The bed which immediately overlies the channel scour contains randomly oriented elongate mud chips. These chips are typically 1.0 x 0.5 centimetres in size. Mud chips are also found in the second bed, where they are concentrated in the first 1.5 centimetres of the bed. Mud chips, of comparable size, are located sporadically throughout similar beds in all outcrops examined. As with the second bed, the chips are typically concentrated in the bottom two centimetres of beds.

A wide variety of other types of beds overlie and underlie the wavy bedding. These beds vary from massive and parallel laminated sandstone, siltstone and mudstone to wavy, lenticular and flaser bedding. Convolute beds and coarsely interlayered bedding are also associated with wavy bedding. While many of the boundaries between the beds and the overlying or underlying beds are sharp, some gradational boundaries are present.

There are two siltstone beds that are the fine-grained equivalents of wavy bedding. The bases of these beds are composed of medium- to coarse-grained silt which is topped by a single layer of asymmetrical ripples. These ripples are the same size as those in the coarse-grained wavy beds. The ripple troughs are filled with mud and fine-grained silt, the ripple crests are thinly covered by the same material. These beds are also comparable in thickness, 6.5 and 9.0 centimetres, to the coarse-grained beds. Neither of the two beds are parallel laminated. One of the beds is overlain by a massive sandstone bed, the other grades into a parallel laminated sandstone bed.

MASSIVE AND PARALLEL LAMINATED SANDSTONE LITHOFACIES

Massive Sandstone Beds

A number of the fine- to coarse-grained sandstone beds in the tidal environment are massive (Figure 2-9). Many of these beds exhibit normal grading, with grainsize decreasing towards the top of the bed. The normally graded massive beds are topped by layers of massive, very fine-grained siltstone or mudstone which range in thickness from 0.2 to 0.5 centimetres. Two millimetre white feldspar grains are present in the coarse-grained base of a number of beds.

Ten percent of the massive beds show no internal grading. Less then two percent of these beds are topped by a very thin layer (0.1 - 0.2 mm) of fine-grained silt. Below this layer of fine-grained silt grainsize remains uniform.

FIGURE 2-9 **Massive, non-graded fine-grained sandstone bed, overlain by a massive fine-grained siltstone bed.**

Bed thicknesses range from 2.0 centimetres to 1.0 metre, with an average thickness of 14.0 centimetres. A large percentage of beds occur as solitary units within sequences of other bed types. In at least six instances though, two to four massive beds are vertically stacked. Boundaries between the vertically stacked beds are sharp and distinct.

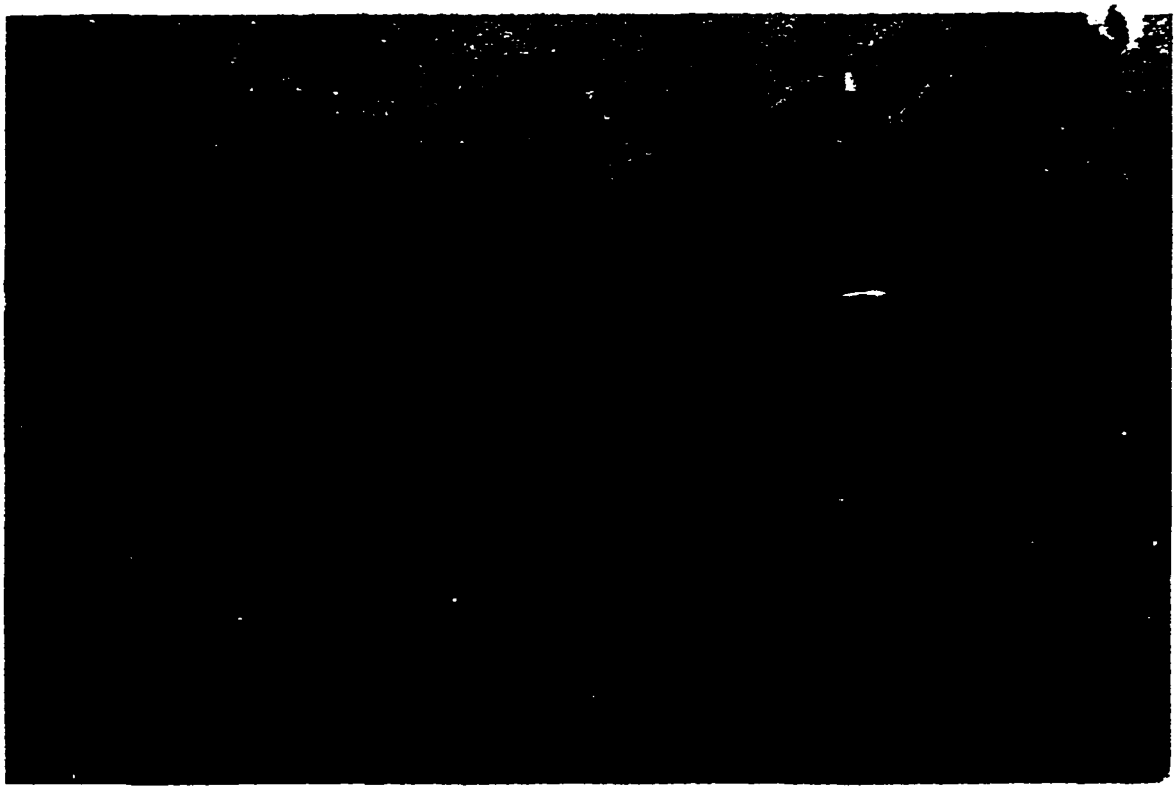
In the tidal flat environment, many of the massive, medium-grained beds remain fairly uniform laterally for the width of the outcrop (2 metres); with very little variation in bed thickness or internal structures. Although the medium-grained portion of a bed remains laterally uniform, the thin silty or muddy tops commonly thin and thicken laterally. Very rarely, the medium-grained portion of the bed will also thin and thicken laterally.

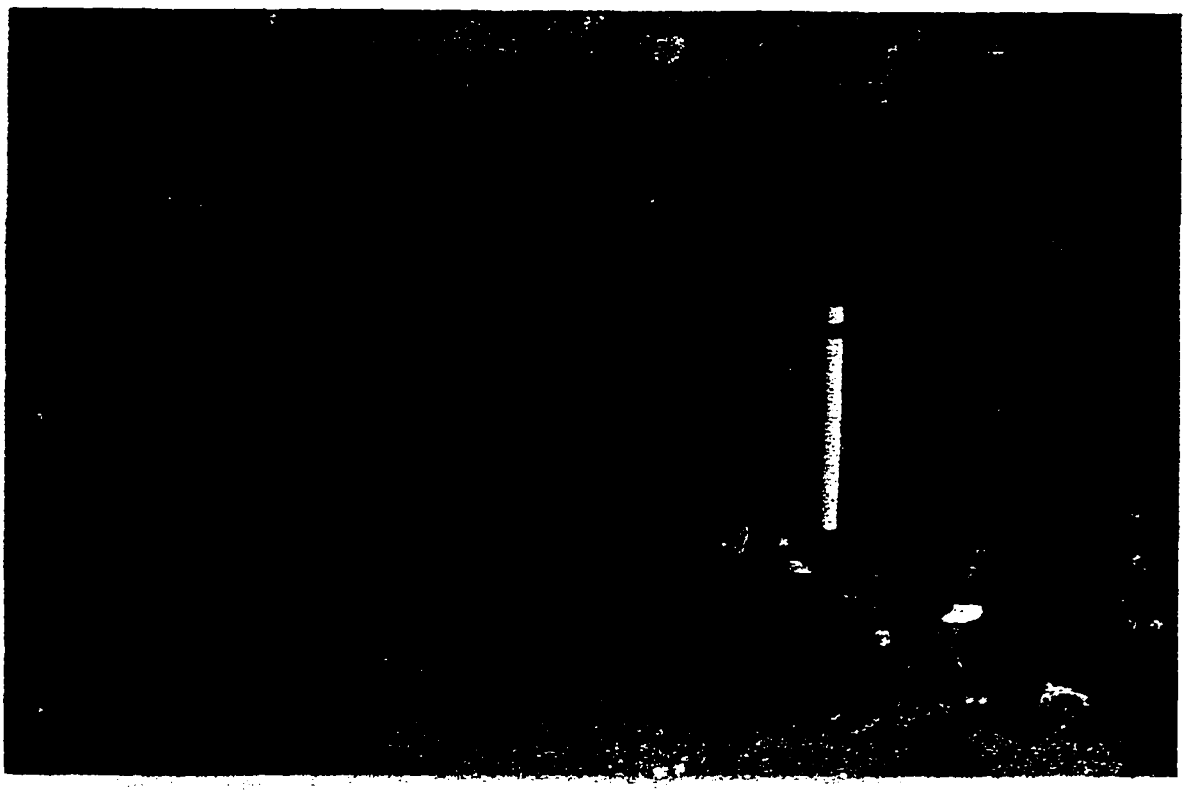
Lenses are also present within the graded and non-graded massive beds. Typically the lenses are composed of fine- to coarse-grained sandstone. One bed contains lenses of very coarse-grained sandstone. In the graded beds, the grainsize of the sandstone within the lenses is usually coarser than the sand which comprises the portion of the bed containing the lenses. In the non-graded beds, the sandstone in the lenses is coarser then the sandstone which makes up the entire bed. Many of theses lenses appear slightly flattened and elongated. Muddy lenses are also present. The only massive bed which dies out laterally contains numerous mud lenses.

Thin discontinuous laminae and wisps of mudstone can be found in two of the

Figure 2-10 Discontinous mudstone wisps and laminae in a massive very fine-grained sandstone bed.

Figure 2-11 Mud chips in a medium-grained massive sandstone bed.





massive, graded beds (Figure 2-10). In outcrop 2, the top of a 6.0 centimetre thick graded bed contains vertically stacked, isolated and discontinuous laminae of mudstone. The mud laminae are slightly wavy and appear to be mudstone drapes over a series of vertically stacked ripples. Mudstone drapes are also present in the uppermost 3.0 centimetres of a 9.0 centimetre thick bed, where they partially drape ripples. Once again, the mud drapes are vertically stacked on top of one another. In the middle of the 3.0 centimetres containing the mud drapes a 5.0 x 1.0 cm lens is present. This lens is filled with medium-grained sandstone. The beds which contain mud drapes are overlain by massive, graded beds.

Mud rip-ups and chips are present in the massive, sandstone beds (Figure 2-11). In one example, a bed which overlies lenticular bedding contains mud rip-ups. The rip-ups occur in the lowest two centimetres of the bed. Half-way up the bed, an isolated mud lens is present. Another bed contains mud chips which are 0.5 to 1.0 centimetres in diameter. These chips are found in the uppermost, fine-grained portion of the bed. In this case, the bed containing the chips is part of a series of vertically stacked massive beds, and immediately underlies a similar massive bed. Mud clasts typically range in size from 0.5 x 2.0 cm to 0.7 x 2.0 cm. Isolated larger sand grains are also present in a small number of beds. In one bed, the top 8.0 centimetres contains small pebbles which average 1.0 x 2.0 centimetres in size. The largest clast is 2.0 x 3.0 centimetres.

In outcrop 1, a 7.0 centimetre thick laterally discontinuous bed fills a channel scour. This scour is 80.0 centimetres wide, and overlies a bed of parallel laminated medium- to coarse-grained sandstone, and underlies a wavy bed. The sand which comprises the channel fill becomes slightly finer grained towards the centre of the channel. Small drapes of mud over the top of coarse-grained sand laminae are found in the upper one centimetre of the bed.

Both the graded and non-graded massive beds are overlain and underlain by a wide range of bed types. These include massive and parallel laminated siltstone/mudstone beds, as well as parallel-laminated sandstone beds. Lenticular, wavy, and flaser bedding are also underlain or overlain by massive sandstone beds. Generally, transisitions and boundaries between all beds are sharp and distinct. A number of the massive beds though, are gradational into overlying beds.

Gradual vertical transitions from massive, sandstone beds into overlying lenticular to flaser bedding are common. These vertical transitions are present in both the graded and non-graded beds. Transitions between these beds are not sharp, but instead, are irregular and indistinguishable. Typically there is a slight decrease in grainsize from the massive bed into the wavy, lenticular or flaser bedding. The 4.5 centimetre bed which is cut by thin layers of siltstone is one of the beds which passes upwards into flaser and lenticular bedding. In a number of beds though the opposite occurs; lenticular and flaser beds are found to gradually pass upwards into the massive, sandstone beds. In two of these cases, the flaser and lenticular beds were convolute laminated. In another case, there was load casting of an overlying massive bed into the top 2.5 centimetres of an underlying layer of lenticular bedding.

Both graded and non-graded massive beds are overlain and underlain by coarsely interlayered bedding. Load casting of an overlying massive bed into a fine-grained layer of tidal bedding is quite common. In this case, the load casting is restricted to the uppermost fine-grained layer in the coarsely interlayered beds.

A non-graded massive bed overlies a light coloured, parallel laminated, graded sandstone bed. The basal portion of the non-graded bed sinks slightly into this underlying sandstone bed, forming a shallow concave load cast. This bed is overlain by an infilled channel scour, which slightly cuts down into the underlying bed. At another location a similar light coloured sandstone bed is overlain by a graded massive bed. As with the non-graded bed, the graded bed sinks slightly down into the top 2.0 centimetres of the sandstone bed.

A number of massive beds are also found in association with other bed types. A 2.0 centimetre thick non-graded bed separates two units of coarsely interlayered bedding. Boundaries between all the beds are sharp. Two non-graded beds occur within a sequence of interbedded massive siltstone and mudstones beds and coarsely interlayered bedding. Once again, boundaries between all the beds are sharp and distinct. Finally, a 2.5 centimetre thick bed separates two units of lenticular bedding.

In the tidal channel sub-environment, non-graded massive beds are commonly associated with beds of small-scale cross-stratification. In Outcrop 2, the massive beds appear to separate cross-stratified beds. Boundaries between the beds are sharp and distinct. In one example, a 37.0 centimetre thick bed separates cross-stratified beds. Small mud chips are concentrated near the boundary between the two different beds, and for the most part, the boundary separating the two beds is clear and distinguishable.

Many of the thicker beds are interbedded with thin, laterally extensive beds of siltstone. One 73.0 centimetre thick sequence contains sandstone beds interbedded with beds of fine-grained silt which are between 0.5 to 4.0 centimetres in thickness. Another 32.0 centimetre thick interbedded sequence contains thin (1.0 cm thick) beds of siltstone and thicker beds of sandstone. Finally, a 4.5 centimetre thick sequence contain thin sandstone and siltstone beds, averaging 0.75 centimetres in thickness.

Parallel Laminated Sandstone Beds

Beds of parallel laminated, very fine- to medium-grained sandstone are also present in the tidal environment (Figures 2-12, 2-13, and 2-14). Approximately half of these beds are internally graded, while the remainder exhibit no form of internal grading. The majority of the beds are laterally extensive, and remain fairly uniform laterally over the width of the outcrop.

The vast majority of the massive or parallel laminated sandstone beds present in the outcrops of the study area are composed of sand which is medium to dark gray

FIGURE 2-12 A graded, parallel laminated sandstone bed. Note the presence of two massive sandstone beds at the top of the photograph.

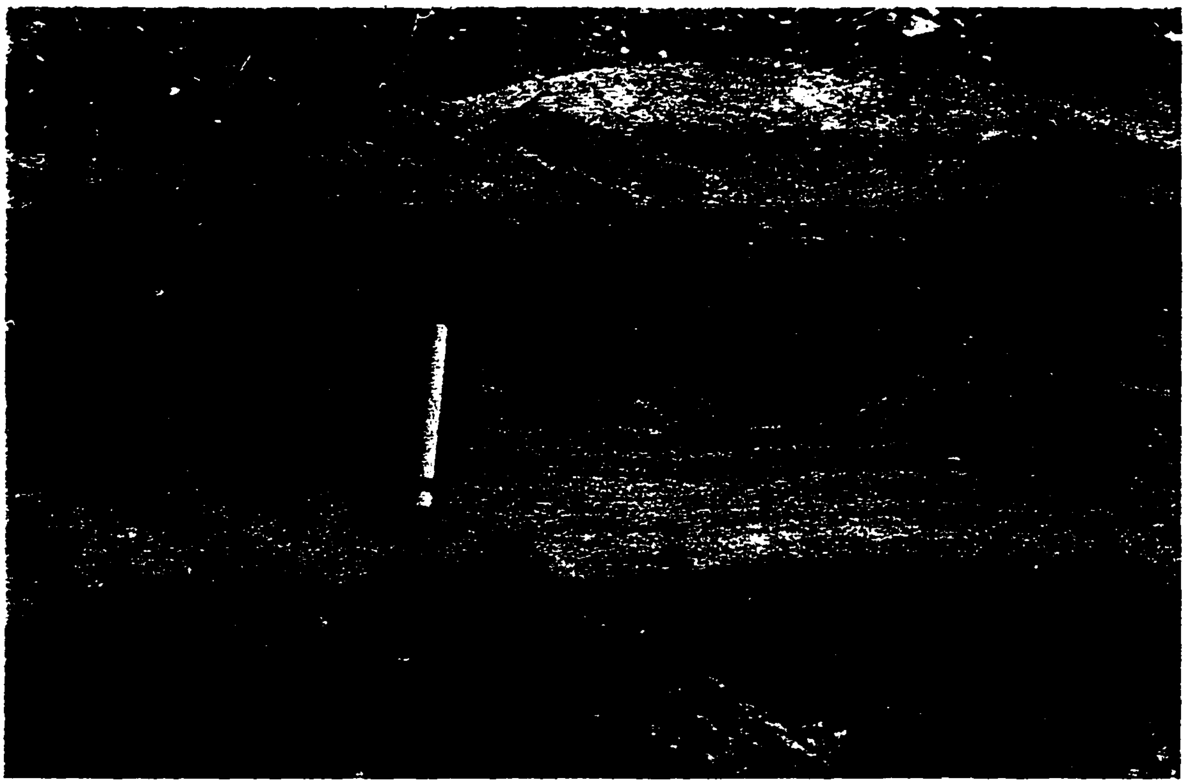
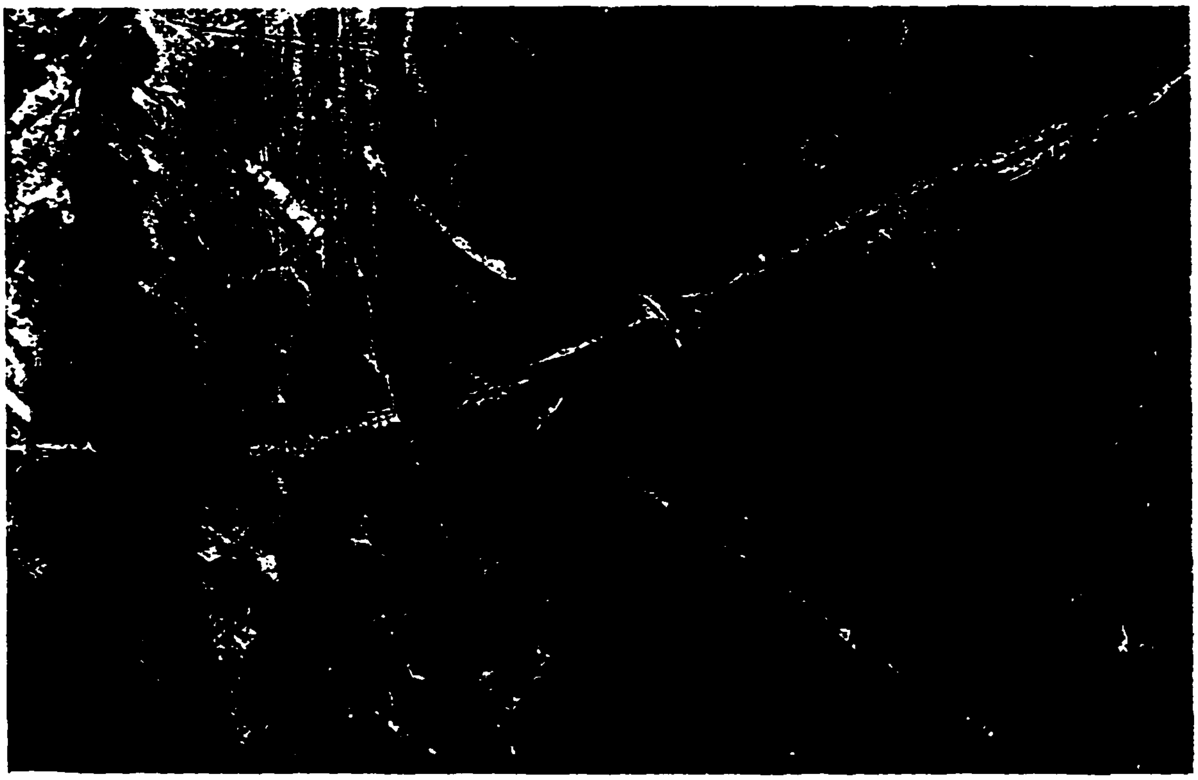
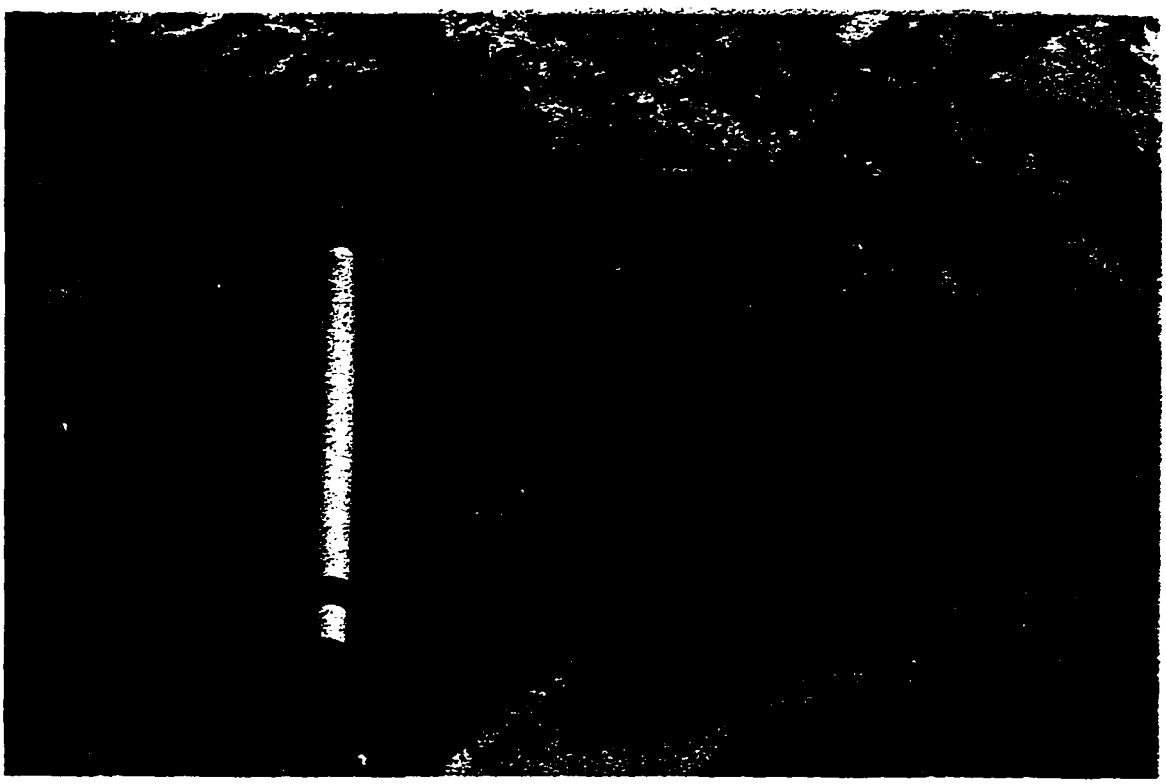


FIGURE 2-13 Parallel laminated sandstone bed in association with other lithofacies present in the tidal environment.

FIGURE 2-14 Close-up of the parallel laminated sandstone bed shown in Figure 2-13





or light black in colour. In marked contrast to these darker coloured beds, are light coloured beds. These beds usually appear to be a light tan or brown in colour. They average between 10 to 20 centimetres in thickness, and occur sporadically throughout the tidal environment. All beds are laterally continuous, and remain uniform in a lateral direction.

The internally graded beds increase in abundance towards the transition zone between the tidal and offshore environments. The thickest of these beds is 67 centimetres in width, the thinnest bed is 3.0 cm, with an average bed thickness of 13.2 centimetres. Beds which exhibit no internal grading are thicker. Nongraded beds range from 2.0 to 97.0 centimetres, with an average bed thickness of 28.3 centimetres.

The internally graded, parallel laminated beds display a vertical transition from a fine- to medium-grained sandy base, upwards into a fine-grained silty or muddy top. Moving upward through an outcrop, the base of beds becomes slightly finer grained. In rare cases (< three percent of the beds) there is a coarse- to very coarse-grained sandstone base. The non-graded parallel laminated beds range in grainsize from fihe-grained to coarse-grained sandstone. One bed is composed of very coarse-grained sand. Once again, moving up the outcrop, grainsize decreases, and the majority of the beds are composed of non-graded very fine- to fine-grained sandstone.

Like many of the other coarse-grained beds, both the parallel laminated graded and non-graded beds often occur as a series of vertically stacked beds. Typically such a series is comprised of two to four beds, all of similar thickness. In outcrop 1, a 2.5 metre portion is composed of numerous small parallel laminated graded beds. These beds range in thickness from 2.0 to 16.0 centimetres. Boundaries between all beds in the vertically stacked series are usually sharp, and it is very rare to see gradations from one bed into the other. In outcrop 1 though, one series of beds do grade into one another. At the point where one bed grades into the other, two layers of vertically stacked ripples are present.

Laminae thickness of the parallel laminated beds varies from 0.05 to 0.2 centimetres. Although the majority of beds contain laminae which are parallel and straight (Figure 2-14), some beds contain laminae which are slightly wavy. Occasionally very thin, discontinuous, isolated wisps or laminae of fine-grained silt or mud occur between individual laminae.

Isolated mud drapes (Figure 2-12) are common in both the graded and non-graded beds. Mud lenses are also prevalent. The mud lenses are abundant in the non-graded beds, but are rare in the graded beds. Isolated mud lenses are present in only one of the graded beds. The mud lenses are typically 8.0 centimetres in length, and 0.3 centimetres in height. In the non-graded beds, the mud lenses are also isolated. These lenses are usually 0.1 to 0.5 centimetres in length, and 0.2 centimetres in height.

Beds that are close to the top of the tidally-influenced environment are punctuated by thin layers of very fine-grained sandstone to medium-grained siltstone. These layers are 0.5 to 1.0 centimetres in thickness, and are laterally continuous. For example, a non-graded 16.0 centimetre thick bed, is broken up by 0.5 to 0.75 thick layers of medium-grained silt. A 67.0 centimetre thick graded bed is cut by a total of thirteen, approximately 1.0 centimetre thick, layers of fine-grained siltstone.

Boundaries between the graded parallel laminated beds and those which overlie or underlie them can be either sharp or gradational (Figure 2-13). Many beds will grade upwards into lenticular and wavy bedding, and occasionally flaser bedding. Gradational and sharp boundaries are also associated with the non-graded, parallel laminated beds. Sharp boundaries can be seen between these beds and the fine-grained beds which typically underlie them. Alternatively, the non-graded, parallel laminated beds will often show a slight gradation into overlying graded, parallel laminated beds. In outcrop 1, one bed cuts downwards and terminates a layer of parallel laminated silt.

Customarily, non-graded, parallel laminated beds and cross-stratified beds occur in association with one another. This association is very apparent in outcrops 1 and 2 and will be discussed in Chapter 3. Usually, the non-graded beds grade vertically into the cross-stratified beds, and then the cross-stratified beds gradually pass back into another non-graded, parallel laminated bed. In one non-graded bed, at the transition between the bed, and the overlying cross-stratified bed, isolated mud clasts are found at the top of the non-graded bed. These mud clasts appear to follow the

FIGURE 2-15 Massive fine-grained siltstone to mudstone beds at the bottom of the picture. A graded, parallel laminated, medium-grained siltstone bed is present in the middle of the picture.

trend of the overlying cross-stratification.

SILTSTONE AND MUDSTONE LITHOFACIES

Massive Siltstone and Mudstone Beds

Approximately sixty percent of all siltstone and mudstone beds present in the tidal environment are massive (Figure 2-15). Bed thicknesses range from 0.5 to 50.0 centimetres, with an average thickness of 9.0 centimetres. Grainsize varies from coarse-grained silt to mud. Normal grading is present in the vast majority of beds. Typically a bed will grade from a medium- or coarse-grained siltstone base into a mudstone top. Rarely, non-graded massive beds of very fine-grained siltstone or mudstone are present.

Many of the massive siltstone and mudstone beds persist laterally; in fact only three of the beds present in the tidal environment terminate laterally. Two of these beds are less then five centimetres in thickness. At the point where the beds pinch out, they are overlain and underlain by massive medium- to coarse-grained sandstone beds.

The third laterally terminating bed is fifteen centimetres thick, and is composed of coarse-grained silt. The bed extends laterally for 65 centimetres where it pinches out. It is overlain by a bed of parallel laminated, medium-grained sandstone which cuts downwards into the siltstone.

Lenses of medium- to coarse-grained sand occur sporadically in a number of the massive beds. The lenses vary in size up to 15.0 x 4.0 centimetres. Lenses infilled with mud are also quite common, and are randomly distributed throughout the fine-grained beds of the tidal environment. The mud lenses tend to be smaller in size than their coarse-grained equivalents.

Very thin (1.0 to 3.0 mm) laterally discontinuous wisps of very fine-grained silt or mud are also present within individual beds. The wisps tend to occur as isolated entities among the fine-grained beds that they are found in. The grainsize of the material supporting the wisps is slightly coarser grained than that of the wisp. In one or two areas, the wisps have a drape-like or amputated ripple-like appearance.

A wide range of beds both overlie and underlie the massive siltstone and mudstone beds, including both massive and parallel laminated sandstone beds, coarsely interlayered bedding, lenticular, wavy and flaser bedding. Boundaries between beds can be either sharp or irregular. Very often, an overlying coarse-grained bed loads into the top portion of the siltstone or mudstone bed.

Boundaries are almost always gradational between the massive siltstone and mudstone beds and overlying or underlying lenticular, flaser or wavy bedding. Gradational boundaries also mark the passage of a massive siltstone and mudstone bed into an overlying parallel laminated siltstone and mudstone bed. This phenomena is also observable in the beds of the massive and parallel laminated sandstone facies.

Very rarely, sharp and irregular boundaries are present.

Siltstone and mudstone beds are present in combination with convolute lenticular bedding. The siltstone and mudstone beds are typically 2.0 centimetres in thickness, and pinch and swell laterally, extending slightly upwards into the overlying beds of convolute lenticular bedding. Massive siltstone and mudstone beds also occur in association with coarsely interlayered bedding. Boundaries between the beds are very sharp and distinct. The massive beds average two centimetres in thickness. This association is discussed fully in the section on coarsely interlayered bedding.

Reversely Graded Siltstone and Mudstone Beds

Although normal grading is common in the majority of the fine-grained beds in the tidal environment, seventeen percent of fine-grained beds exhibit reverse grading. These beds have a medium- to coarse-grained silty base, and coarsen upwards into a fine- to medium-grained sandy top. All of these beds are massive. The thickest bed (54.0 cm) of the reversely graded fine-grained sediments is present in the transition zone from a tidal channel into a tidal flatl. In other words, the bed coarsens upwards in the direction of the tidal flat. All of the reversely graded beds are overlain by either a bed of massive, medium-grained sandstone, or coarsely interlayered bedding. Boundaries between all the beds are gradual.

One of the coarsening upwards beds occurs in a small channel incised in the top of a bed of herringbone cross-stratification. This channel is 15.0 centimetres in width, and 5.0 centimetres in depth. Long and narrow chips of mud are also present within this bed. A bed of massive, medium-grained sandstone overlies the reversely graded siltstone.

Parallel Laminated Siltstone and Mudstone Beds

Twenty-three percent of the siltstone and mudstone beds are parallel laminated. Grainsize in the parallel laminated beds ranges from coarse-grained silt to mud. The beds vary from 3.0 to 60.0 centimetres in thickness. The average bed thickness is 17.0 centimetres. Normal grading is common in these beds; as with the massive siltstone and mudstone beds, these grade from a medium- or coarse-grained silty base up into a very fine-grained silty or muddy top (Figure 2-15). All of the parallel laminated beds are laterally continuous for at least the width of the outcrop (2.0 metres)..

Laminae in the beds will sometimes have a slightly wavy appearance, but overall, the beds are horizontally, parallel laminated. Laminae are typically 0.1 to .05 centimetres in thickness and are laterally continuous. The laminae are composed of sediment ranging in size from fine-grained silt to mud.

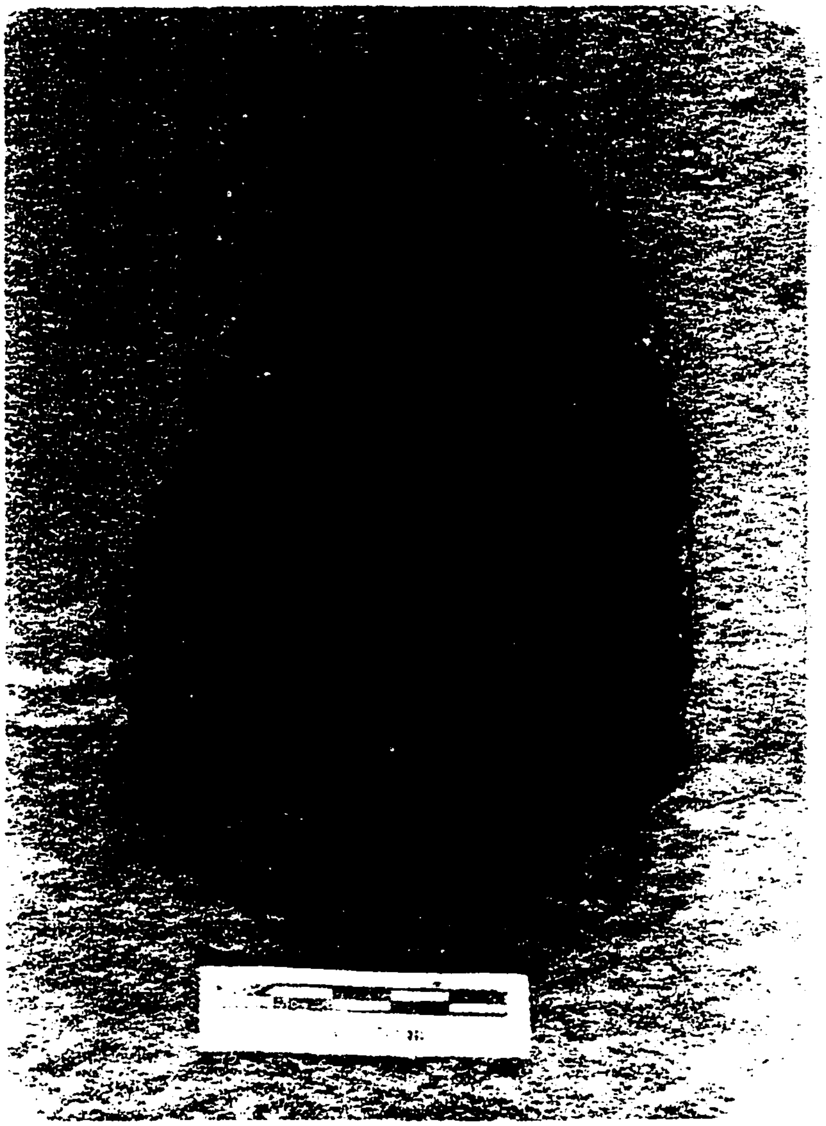
Many of the features observed in the massive siltstone and mudstone beds are also present in the parallel laminated siltstone and mudstone beds. Lenses filled with fine- to coarse-grained sand or mud which are present in the massive siltstone and mudstone beds are also common in the parallel laminated siltstone and mudstone beds. Sand lenses average 0.5 centimetres in height, and 4.0 centimetres in width. Thin, isolated, laterally discontinuous wisps of very fine-grained silt and mud are present as well.

As with the massive sandstone beds, the parallel laminated siltstone and mudstone beds are also overlain and underlain by massive and parallel laminated sandstone beds, coarsely interlayered bedding, and lenticular to flaser bedding. The parallel laminated siltstone and mudstone beds are also underlain by beds of the massive siltstone and mudstone facies. As described in the previous section on massive siltstone and mudstone beds, the massive beds will gradually pass up into an overlying parallel laminated bed of siltstone or mudstone. Gradational boundaries such as this are also common between lenticular, wavy, and flaser bedding and the parallel laminated siltstone and mudstone beds.

COARSELY INTERLAYERED BEDDING LITHOFACIES

Sequences consisting of alternating layers composed of fine- and coarse-grained sediments are present (Figures 2-1, 2-2, & 2-16). The coarse-grained layers are sandstones and the fine-grained layers consist of either siltstone or mudstone. These interlayered sequences are commonly referred to as tidal bedding, but this term is ambiguous and non-descriptive. A more useful term is coarsely interlayered bedding (Reineck and Singh, 1973). The coarsely interlayered bedding found within the study area contains alternating layers of fine- to coarse-grained sandstone and coarse-

FIGURE 2-16 Coarsely interlayered bedding is present in the lower portion of the photograph. Note the alternation of the thin, very dark siltstone layers with the slightly lighter and thicker sandstone layers.



grained siltstone to mudstone.

Sequences of coarsely interlayered bedding range in thickness from 1.0 cm to 57.0 cm. In the thinner sequences, thickness of the individual layers varies from 0.1 to 0.4 centimetres. In the thicker sequences, individual layers up to 4.0 cm thick are present, though it is rare to find individual units of this thickness, typically individual layers are less than 2.0 centimetres thick. The thicker layers represent less then 5 percent of the total layers present in coarsely interlayered bedding. More commonly, individual layers have thicknesses between 0.1 to 2.0 centimetres.

In outcrop 1, which contains the entire succession through tidal flat and channel sub-environments, a trend can be observed within sequences of coarsely interlayered bedding. As one moves up towards the top of the outcrop, the thickness of the individual fine-grained layers within the bedding increases. Overall, the amount of individual fine-grained silt and mud layers also increase in number. A similar trend is also present within individual coarsely interlayered beds. Within many of the interlayered beds, there is also an increase in the thickness and abundance of individual fine-grained layers towards the top of the bed.

Transitions between the alternating fine- and coarse-grained layers are usually sharp. Rarely load casting of one of the individual coarse-grained layers into the underlying fine-grained layer is present. Typically the coarsely interlayered beds are topped by a final layer of silt or mud, so load casting of coarse-grained material in an overlying bed into this final fine-grained layer of a coarsely interlayered bed is common.

Some of the coarsely interlayered beds are topped by a layer of parallel laminated silts and muds. These uppermost layers are generally 0.5 to 2.0 centimetres in thickness. In one coarsely interlayered bed in outcrop 2, there is a coarse-grained layer which pinches and swells laterally at the transition between the lower portion of the bed and the fine-grained layer which tops it..

Though beds pinch and swell laterally the coarsely interlayered beds are laterally continuous. Many of the individual fine- and coarse-grained layers which comprise the coarsely interlayered bedding are laterally continuous within the beds. A few layers though, do terminate laterally, and grade horizontally into either the overlying fine- or coarse-grained layer.

Occasionally, the coarsely interlayered beds will have a slightly wavy appearance, similar to an interlayered sequence of wavy beds. The wavy appearance dies out laterally, and the layers once again appear straight and parallel. In some locations, the coarsely interlayered beds are convolute.

Many of the individual layers within coarsely interlayered beds appear to be parallel laminated. Laminae consist of very fine-grained silt and mud within the medium- to coarse-grained sand layers, and the inverse in the silt and mud layers. Laminae are iess then 0.5 millimetres in thickness and persist laterally throughout the individual layers.

Internally, some of the thicker medium- to coarse-grained sandy layers exhibit normal grading. These individual layers fine upwards from a medium- to coarse-grained sandy base into a fine-grained sandy top. Fining trends were not presente in the thinner, silty or muddy layers.

Rarely, lenses of coarse-grained sand are present within the coarsely interlayered beds. These lenses range from 1 to 5 centimetres in length, and 0.5 to 1.5 centimetres in thickness. The lenses occur randomly throughout the coarsely interlayered beds.

The majority of coarsely interlayered beds are overlain by fining upwards massive and parallel laminated sandstone beds. Transitions between the overlying massive and parallel laminated beds and the coarsely interlayered beds are usually gradual. Massive medium to coarse-grained sandstones beds also underlie the interlayered bedding. Once again, transitions between the beds are gradual.

Wavy, flaser and lenticular bedding also underlie coarsely interlayered beds. Where the coarsely interlayered beds are underlain by flaser and lenticular or wavy bedding, there is a gradual transition from this bedding type upwards into the coarsely interlayered bed.

At one location in outcrop 2, a 8.5 centimetre thick section occurs in which coarsely interlayered beds alternate with laterally continuous beds of massive siltstone. The coarsely interlayered and massive beds average one centimetre in thickness. Transitions between the massive siltstone and mudstone beds and the coarsely interlayered bedding are sharp. This association is discussed in Chapter 3.

Finely Rhythmically Laminated Bedding

There are also rare occurrences of finely rhythmically laminated bedding. This bedding also consists of alternating layers of fine- and coarse-grained sediment, but on a much smaller scale than the coarsely interlayered bedding. In this case, the individual fine- and coarse-grained layers within a bed are only a few millimetres in thickness. The layers appear to rhythmically repeat, and it is this repetition that has resulted in the term tidal rhythmites being assigned to this type of bedding.

CROSS-STRATIFIED LITHOFACIES

Herringbone Cross-Stratification

Herringbone cross-stratification is a term applied to cross-stratified beds showing opposite dip directions of foreset laminae in adjacent layers (Reineck and Singh, 1975). This form of cross-stratification is characteristic of the tidal channel sub-environment where typically two opposite-dipping cross-stratified units are separated by a thin layer of mud. Herringbone cross-stratified beds occur with regularity throughout the tidal channel sub-environment. Usually the presence of herringbone cross-stratification is accentuated by carbon staining of the rocks (Figures 2-17 and 2-18).

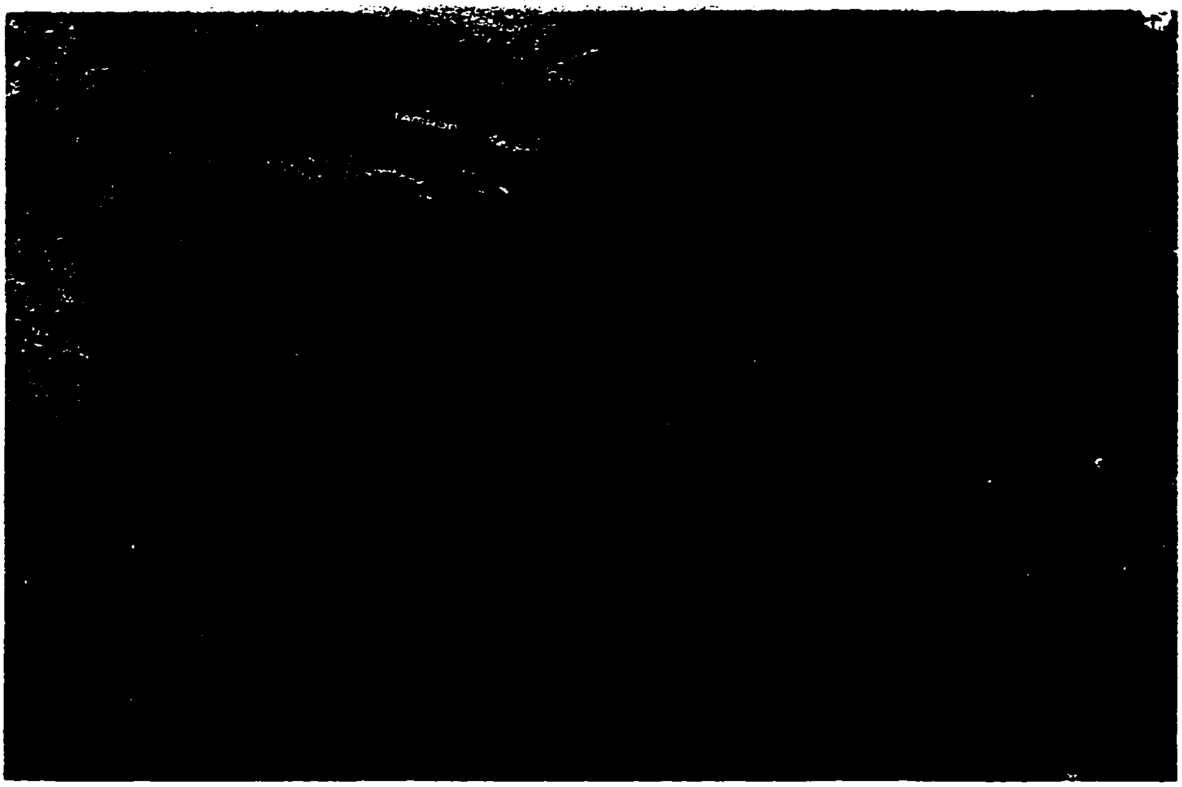
Thicknesses of herringbone cross-stratified beds range from 2.0 to 53.0 centimetres. The majority of these beds are laterally continuous. Within the herringbone cross-stratified beds, thin (0.1 - 0.3 cm) laminae of silt and mud are present. Grain size within the herringbone cross-stratified units varies from fine-grained silts to coarse-grained sands. Rarely there is a slight decrease in grainsize from the base of the bed to the top.

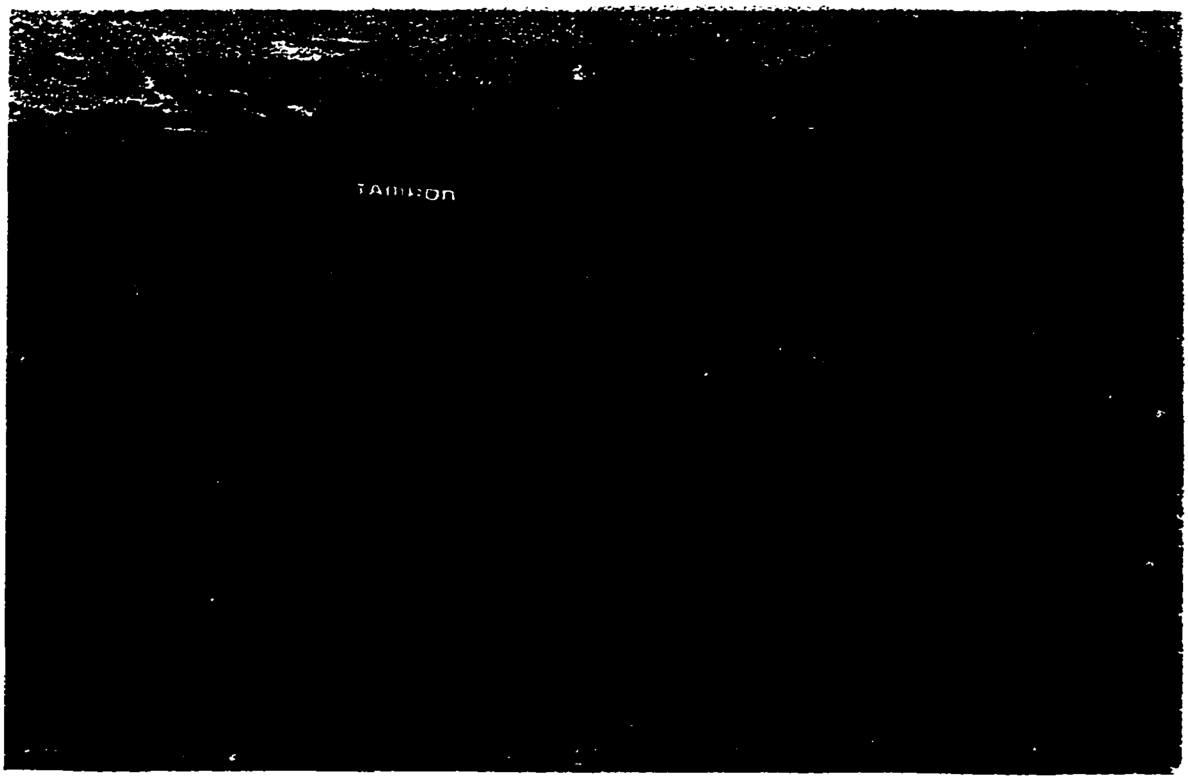
Herringbone cross-stratification will rarely occur in association with the parallel laminated and massive sandstone, siltstone and mudstone beds. In one portion of the outcrop, a very thin lens (2.0 cm), occurs within a thick bed (48.0 cm) of massive, very fine-grained sandstone containing isolated lenses of coarse-grained sand. The boundaries between these beds are sharp. Parallel laminated siltstone beds underlie thick sequences of herringbone cross-stratified beds.

In another instance, a 7.5 cm thick bed of herringbone cross-stratification is erosively cut by numerous small, vertically stacked channels. These small channels have been infilled with fine-grained silt, and contain very thin, long slivers of mud. Upwards from the infilled channels, grainsize increases until eventually small grains of feldspar become visible to the naked eye.

FIGURE 2-17 Herringbone cross-stratification accentuated by carbon staining.

FIGURE 2-18 Close-up of Figure 2-17.





The majority of herringbone cross-stratified beds occur in association with beds of trough and epsilon cross-stratification. In the lower portions of the tidal channels, interbedded units of trough and herringbone cross-stratification are common. Usually, the trough cross-stratification passes upwards into herringbone cross-stratification.

Small-Scale and Large-Scale Planar Cross-Stratification

Sequences of small-scale and large-scale planar cross-stratification are common. The large-scale cross-stratified beds are found at the base of these sequences, while the small-scale cross-stratification dominates at the top of a sequence (Figure 2-19). Typically, the majority of the beds exhibiting cross-stratification are composed of fine- to coarse-grained sand. Occasionally, the beds will exhibit internal grading, fining up the dip of the laminae into a coarse-grained silt. These beds may also be overlain by a very thin ($\leq$0.5 cm) layer of massive fine-grained silt or mud. Bed thicknesses range from 3.5 to 21.0 centimetres.

Within the beds, foreset laminae average 0.2 centimetres in thickness. The laminae are usually at angles of 15 - 30° to the base. In many of the beds, small mud flakes are present in the basal portion of the bed. These small mud flakes parallel the laminae, and are orientated at a similar angle to the base of the bed as the laminae.

FIGURE 2-19 Planar cross-stratification - note the slight decrease in bed thickness towards the top of the photograph.

The majority of the cross-stratified beds are laterally extensive. Though one 10 centimetre thick bed exhibits both lateral and vertical variations. In both the lateral and vertical directions, the bed changes from a cross-stratified sandy bed into a massive, graded sandy bed.

Trough Cross-Stratification

Beds of trough cross-stratified sandstone are found in both the tidal flat and tidal channel sub-environments. They are composed of fine- to coarse-grained sand. Beds range from 3.0 to 23.5 centimetres in thickness. Randomly scattered, rare, isolated mud chips are present in some of the beds.

When trough cross-stratification is present in the tidal channel sub-environment, it is always found in association with beds of herringbone cross-stratification. In the tidal flat sub-environment, it is usually interbedded with either massive or parallel laminated sandstone beds. Boundaries between the interbedded sandstone and cross-stratified beds are typically sharp and distinct.

Epsilon Cross-Stratification

The only beds with epsilon cross-stratification surfaces present in the study area, occur in the tidal channel sub-environment. These beds range in size from 4.0 to 36.0 centimetres. Internally, the beds are composed of small-scale planar cross-stratification. Occasionally, small pebbles of mud are randomly scattered throughout the beds. Transitions between beds with epsilon cross-stratification surfaces and herringbone cross-stratified beds are fairly sharp. Typically these beds separate thicker beds of herringbone cross-stratification.

OTHER SEDIMENTARY FEATURES

Ripples

Evidence of combined current/wave ripples is present throughout many of the outcrops in the study area. Ripplemarks are occasionally found on the surface of the outcrop. The ripples are typically composed of fine- to medium-grained sandstone, and are present as undulations on the tops of siltstone and sandstone beds. Most of the ripples are small in scale, with ripple wavelengths of 2.0 to 5.0 centimetres, and heights of 0.5 to 3.0 centimetres. Many of the ripples exhibit some degree of asymmetry. Both rounded and flat-topped ripples are present in the siltstone and sandstone beds.

The majority of the combined current/wave ripples are present as reworked and erosive forms. These two forms belong to a subgroup of form-discordant ripples that Reineck and Singh (1975) have termed as secondarily form-discordant ripples. In form-discordant ripples, the outer shape of the ripple does not correspond to the internal structure, and the outer form of the ripple is not genetically related to the internal structure of the ripple (after Reineck and Singh, 1975).

At one location (outcrop 1), the presence of ladderback ripples (Figure 2-20) has been observed. The occurrence of ladderback ripples occurs in close proximity to a bed of herringbone cross-stratification. These ripples have very little preservation potential, therefore the presence of ladderback ripples in rocks of the study area, represents a rare occurrence.

Deformation Structures

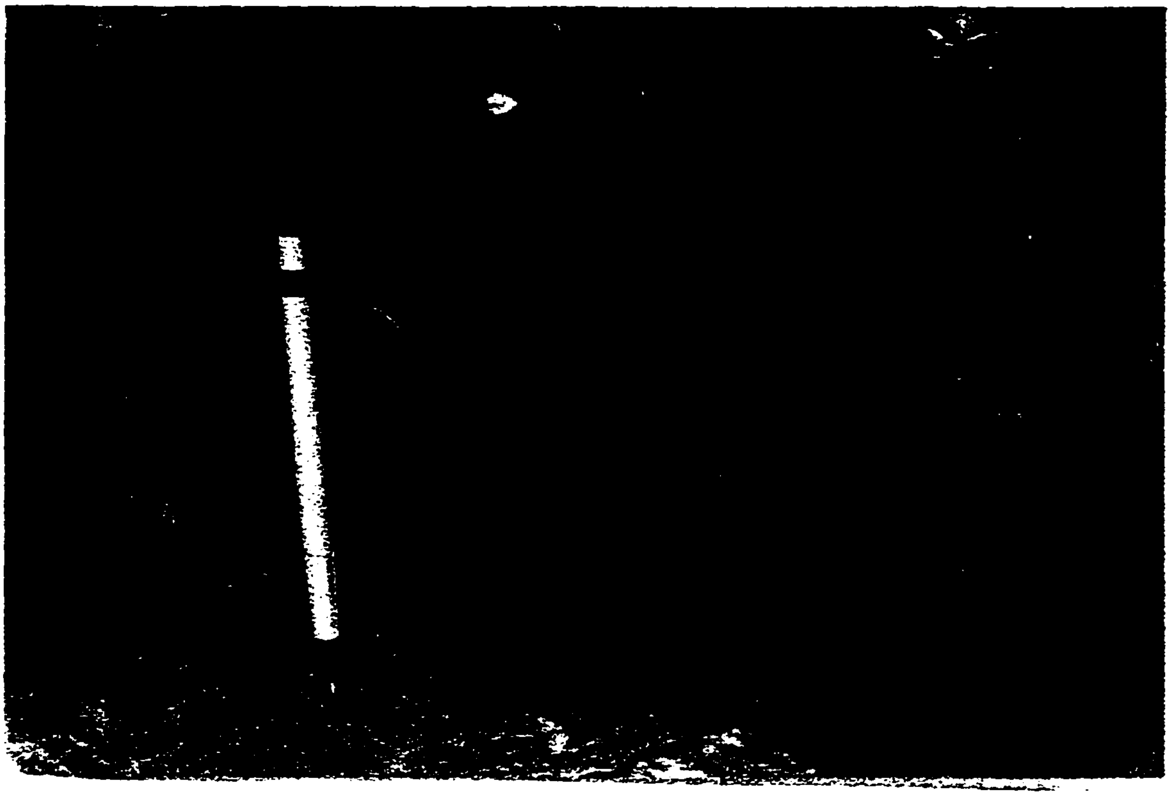
Although only 3 to 4 percent of all beds are convolute in appearance, these beds occur indiscriminantly scattered throughout the outcrops of tidal flat sediments. The convolute beds range from 2.0 to 20.0 centimetres in thickness. Many of the convolute beds consist of interlayered fine- to medium-grained sand, silt and mud (Figure 2-21). Towards the tops and bottoms of the convoluted beds, the layers become parallel laminated. Laterally, the convolute portions of the layers are commonly discontinuous, and pass into parallel laminated sand, silt, and mud. Although the majority of the convolute layers are associated with parallel laminated sandstones and siltstones, layers of wavy bedding also occasionally exhibit a convolute appearance.

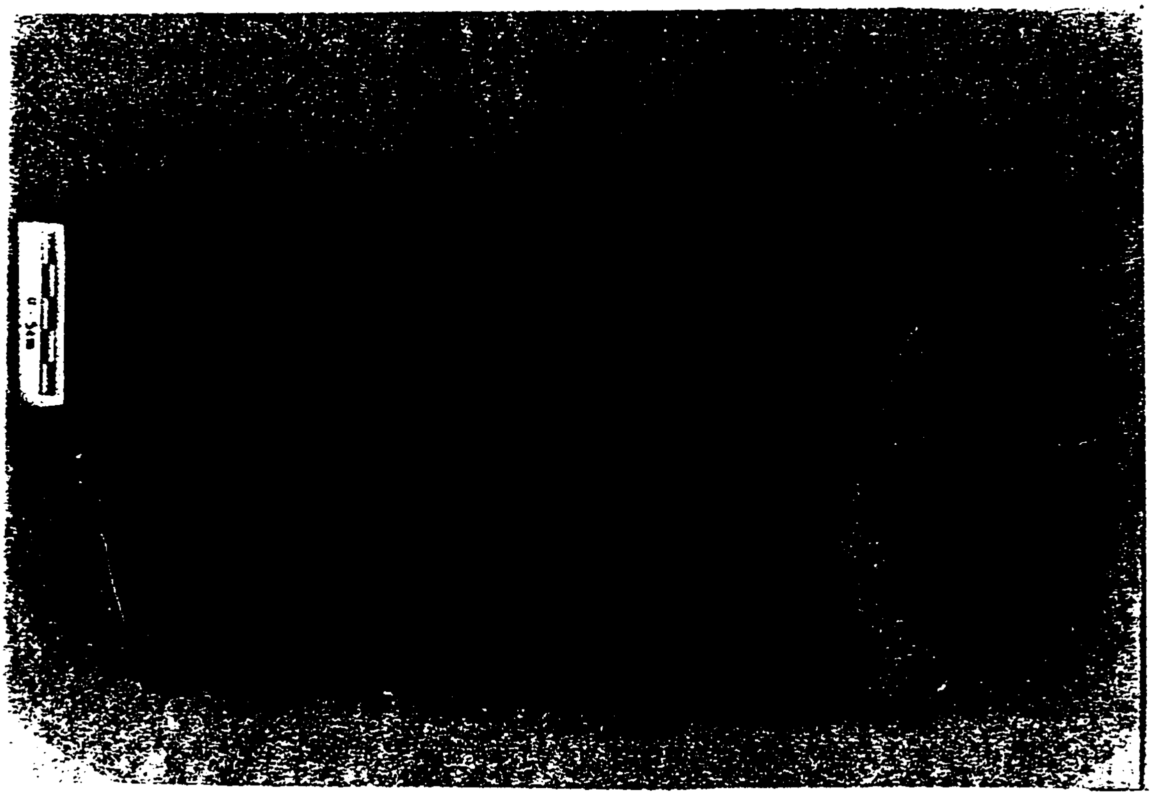
Convolute interlayered sequences of sandstones, siltstones, and mudstones are also present. In this case, a series of alternating individual, thin beds of sand, silt, and mud are highly deformed. These interlayered sequences appear to represent convoluted coarsely interlayered bedding. Units of lenticular and flaser bedding are also convolute in some sections of the outcrop. Typically the flaser and lenticular beds gradually become convolute for a couple of centimetres, and then pass back into

FIGURE 2-20 Ladderback ripples.

FIGURE 2-21 Convolute bedding, near top of sequence.

FIGURE 2-22 Convolute bedding near the middle of a sequence of lenticular, flaser and coarsely interlayered bedding.





the flaser and lenticular bedding (Figure 2-22).

Load structures (or load casting) is present in many areas of the outcrops. These structures are produced by the sinking of a layer of more dense sediment into a layer of less dense sediment (Blatt *et. al.*, 1980) The load structures are usually present at the boundary between an overlying coarse-grained layer and an underlying layer of fine-grained sand, silt, or mud. The coarse-grained material has sunk down into the underlying fine-grained sediments in a series of bulbous or pillow-like protrusions. This gives many of the load structures an ellipsoidal appearance.

There is a large degree of variety in the size of the load structures, the majority are two to five centimetres in depth. Load casts vary in size from 0.5 to 15.0 centimetres in width. In the transition zone between the tidal environment and the offshore environment, a number of load casts are as large as 25 centimetres in width and five centimetres in depth, forming long sand protrusions .

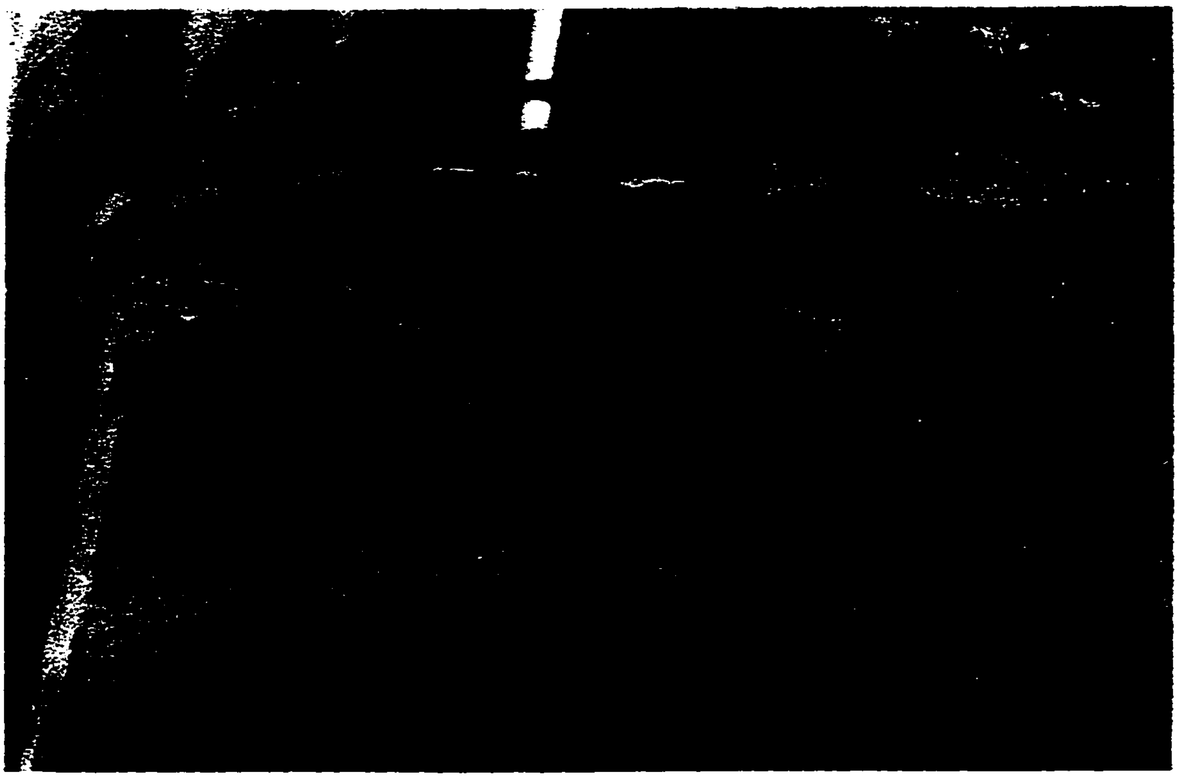
In many of the examples of load structures the coarser material which has protruded into the upper fine-grained portion of an underlying bed, has remained connected with the coarse-grained basal portion of the overlying bed. At times, the load structures have become cut off from the overlying coarse-grained layer. As a result, the ellipsoidal masses of coarser material appear to float freely in the fine-grained top of the underlying layer. These isolated ellipsoidal portions of the coarse-grained material show a wide size range.

Underlying beds of fine- and coarse-grained sediment will also extend upwards into an overlying bed as tongue-like forms. These tongue-like forms, or flames will often extend up to five centimetres into the overlying bed.

Climbing Ripple Lamination

At one location in outcrop 1, climbing ripple lamination is present (Figure 2-23), but it is poorly exposed. This lamination has formed in a medium-grained sandstone and is topped by a thin layer of mud. Using the work of McKee (1965), the lamination has been tentatively classified as ripple laminae in-drift.

FIGURE 2-23 Climbing ripple-lamination.

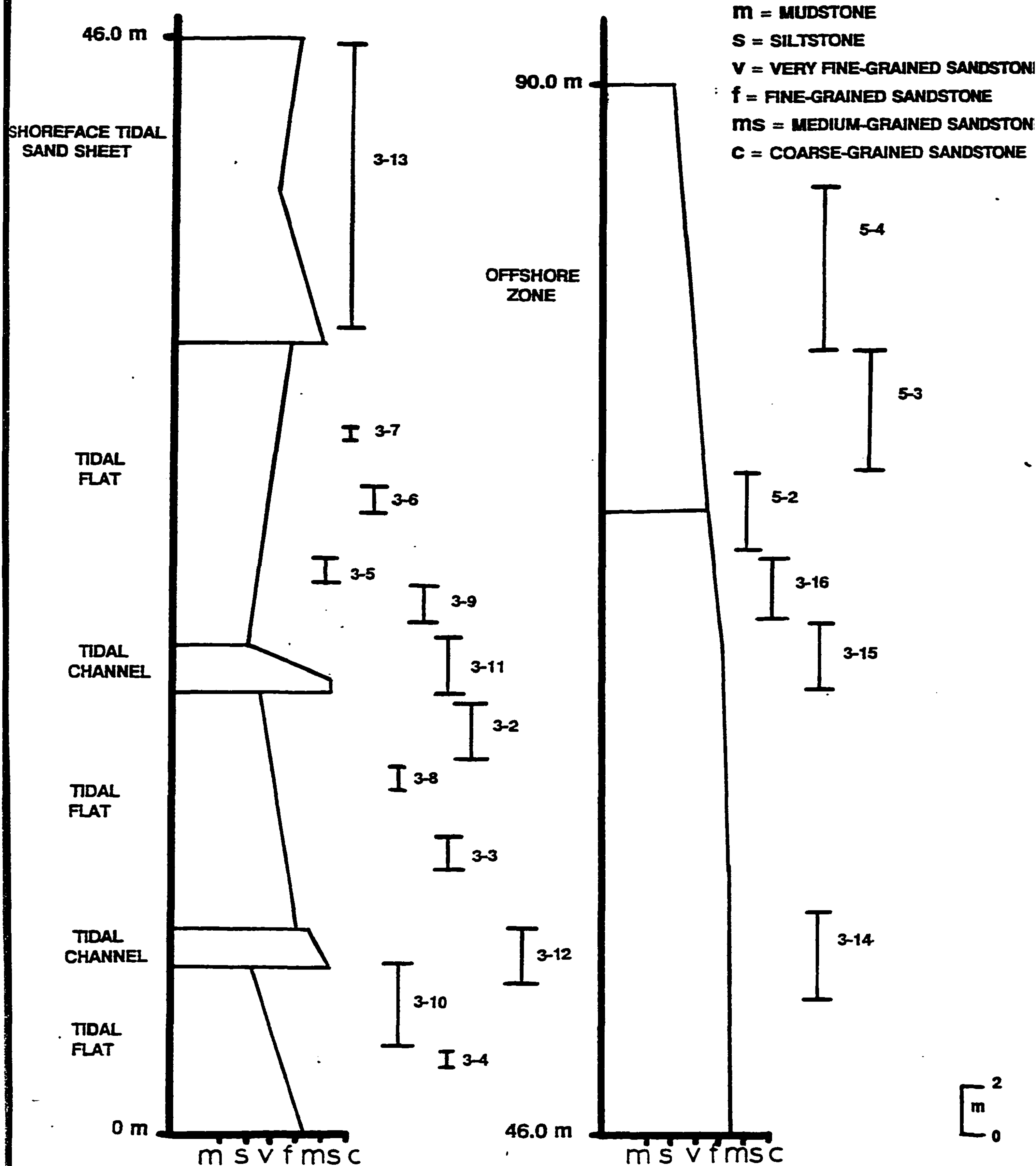


CHAPTER 3 -- TIDAL ENVIRONMENT - LITHOFACIES ASSOCIATIONS

Work by Parker (1980) has identified the existence of at least one main depositional environment within the current study area. He divided this environment, which he interpreted as tidally-influenced (Parker, 1980), into tidal flat and tidal channel sub-environments. The presence of the third sub-environment, a shoreface tidal sand sheet has been recorded by Fralick and Barrett (1991) and Eriksson *et. al.* (1994). Between the three sub-environments are a series of transition zones that mark the passage from one sub-environment to the next. Lithofacies associations within these sub-environments and transition zones will be discussed in this chapter, with the aid of stratigraphic sections.

The generalized stratigraphic section (Figure 3-1) depicts the relative positions of the tidal flat, tidal channel, and offshore tidal sand sheet sub-environments. More detailed stratigraphic sections are presented throughout this chapter. The sections are of sequences contained within the three sub-environments, and depict the lithofacies associations present in these sub-environments. The locations of the sequences described and discussed in this chapter are indicated on the generalized section.

FIGURE 3-1 Generalized stratigraphic section depicting the relative positions and average grain size of the tidal, shoreface, and offshore environments and associated sub-environments (tidal channel and flat). Positions of detailed stratigraphic sections (Figures 3-2 - 3-16) are indicated. The majority of sections are from outcrop 1. Sections depicted in Figures 3-5 and 3-7 are located in outcrop 2. Meterage indicated in the two figures corresponds to their positions in outcrop 2. The sections have been placed in approximate positions within the generalized stratigraphic section.



46.0 m
SHOREFACE TIDAL SAND SHEET
3-13
TIDAL FLAT
3-7
3-6
3-5
3-9
TIDAL CHANNEL
3-11
3-2
TIDAL FLAT
3-8
3-3
TIDAL CHANNEL
3-12
3-10
TIDAL FLAT
3-4
0 m
m s v f ms c
90.0 m
OFFSHORE ZONE
5-4
5-3
5-2
3-16
3-15
3-14
46.0 m
m s v f ms c
m = MUDSTONE
s = SILTSTONE
v = VERY FINE-GRAINED SANDSTONE
f = FINE-GRAINED SANDSTONE
ms = MEDIUM-GRAINED SANDSTONE
c = COARSE-GRAINED SANDSTONE
2
m
0

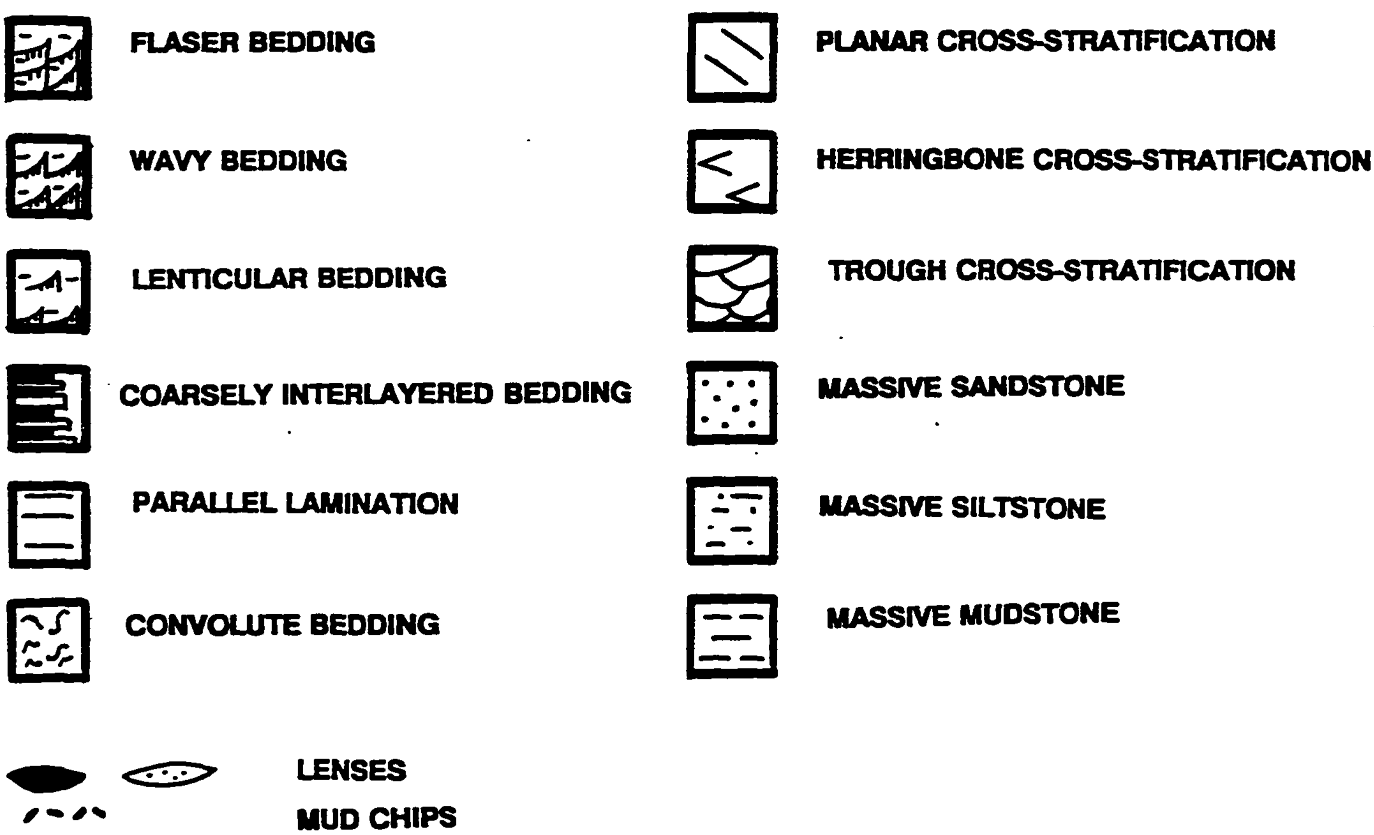
TIDAL FLAT SUB-ENVIRONMENT

The tidal flat sub-environment is composed of a wide variety of lithofacies. Dominating the collection of lithofacies present are those characteristic of tidal flats; flaser and lenticular bedding, wavy bedding, and coarsely interlayered bedding. Also present are massive and parallel laminated mudstone, siltstone and sandstone beds, which are either graded or non-graded. More rarely, convolute beds appear within the sub-environment.

Figures 3-2 to 3-4 show typical arrangements and associations of lithofacies in the tidal flat sub-environment. These sequences are dominated by flaser, lenticular and wavy bedding, as well as units of coarsely interlayered bedding. Minor amounts of parallel laminated and massive mudstone, siltstone and sandstone beds are also present.

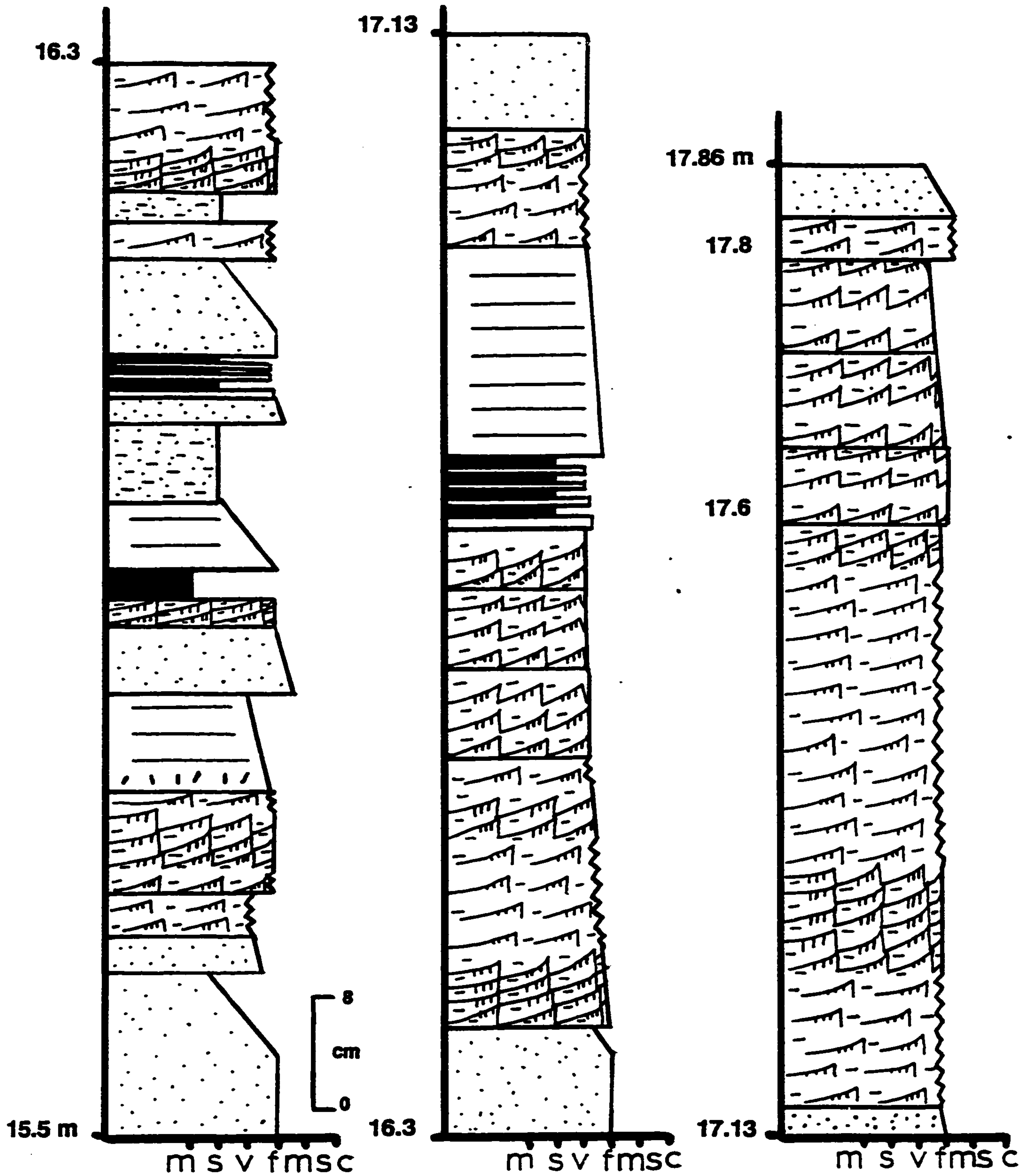
Figure 3-2 depicts a 2.35 metre sequence through a portion of a tidal flat. All of the various lithofacies common to this sub-environment are present in this sequence. These lithofacies include: lenticular and flaser bedding; wavy bedding; coarsely interlayered bedding; massive mudstone and siltstone beds; massive sandstone; and parallel laminated sandstone beds. This sequence is dominated by units of flaser and lenticular bedding, although sandstone beds and wavy bedding are also strongly represented. The wavy bedding is present in a series of vertically stacked beds. One such series is present towards the top of the sequence (17.6 m to 17.8 m). Many of the boundaries between the beds are sharp and distinct, but gradational boundaries

FIGURE 3-2 Tidal flat sub-environment.



m = MUDSTONE
s = SILTSTONE
v = VERY FINE-GRAINED SANDSTONE
f = FINE-GRAINED SANDSTONE
ms = MEDIUM-GRAINED SANDSTONE
c = COARSE-GRAINED SANDSTONE

FIGURE 3-2



16.3
15.5 m
m s v f m s c
17.13
16.3
m s v f m s c
17.86 m
17.8
17.6
17.13
m s v f m s c
8
cm
0

are also present. Typically these gradations are present when moving into or out of units of lenticular and flaser bedding.

With the exception of the vertically stacked series of wavy bedding, all of the other lithofacies present are randomly interbedded with each other. There is a slight decrease in grainsize when moving towards the top of the sequence. This particular sequence occurs close to the transition zone from the tidal flat into the tidal channel sub-environment.

Another typical sequence through a portion of a tidal flat is depicted in Figure 3-3. The following lithofacies are present in this sequence: lenticular and flaser bedding; coarsely interlayered bedding; and both parallel laminated and massive siltstone and sandstone beds. As with the sequence shown in Figure 3-2, this one is dominated by units of flaser and lenticular bedding randomly interbedded with the siltstone and sandstone beds. Gradational boundaries are present between a small number of beds, but commonly, boundaries between beds are sharp and regular. There is also a series of vertically stacked, parallel laminated sandstone beds present in the first 0.8 metres of the sequence.

The 0.55 metre sequence in Figure 3-4 provides a closer view of the lithofacies that dominate and characterize the tidal flat sub-environment. This small sequence contains coarsely interlayered bedding, wavy bedding, flaser and lenticular bedding, and massive sandstone beds. Convolute bedding is also present. This sequence is

FIGURES 3-3 & 3-4 Tidal flat sub-environment.

FLASER BEDDING

WAVY BEDDING

LENTICULAR BEDDING

COARSELY INTERLAYERED BEDDING

PARALLEL LAMINATION

CONVOLUTE BEDDING

PLANAR CROSS-STRATIFICATION

HERRINGBONE CROSS-STRATIFICATION

TROUGH CROSS-STRATIFICATION

MASSIVE SANDSTONE

MASSIVE SILTSTONE

MASSIVE MUDSTONE

LENSES

MUD CHIPS

m = MUDSTONE
s = SILTSTONE
v = VERY FINE-GRAINED SANDSTONE
f = FINE-GRAINED SANDSTONE
ms = MEDIUM-GRAINED SANDSTONE
c = COARSE-GRAINED SANDSTONE

FIGURE 3-3

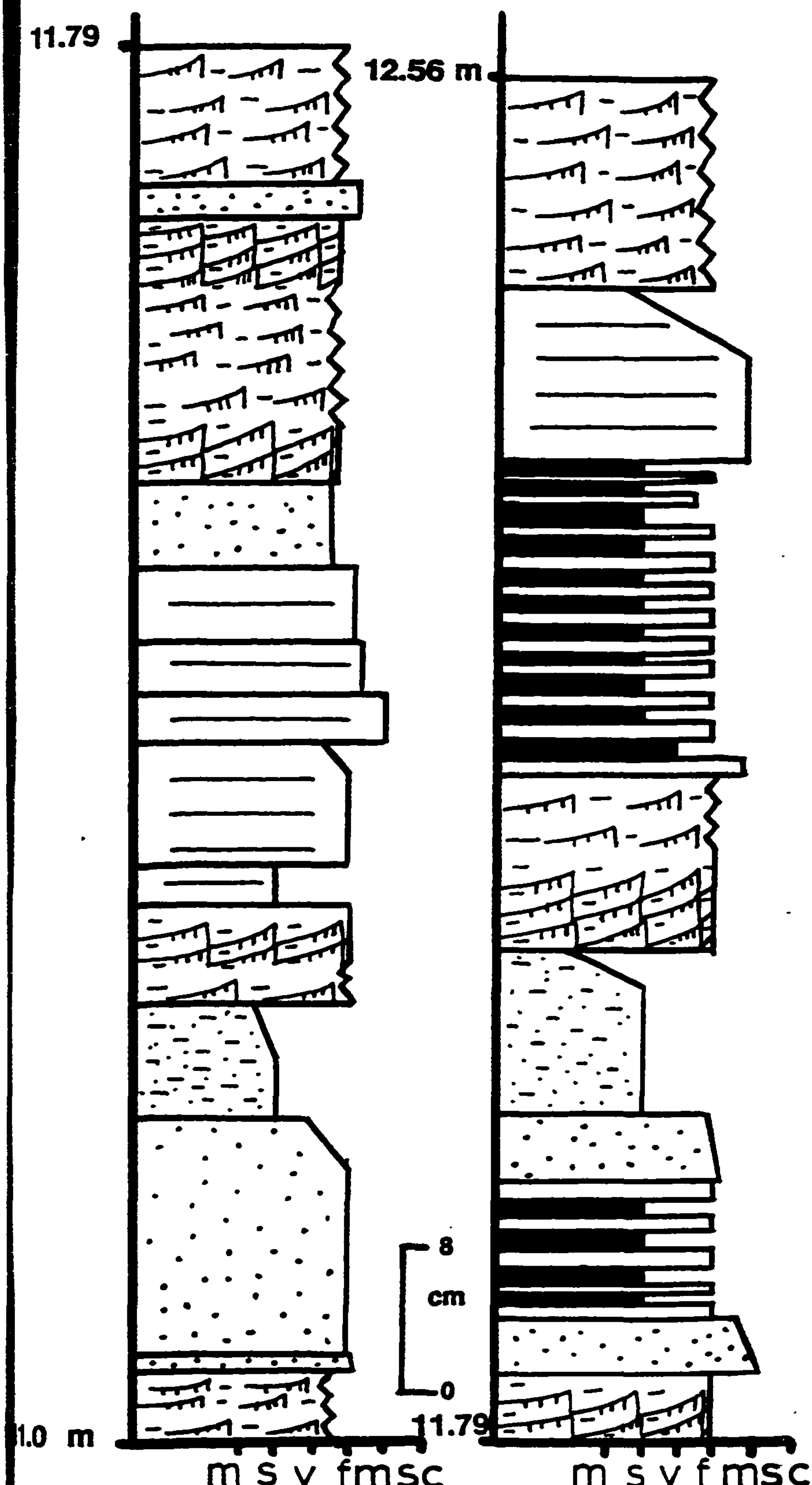
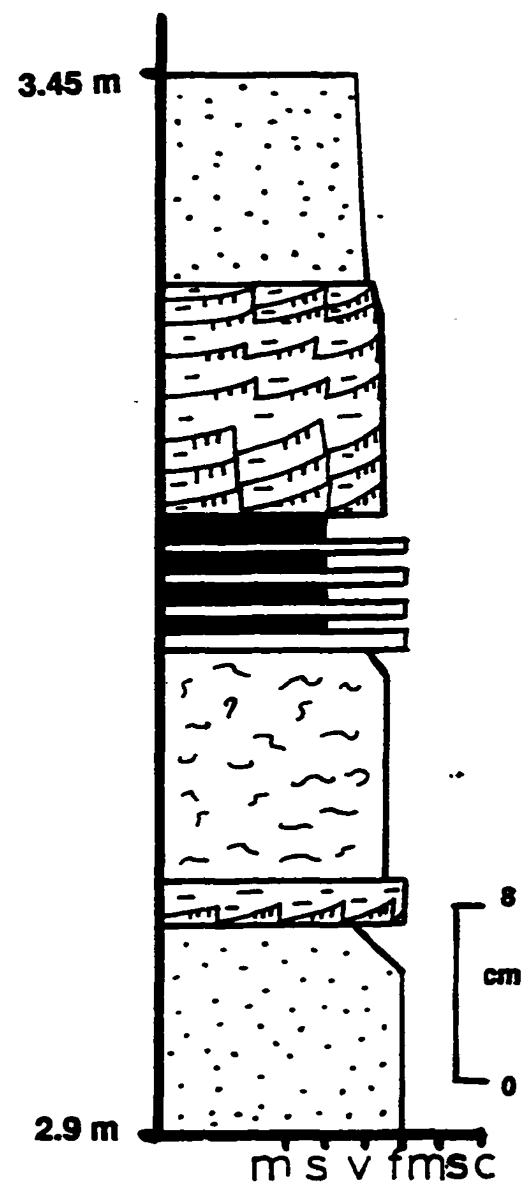


FIGURE 3-4



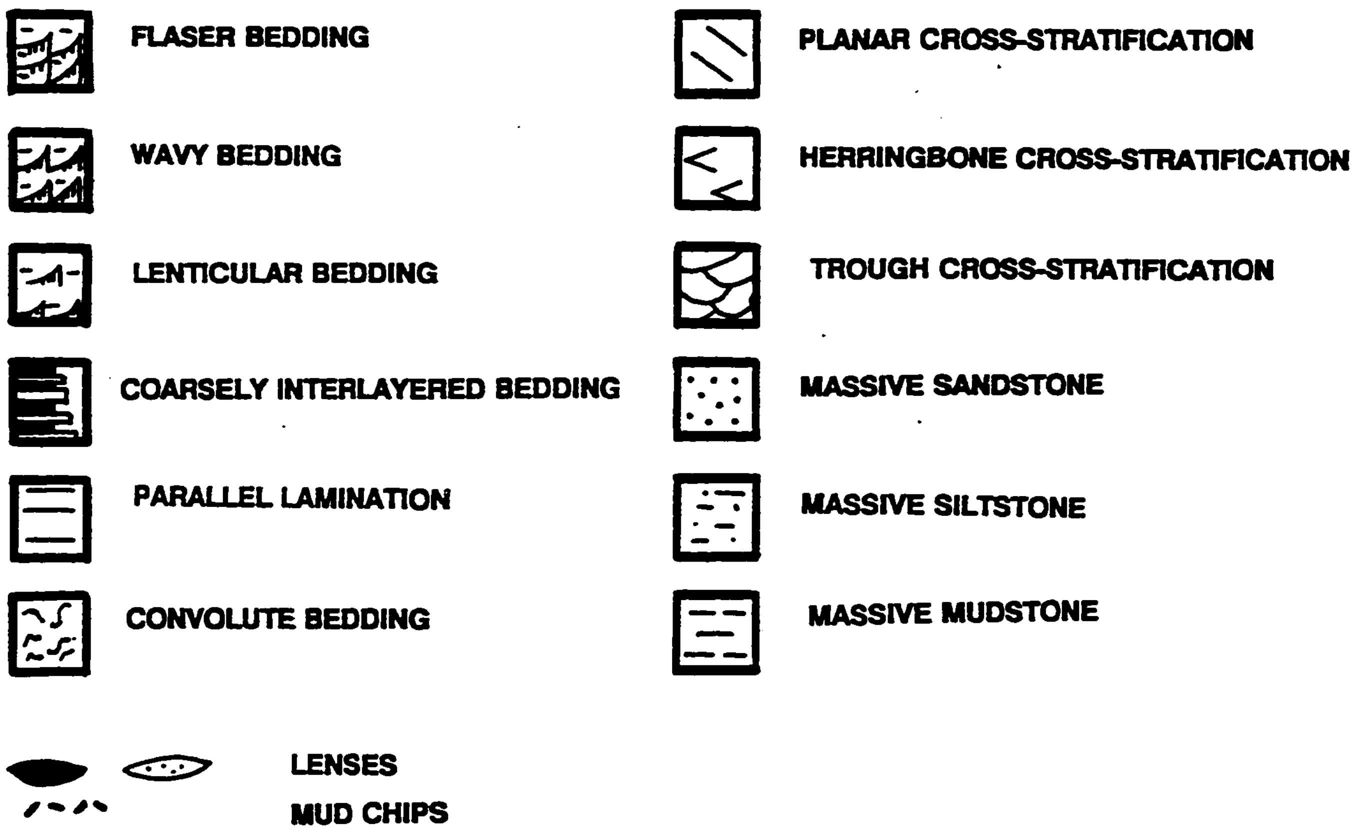
located in close proximity to the transition zone from a tidal flat to a tidal channel sub-environment and has a slight overall fining upwards trend.

Figures 3-5 to 3-7 illustrate other arrangements or associations of lithofacies that can be found in the tidal flat sub-environment. These sequences contain none of the units of flaser and lenticular bedding that characterize the tidal flat, but are still commonly found in this sub-environment. Figure 3-5 depicts an interbedded sequence of massive and parallel laminated sandstone beds and coarsely interlayered bedding. This sequence also contains a thin (0.5 cm) siltstone bed. All boundaries between the beds are sharp and distinct.

Another bedding sequence is illustrated in Figure 3-6. It contains interbedded massive siltstone and sandstone beds. As with the sequence shown in Figure 3-5, all of the boundaries between the siltstone and sandstone beds are sharp. This particular sequence is located closer to the shoreface tidal sand sheet then any of the other tidal flat sequences discussed in this chapter. Grainsize increases slightly towards the top of the sequence.

The sequence depicted in Figure 3-7 contains: coarsely interlayered bedding, massive mudstone and siltstone beds and sandstone beds. The sequence is dominated by the mudstone and siltstone beds and coarsely interlayered bedding. The two massive sandstone beds, are found between thinner beds of siltstone. As with the previous two sequences, all of the boundaries between the various lithofacies are

FIGURES 3-5, 3-6 and 3-7 Tidal flat sub-environment.



m = MUDSTONE
s = SILTSTONE
v = VERY FINE-GRAINED SANDSTONE
f = FINE-GRAINED SANDSTONE
ms = MEDIUM-GRAINED SANDSTONE
c = COARSE-GRAINED SANDSTONE

FIGURE 3-5

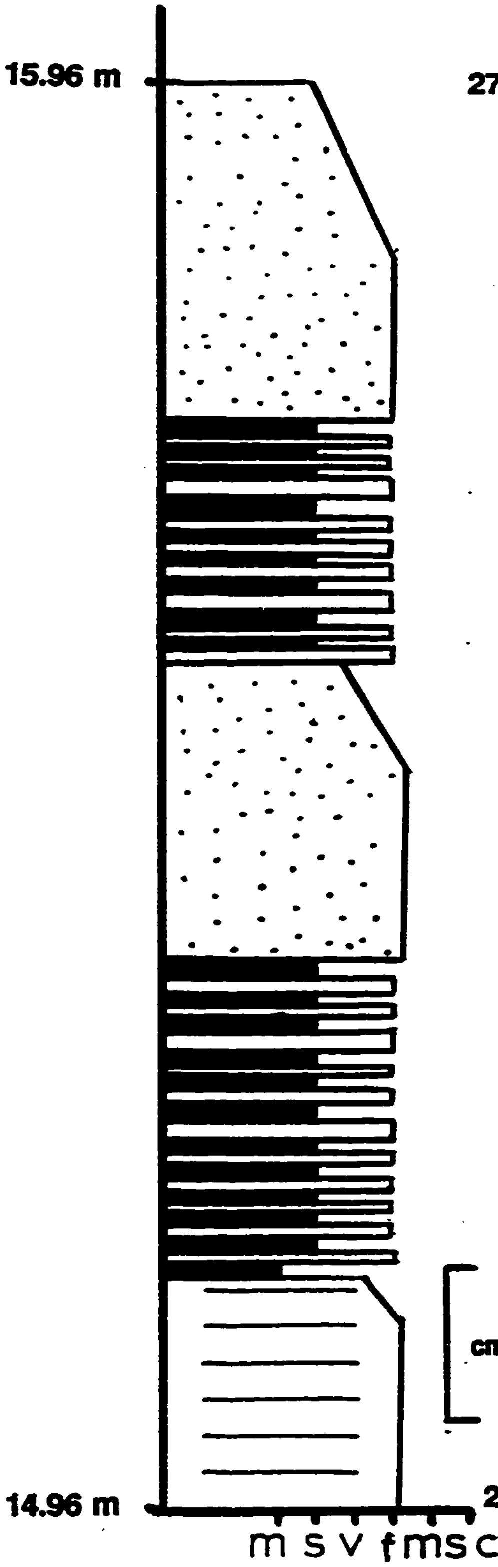


FIGURE 3-6

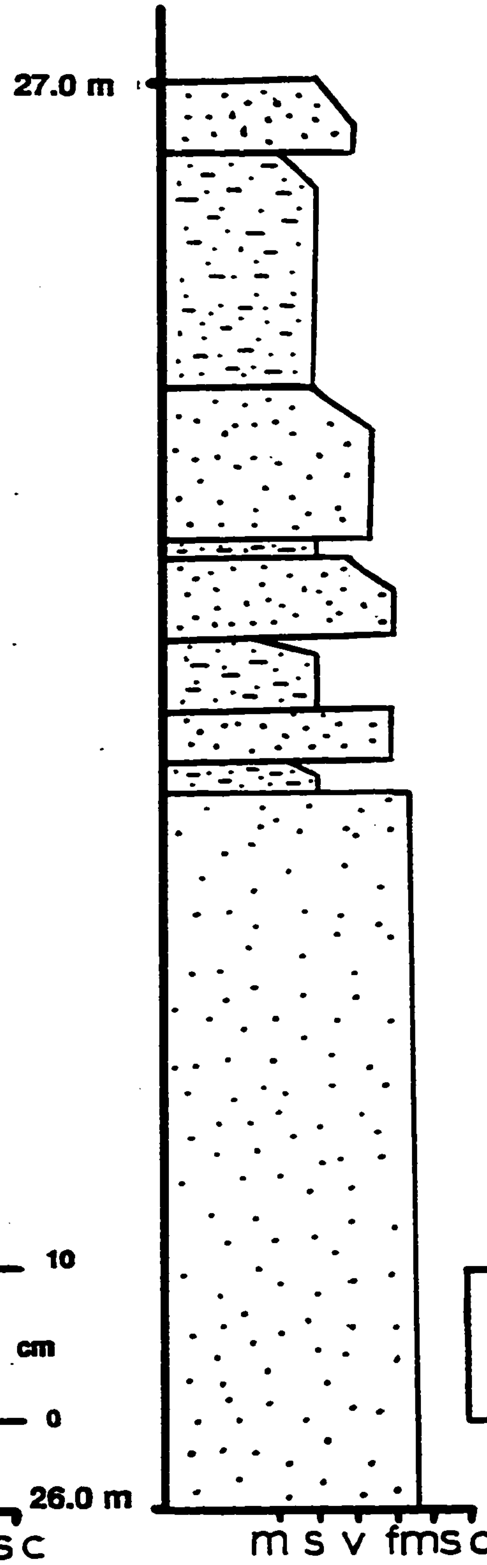
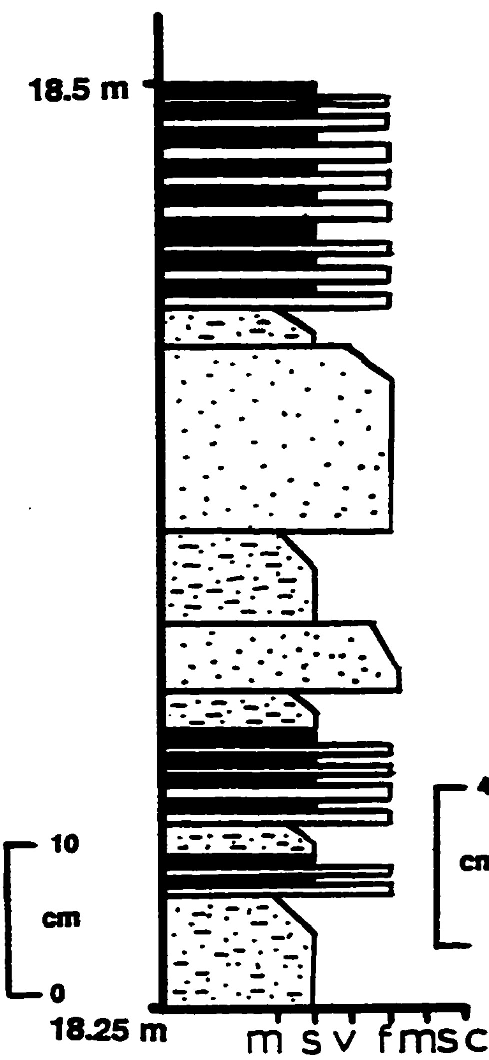


FIGURE 3-7



sharp and distinct.

The next two sequences (Figures 3-8 and 3-9), include two parallel laminated sandstone beds which differ slightly in colour and grainsize from the majority of the sandstone beds present in the tidal flat sub-environment. These beds have been described in the previous chapter. The sequence in Figure 3-8 contains wavy bedding, massive mudstone and siltstone beds, massive sandstone beds, lenticular and flaser bedding, and convolute bedding. Near the top of the sequence is the light coloured, parallel laminated sandstone bed. This layer sharply overlies a unit of flaser and lenticular bedding. Similar to Figures 3-2 to 3-4, the different lithofacies are randomly interbedded with each other. Figure 3-9 is located near the tidal channel to tidal flat transition zone and will be described in the next section.

INTERTIDAL TRANSITION ZONE

The first two sequences (Figures 3-9 and 3-10) are characteristic of the upwards transition between the tidal channel and tidal flat sub-environment. The last sequence (Figure 3-11) presented in this section depicts the transition from the tidal flat sub-environment upwards into the tidal channel sub-environment.

Tidal Channel to Tidal Flat Transition

The sequence shown in Figure 3-9 is located near the top of a transition zone out of a tidal channel into the tidal flat sub-environment. This sequence contains coarsely

FIGURES 3-8 and 3-9 Tidal flat sub-environment.

FLASER BEDDING

WAVY BEDDING

LENTICULAR BEDDING

COARSELY INTERLAYERED BEDDING

PARALLEL LAMINATION

CONVOLUTE BEDDING

PLANAR CROSS-STRATIFICATION

HERRINGBONE CROSS-STRATIFICATION

TROUGH CROSS-STRATIFICATION

MASSIVE SANDSTONE

MASSIVE SILTSTONE

MASSIVE MUDSTONE

LENSES

MUD CHIPS

m = MUDSTONE
s = SILTSTONE
v = VERY FINE-GRAINED SANDSTONE
f = FINE-GRAINED SANDSTONE
ms = MEDIUM-GRAINED SANDSTONE
c = COARSE-GRAINED SANDSTONE

FIGURE 3-8

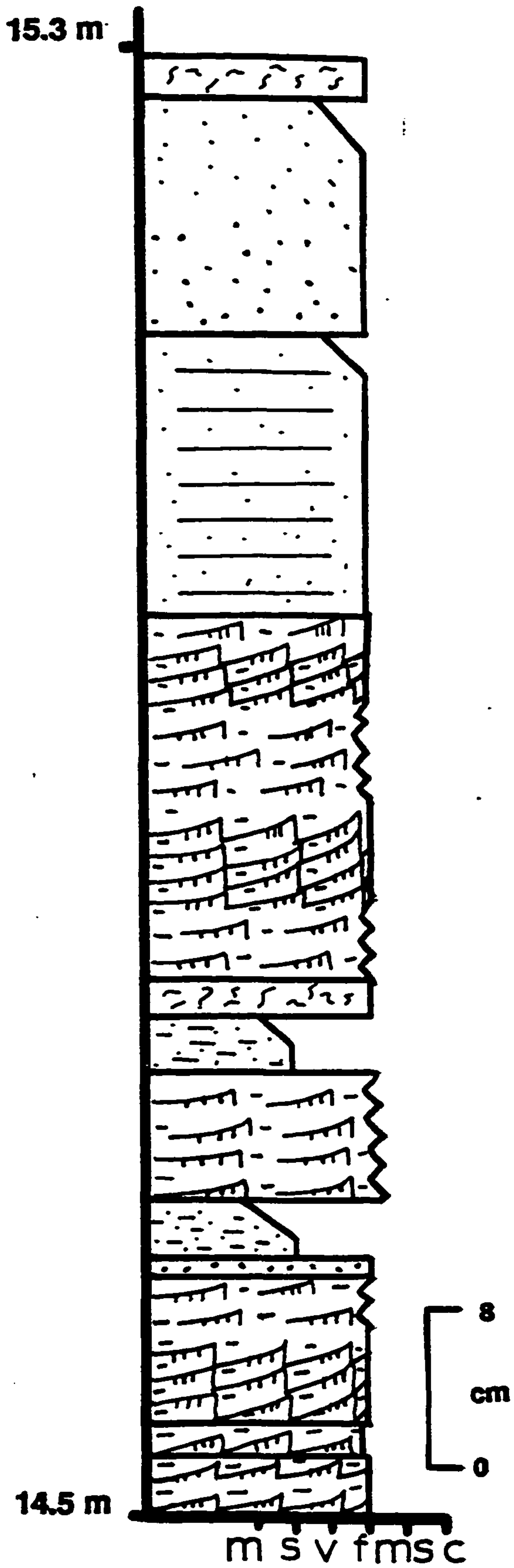
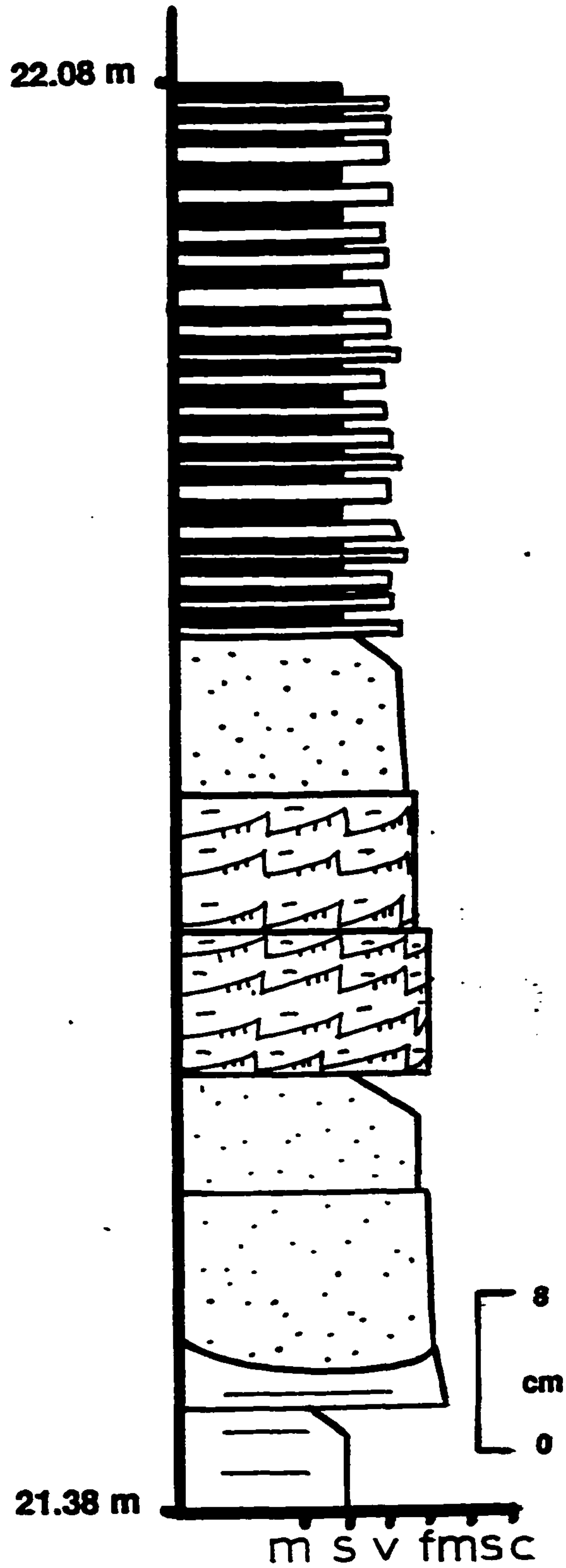


FIGURE 3-9



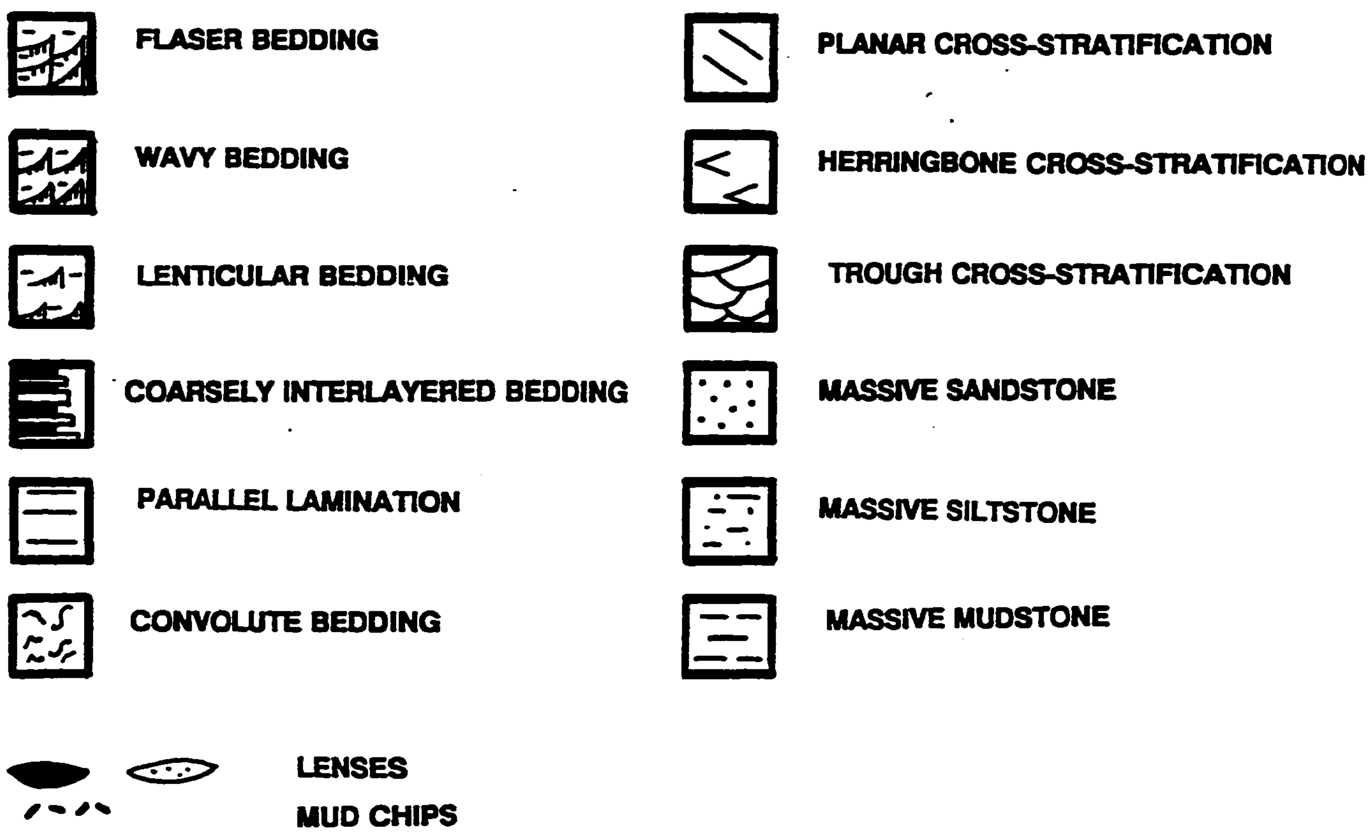
interlayered bedding, wavy bedding, massive sandstone beds, a parallel laminated siltstone bed, and a light coloured, parallel laminated sandstone bed. The light coloured sandstone bed is found near the base of the sequence, where it overlies the solitary siltstone bed present in the sequence. The top of the massive sandstone bed overlying the parallel laminated sandstone bed is incised by a small channel. This channel is filled with a fining upwards, massive sandstone. The entire sequence exhibits a moderate fining-upwards trend.

Figure 3-11 contains a sequence depicting the upwards transition into the tidal flat sub-environment. The dominant lithofacies in this sequence is herringbone cross-stratified beds. Lithofacies present as minor components in this sequence include: massive sandstone beds; parallel laminated mudstone and siltstone beds; and small-scale planar cross-stratified beds. The middle of the sequence is dominated by thick beds of herringbone cross-stratification interbedded with very thin beds of small-scale planar cross-stratification. At the base and near the top of the sequence, the herringbone cross-stratified beds are interbedded with thin, parallel laminated siltstone beds. A bed near the top of the sequence has been incised by a channel which is infilled with a fining-upward sequence. An interbedded sequence of sandstone and siltstone and mudstone beds is present at the very top of the sequence.

Tidal Flat to Tidal Channel Transition

As already stated, Figure 3-10 depicts the transition from a tidal flat into a tidal channel. This sequence consists primarily of interbedded siltstone and sandstone

FIGURE 3-10 Tidal flat to tidal channel transition.



m = MUDSTONE
s = SILTSTONE
v = VERY FINE-GRAINED SANDSTONE
f = FINE-GRAINED SANDSTONE
ms = MEDIUM-GRAINED SANDSTONE
c = COARSE-GRAINED SANDSTONE

FIGURE 3-10

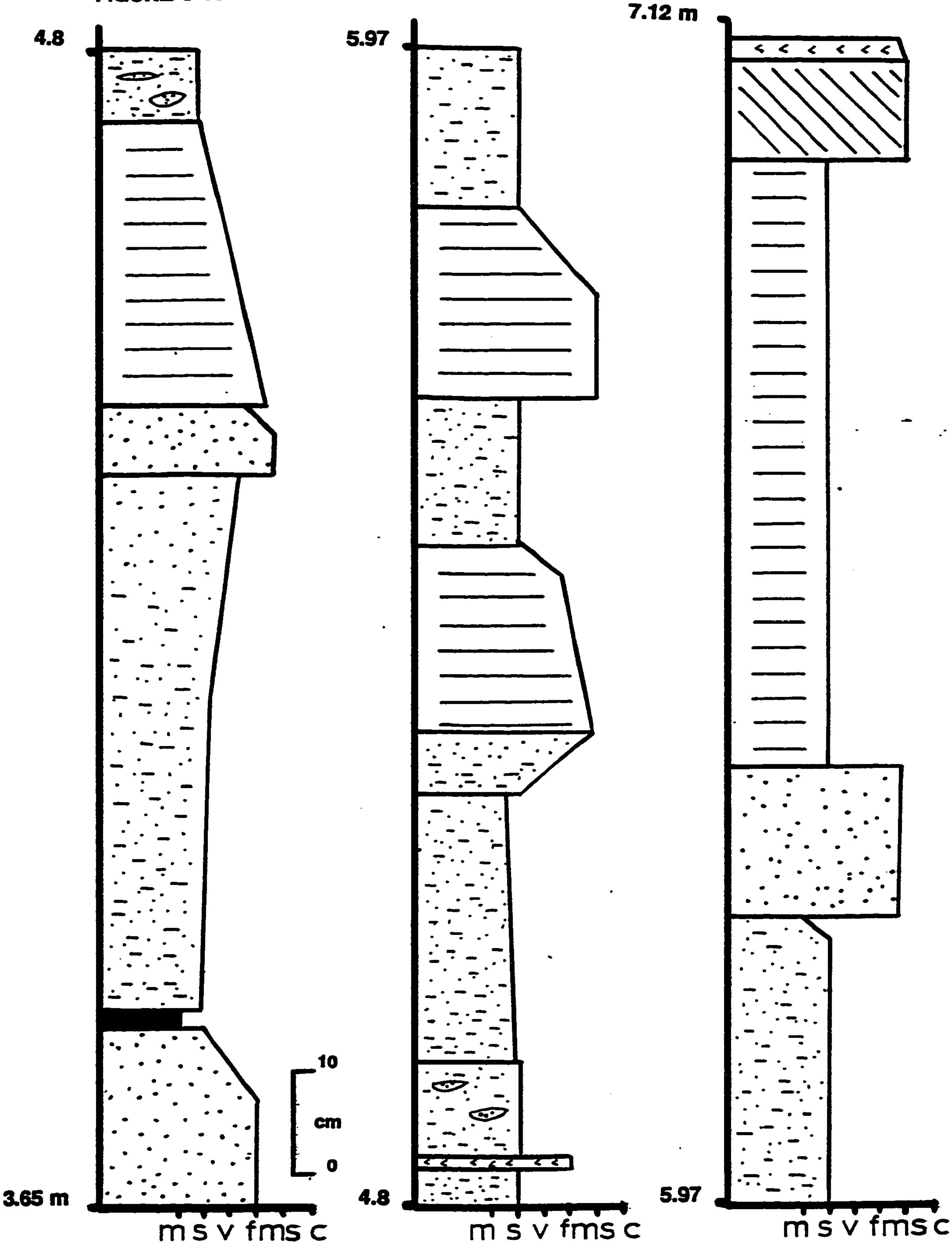
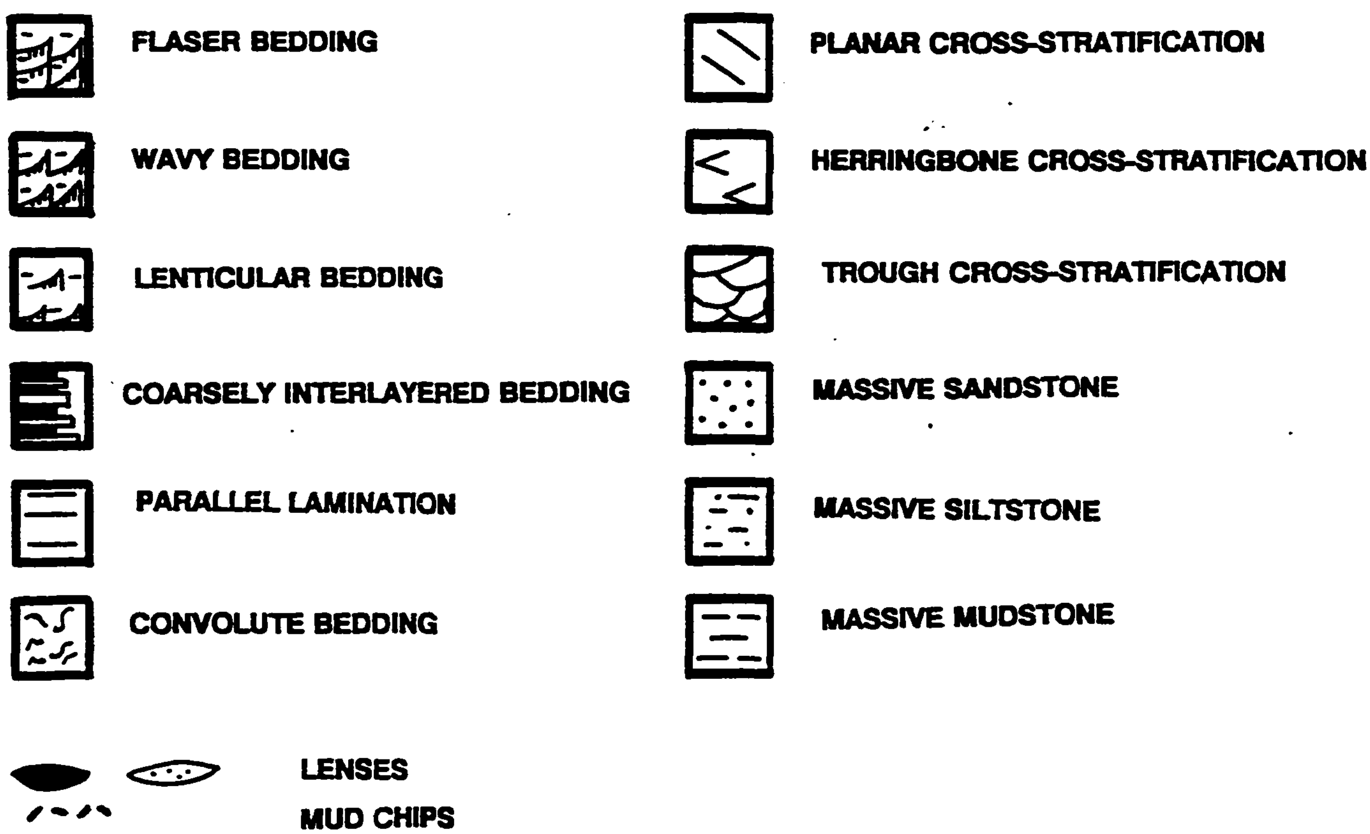
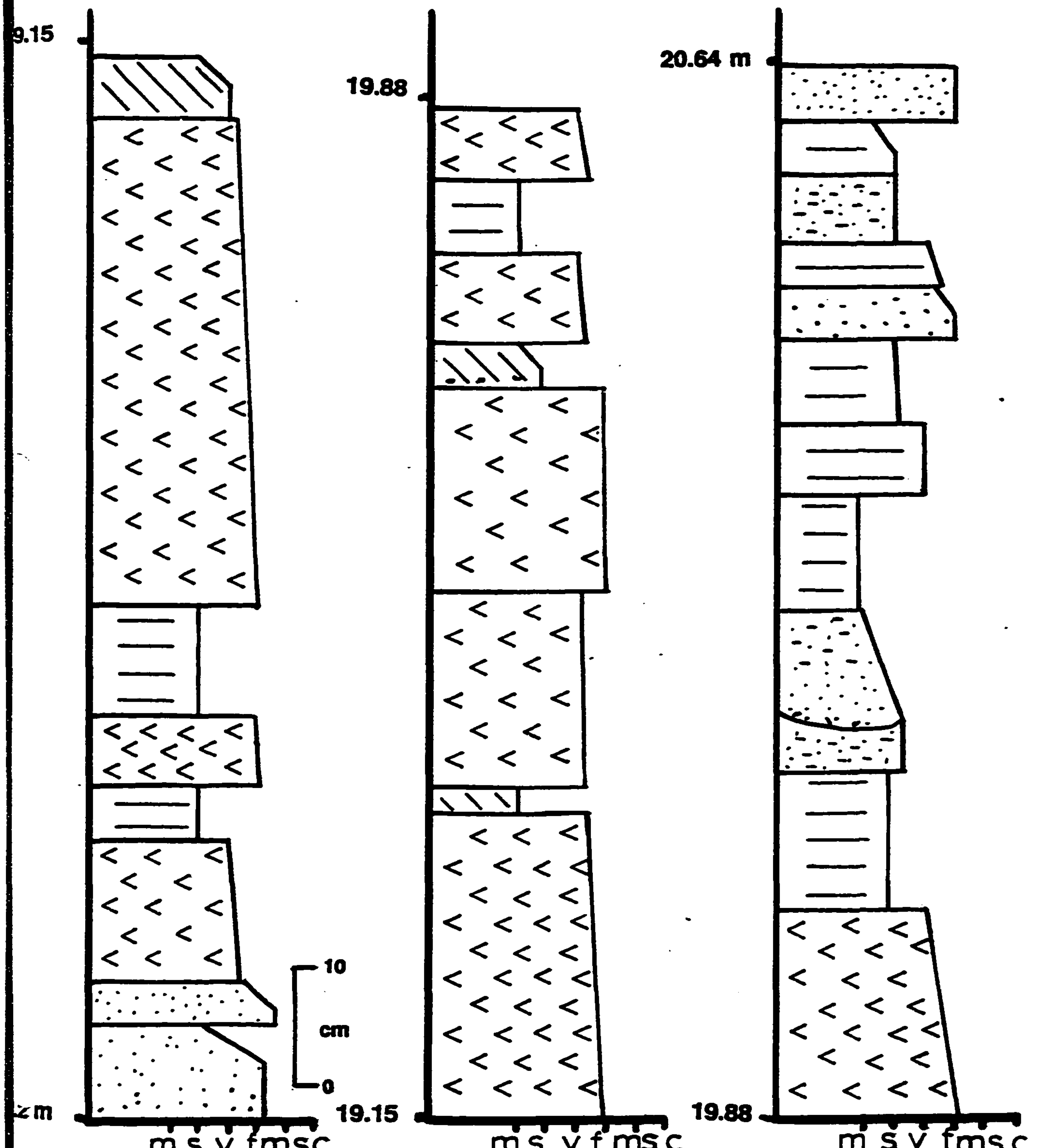


FIGURE 3-11 Tidal channel to tidal flat transition.



m = MUDSTONE
s = SILTSTONE
v = VERY FINE-GRAINED SANDSTONE
f = FINE-GRAINED SANDSTONE
ms = MEDIUM-GRAINED SANDSTONE
c = COARSE-GRAINED SANDSTONE

FIGURE 3-11



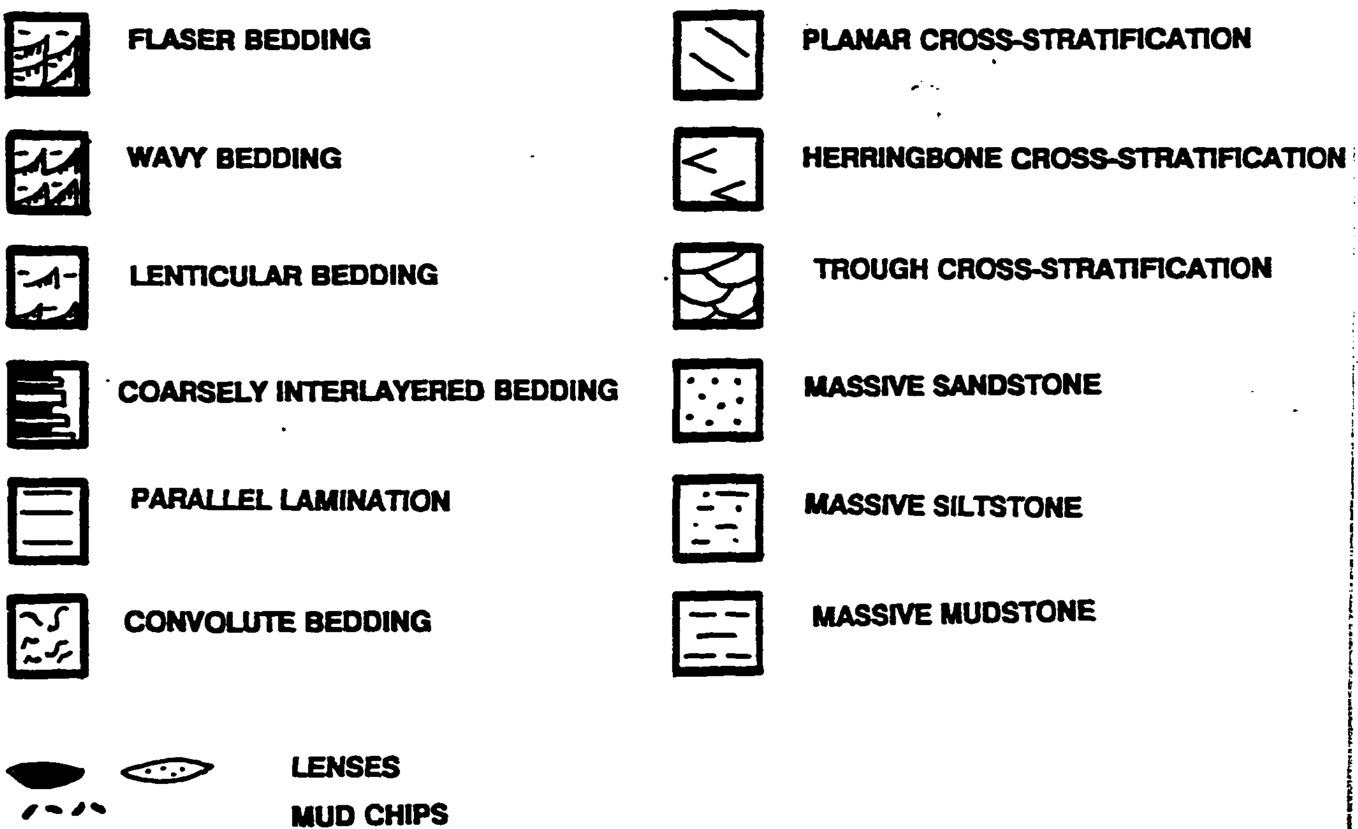
beds, with massive siltstone beds dominating. The following lithofacies: massive and parallel laminated sandstone beds; parallel laminated mudstone and siltstone beds; herringbone cross-stratified beds; and a planar cross-stratified bed are present in lesser amounts. There are also two beds of massive, reversely graded siltstone present in the sequence. These siltstone beds are sharply overlain by sandstone beds. The sandstone beds are concentrated in the lower part of the sequence, and decrease in number and thickness towards the top of the sequence.

TIDAL CHANNEL SUB-ENVIRONMENT

A limited number of lithofacies are present in the tidal channel sub-environment; this differs greatly from what is observed in the tidal flat sub-environment where there is a wide range of lithofacies. Channel sequences are dominated by herringbone cross-stratification; a bedding type which is common in tidal channel sub-environments.

The sequence in Figure 3-12 passes through the tidal channel sub-environment into the extreme lower portion of the next tidal flat. The sequence is dominated by interbedded herringbone cross-stratified units and small-scale planar cross-stratified beds. Parallel laminated siltstone beds are present at the base and near the top of the sequence. The final bed of herringbone cross-stratification near the top of the sequence is cut by a channel. This channel is infilled with a reversely graded siltstone bed.

FIGURE 3-12 Tidal channel sub-environment.



m = MUDSTONE
s = SILTSTONE
v = VERY FINE-GRAINED SANDSTONE
f = FINE-GRAINED SANDSTONE
ms = MEDIUM-GRAINED SANDSTONE
c = COARSE-GRAINED SANDSTONE

FIGURE 3-12

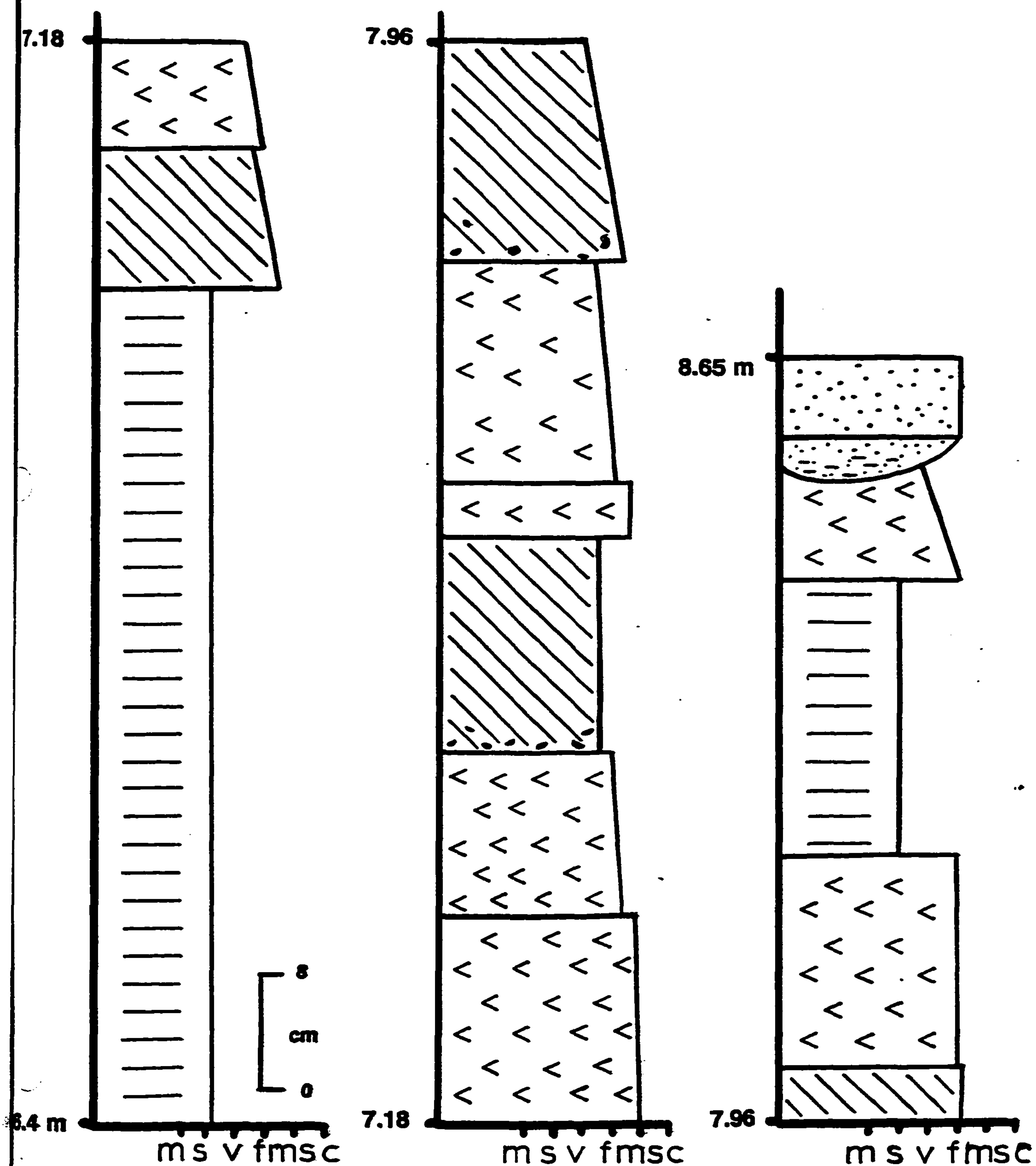


FIGURE 3-13 Shoreface transition zone.

FLASER BEDDING

WAVY BEDDING

LENTICULAR BEDDING

COARSELY INTERLAYERED BEDDING

PARALLEL LAMINATION

CONVOLUTE BEDDING

PLANAR CROSS-STRATIFICATION

HERRINGBONE CROSS-STRATIFICATION

TROUGH CROSS-STRATIFICATION

MASSIVE SANDSTONE

MASSIVE SILTSTONE

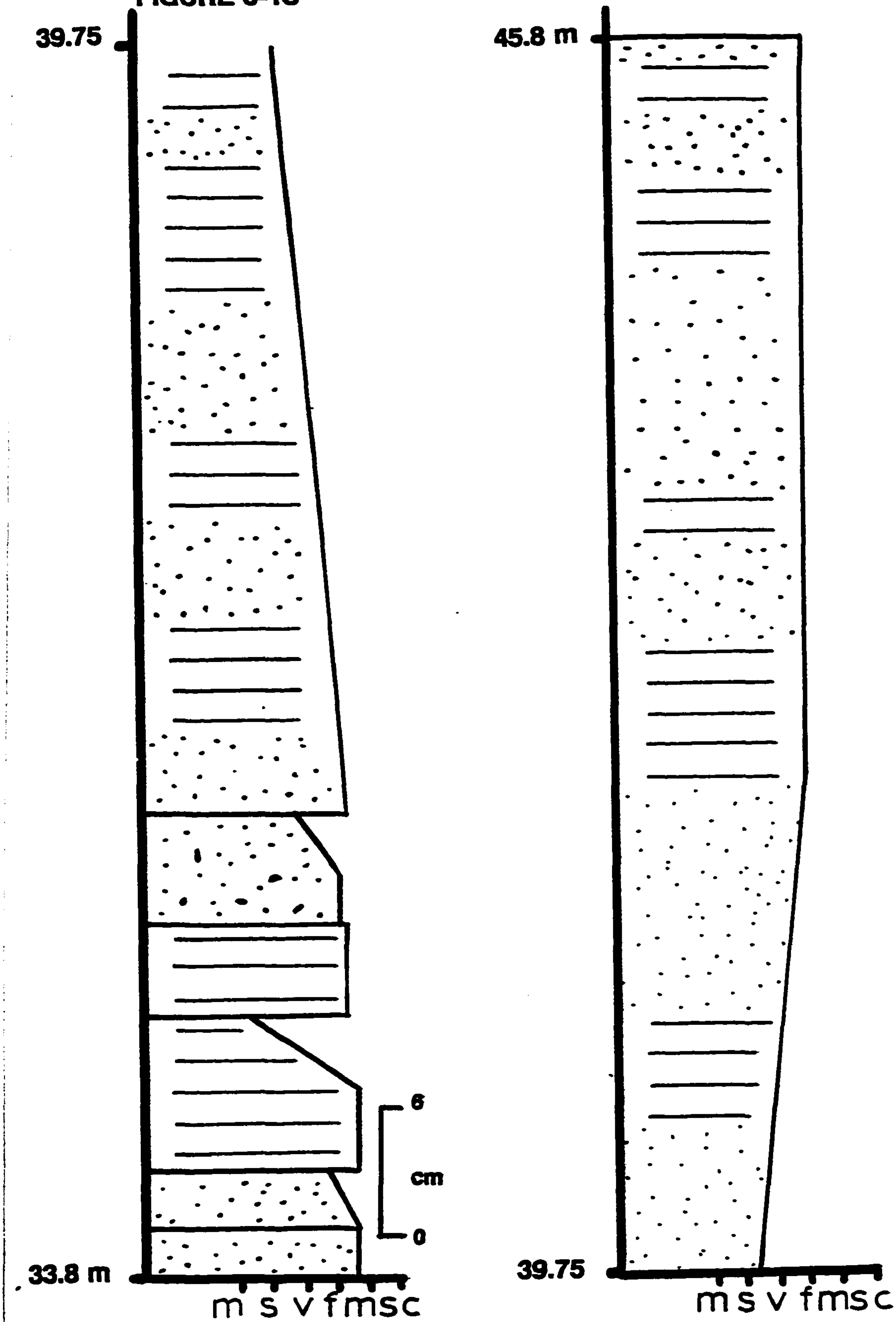
MASSIVE MUDSTONE

LENSES

MUD CHIPS

m = MUDSTONE
s = SILTSTONE
v = VERY FINE-GRAINED SANDSTONE
f = FINE-GRAINED SANDSTONE
ms = MEDIUM-GRAINED SANDSTONE
c = COARSE-GRAINED SANDSTONE

FIGURE 3-13



SHOREFACE TRANSITION ZONE

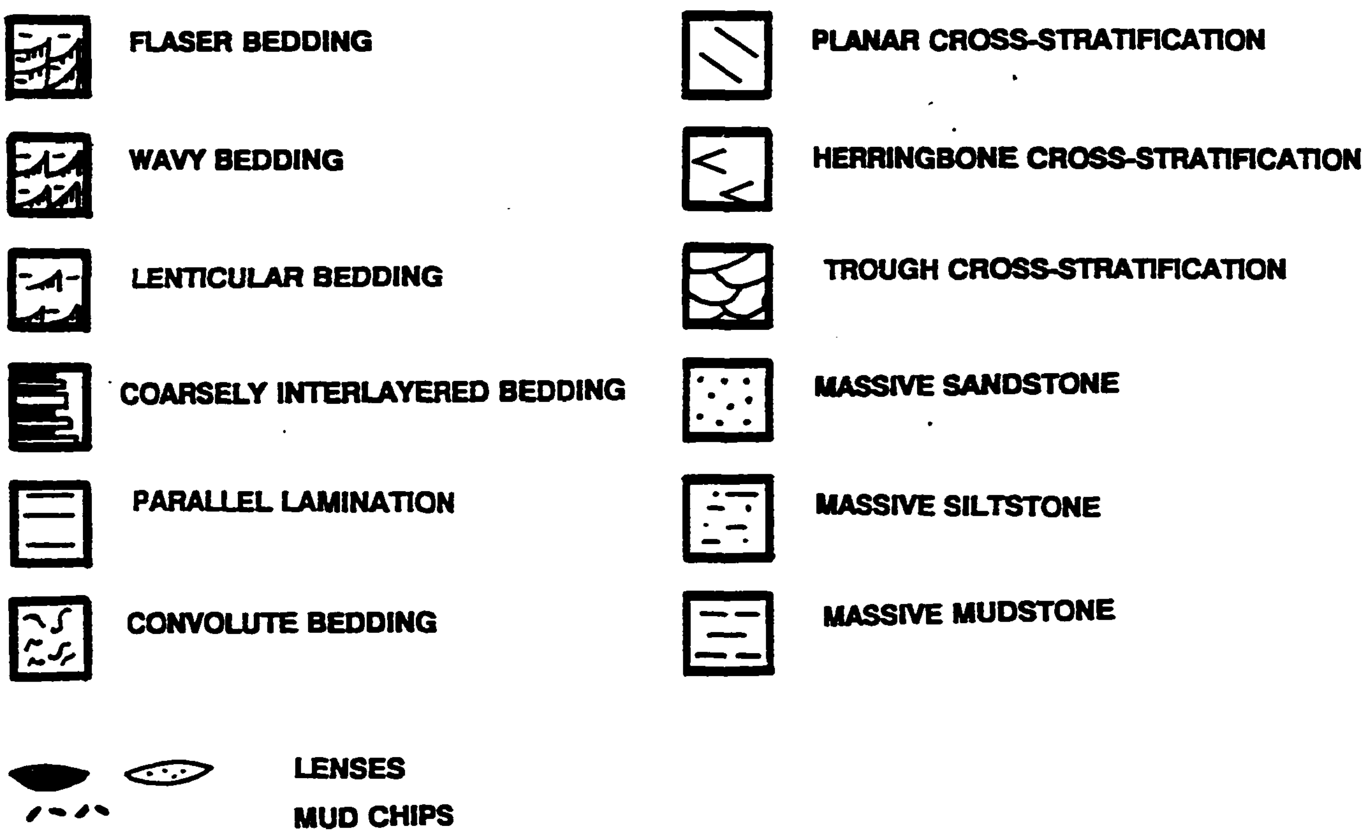
Figure 3-13 depicts a monotonous, 12.0 metre thick sequence, which is part of the shoreface transition zone. This sequence is composed entirely of massive and parallel laminated fine- to coarse-grained sandstone beds. A number of the beds grade upwards into a fine- to medium-grained siltstone tops, but the majority of beds are non-graded. From 36.0 to 45.8 metres, the sequence consists of a series of massive and parallel laminated sandstone horizons. The massive and parallel laminated horizons appear to gradually grade into one another. This 9.8 metre portion becomes finer-grained toward the centre, but then coarsens again at the top of the sequence.

SHOREFACE TIDAL SAND SHEET SUB-ENVIRONMENT

The shoreface tidal sand sheet is dominated by monotonous sequences of massive and parallel laminated fine- to coarse-grained sandstone beds, and trough cross-stratified, herringbone cross-stratified, and planar cross-stratified siltstones to coarse-grained sandstones. The following three sequences contain all of the dominant lithofacies.

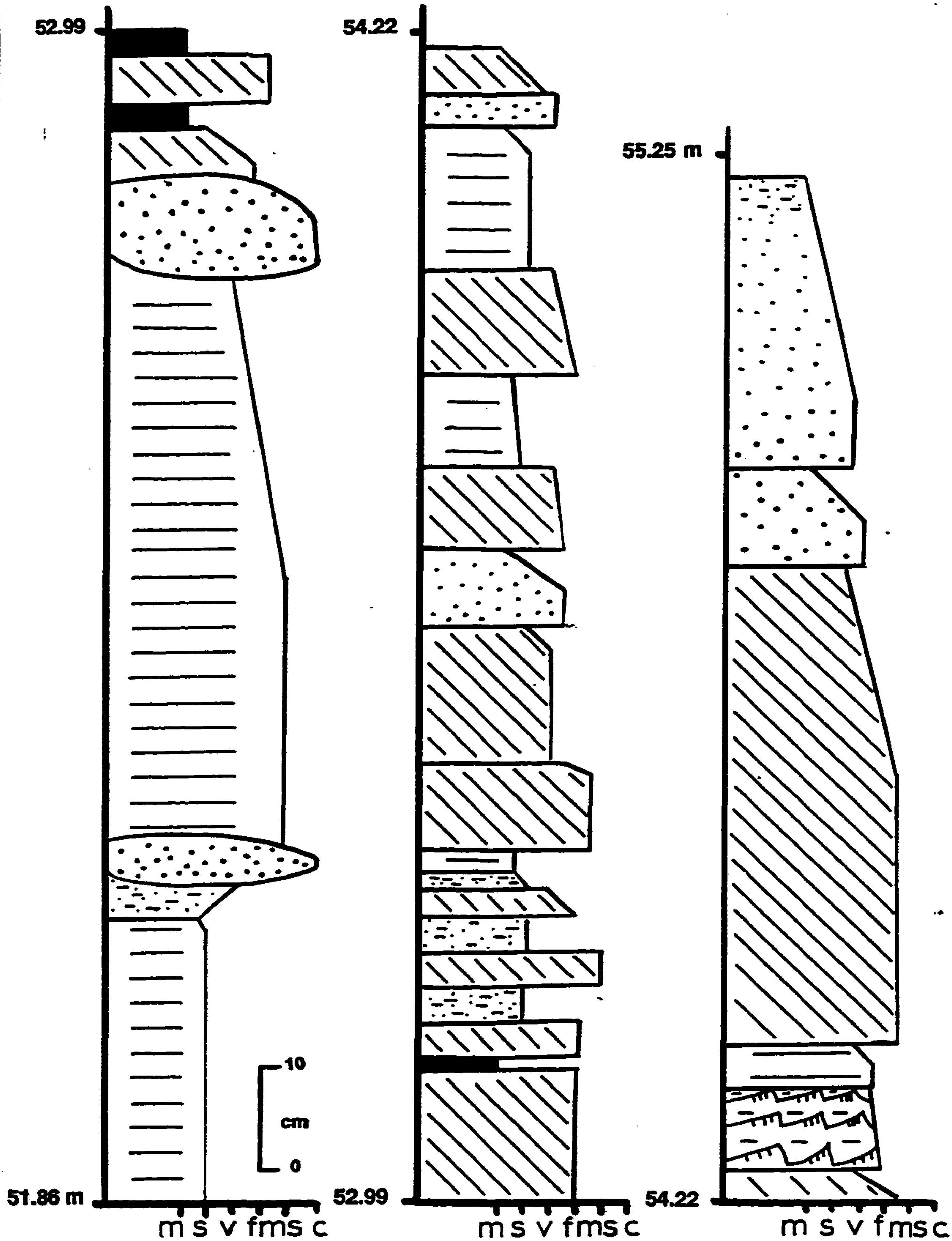
The sequence depicted in Figure 3-14 is dominated by beds containing planar cross-stratification. Massive and parallel laminated mudstone/siltstone and sandstone beds, and wavy bedding are also present. Two very coarse-grained, laterally discontinuous lenses occur in the first 1.0 metre of the sequence. The majority of the sequence is composed of planar cross-stratified beds interlayered with thin beds of massive and parallel laminated fine- to coarse-grained siltstone. This association is particularly noticeable between 52.9 and 54.3 metres. The massive and parallel

FIGURE 3-14 Shoreface tidal sand sheet.



m = MUDSTONE
s = SILTSTONE
v = VERY FINE-GRAINED SANDSTONE
f = FINE-GRAINED SANDSTONE
ms = MEDIUM-GRAINED SANDSTONE
c = COARSE-GRAINED SANDSTONE

FIGURE 3-14

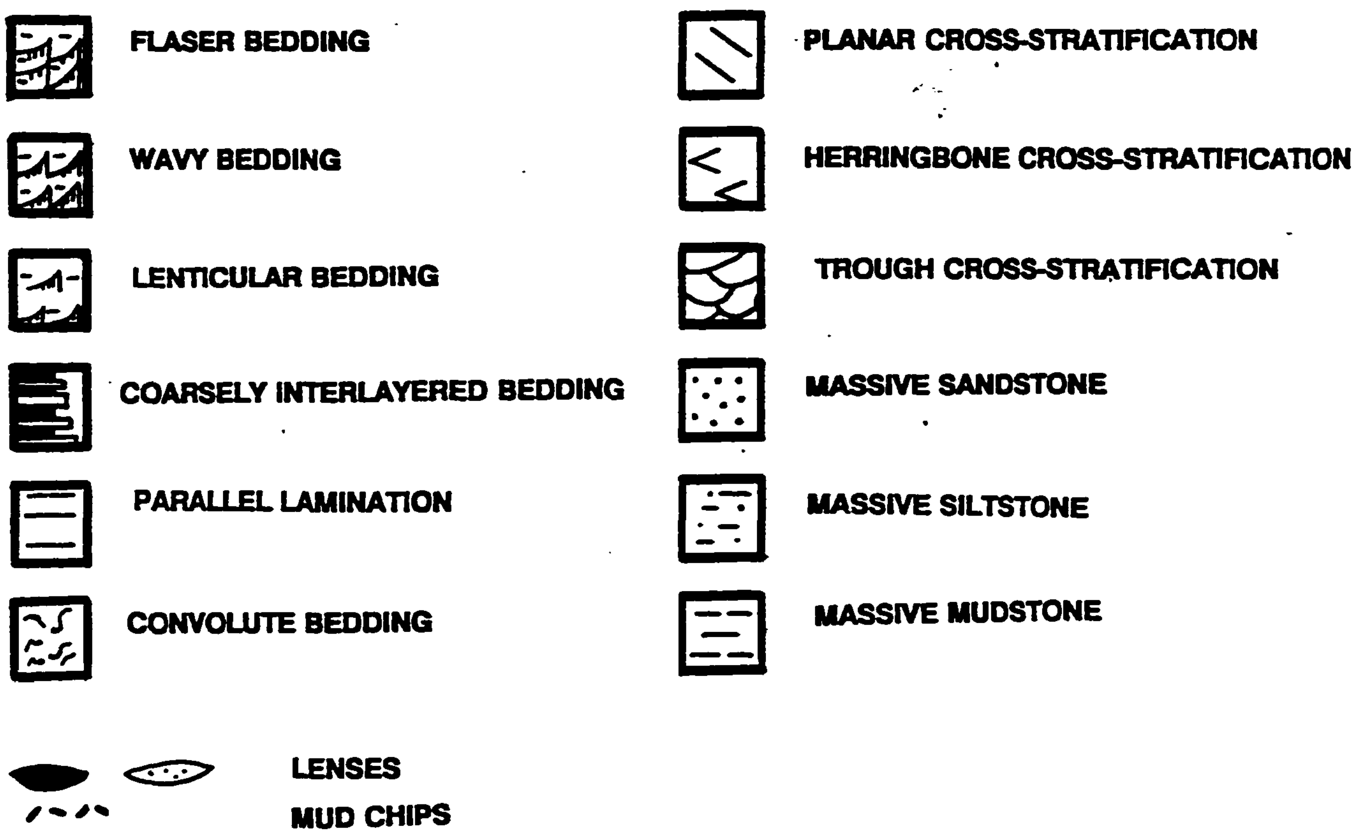

52.99
54.22
55.25 m
10
cm
0
51.86 m
52.99
54.22
m s v f m s c
m s v f m s c
m s v f m s c

laminated sandstone beds are found at the top and near the base of the sequence. Once again, boundaries between all beds are sharp and distinct.

In contrast to the sequence depicted in Figure 3-14, the sequence in Figure 3-15 is dominated by trough cross-stratified beds. Other lithofacies present in this sequence in minor amounts include coarsely interlayered bedding, wavy bedding, massive and parallel laminated sandstone beds, and planar cross-stratified beds. With the exception of the mudstone and siltstone layers in the coarsely interlayered bedding, no mudstone and siltstone lithofacies are present. Many of the trough cross-stratified units are present as series of vertically stacked beds. Boundaries between all beds within this sequence are sharp and distinct, no gradations exist between overlying and underlying beds. Overall, there is a fining upwards trend throughout the sequence.

Figure 3-16 depicts a sequence dominated by herringbone cross-stratification. This sequence is located towards the top of the shoreface tidal sand sheet. Other lithofacies present in this association include: parallel laminated and massive sandstone beds; massive siltstone and mudstone beds; wavy bedding; and coarsely interlayered bedding. All of these lithofacies appear to be randomly interbedded with one another. The number of herringbone cross-stratified beds increases when moving up through the sequence. There is also a slight decrease in grainsize towards the top of the sequence.

FIGURE 3-15 Shoreface tidal sand sheet.



m = MUDSTONE
s = SILTSTONE
v = VERY FINE-GRAINED SANDSTONE
f = FINE-GRAINED SANDSTONE
ms = MEDIUM-GRAINED SANDSTONE
c = COARSE-GRAINED SANDSTONE

FIGURE 3-15

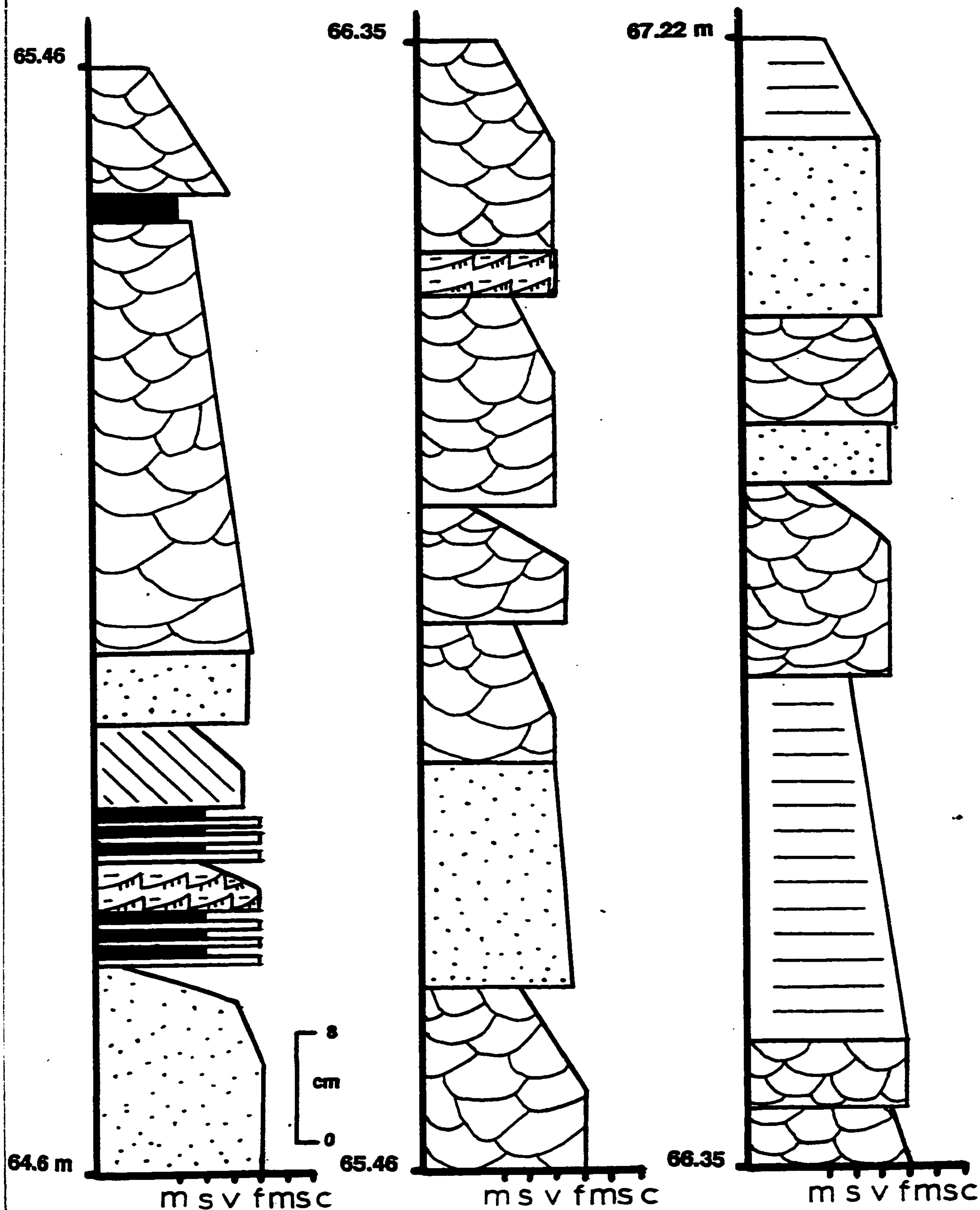
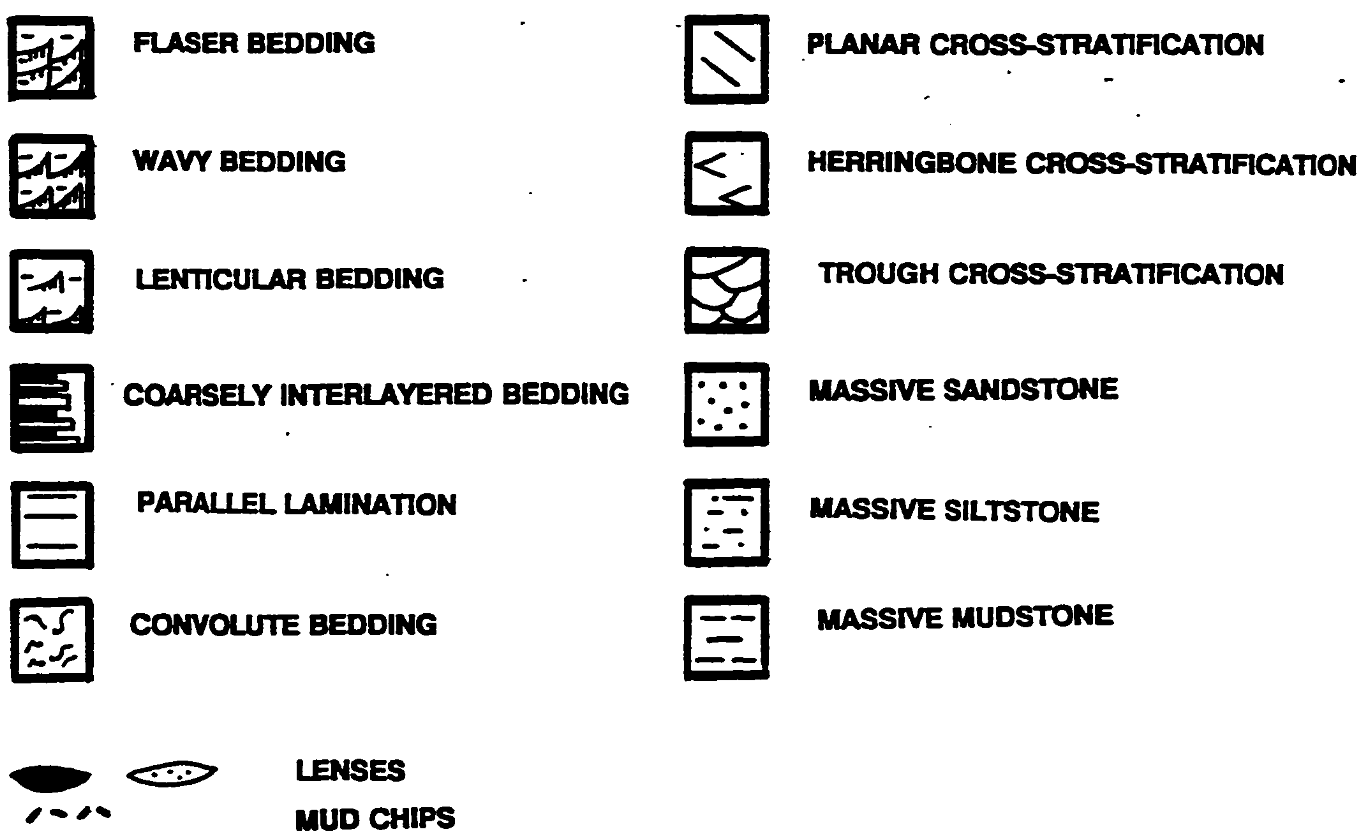
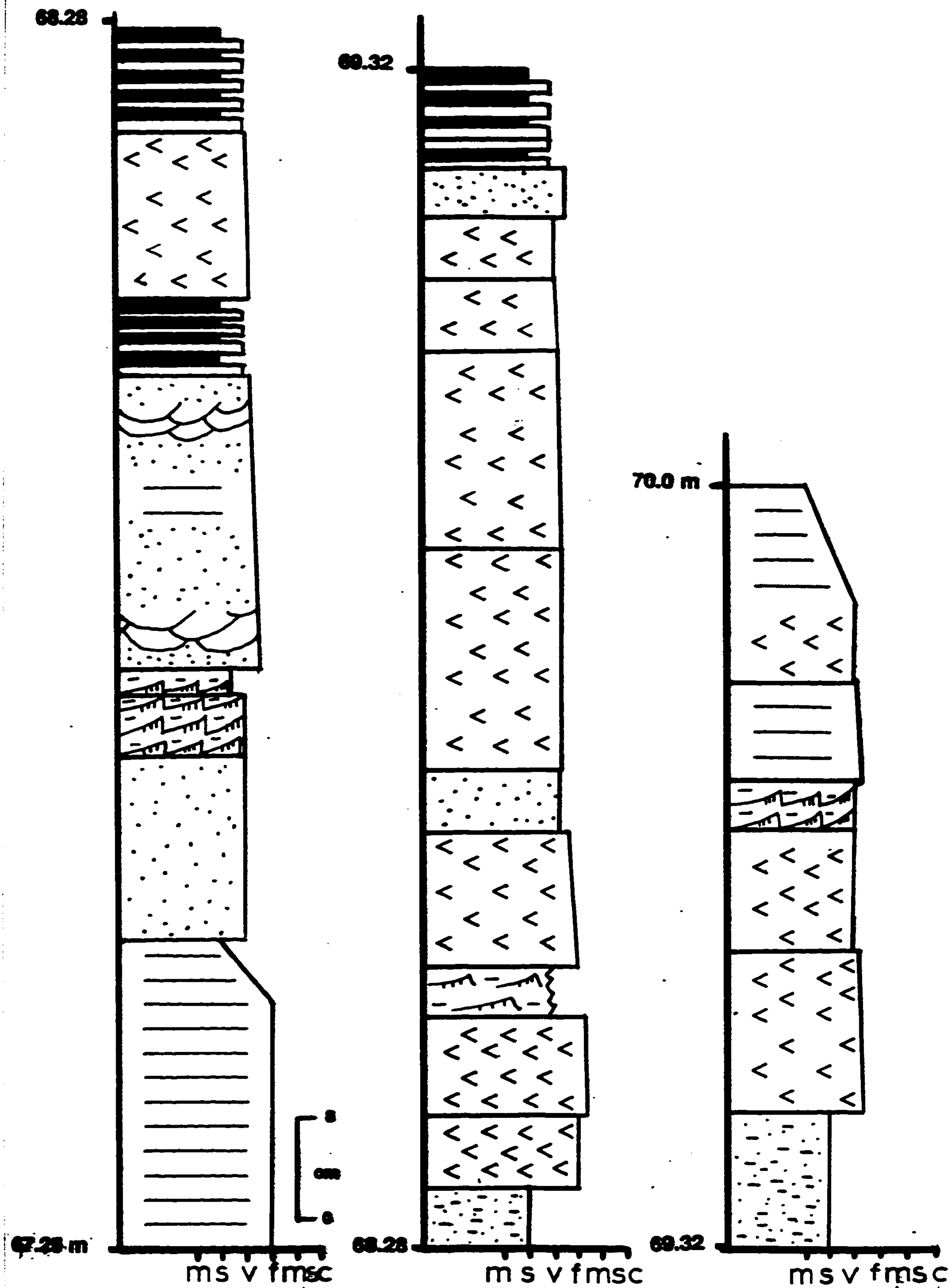

65.46
64.6 m
m s v f m s c
8
cm
0
66.35
65.46
m s v f m s c
67.22 m
66.35
m s v f m s c

FIGURE 3-16 Shoreface tidal sand sheet.



m = MUDSTONE
s = SILTSTONE
v = VERY FINE-GRAINED SANDSTONE
f = FINE-GRAINED SANDSTONE
ms = MEDIUM-GRAINED SANDSTONE
c = COARSE-GRAINED SANDSTONE

FIGURE 3-16



CHAPTER FOUR -- OFFSHORE ENVIRONMENT

This chapter concentrates on the sedimentary units present in the upper portion of outcrop 1. In contrast to the many different lithofacies in the lower portion of this outcrop, only a small number of lithofacies occur in the upper part. These lithofacies are the sandstone and siltstone and mudstone lithofacies. Hummocky cross-stratification is found in the sandstone lithofacies.

Two major trends are discernable moving upwards through the top portion of outcrop 1. First, there is an overall fining-upwards trend, and secondly there exists a change in the degree of lateral continuity within individual layers. Near the bottom of the upper portion there is very little lateral continuity. Towards the top, there is little change in lateral directions, with individual beds remaining fairly uniform in both thickness and sedimentary structures present.

SANDSTONE LITHOFACIES

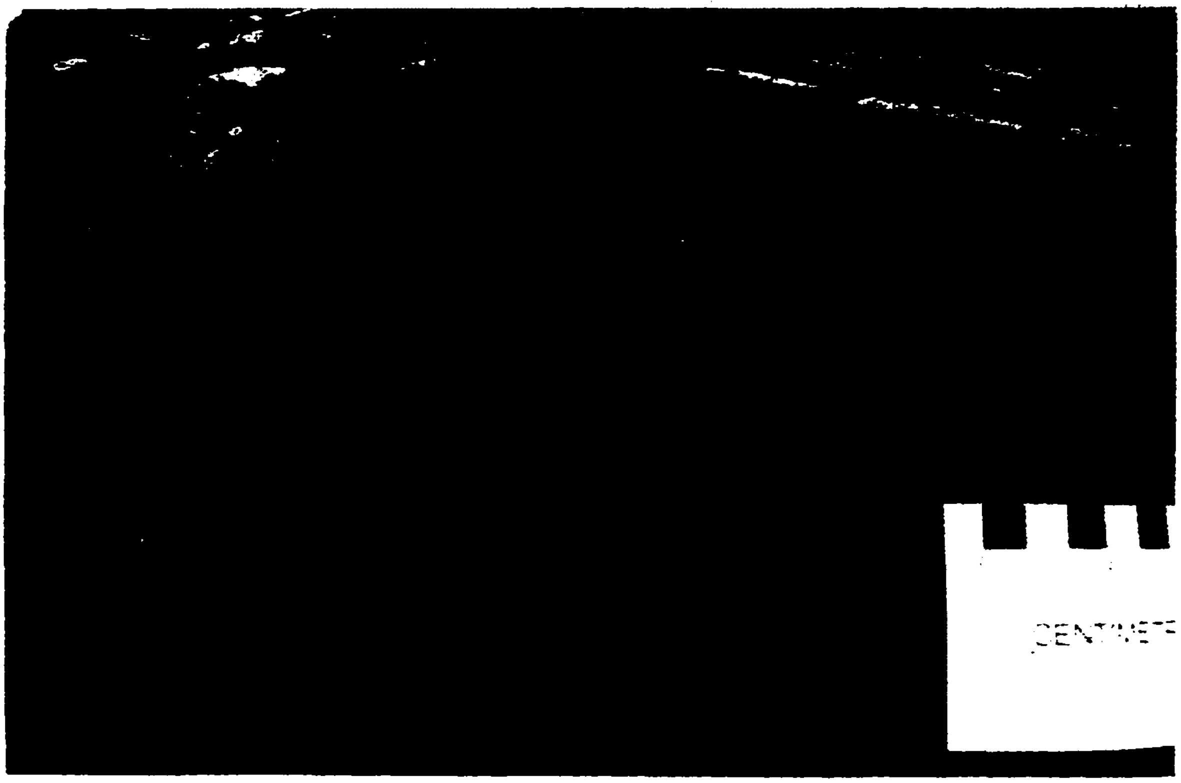
The presence of sandstone beds becomes exceedingly rarer upwards through the section. There is a huge degree of heterogeneity between many of these beds; some are massive, and others are parallel laminated or hummocky cross-stratified. Graded and nongraded beds occur.

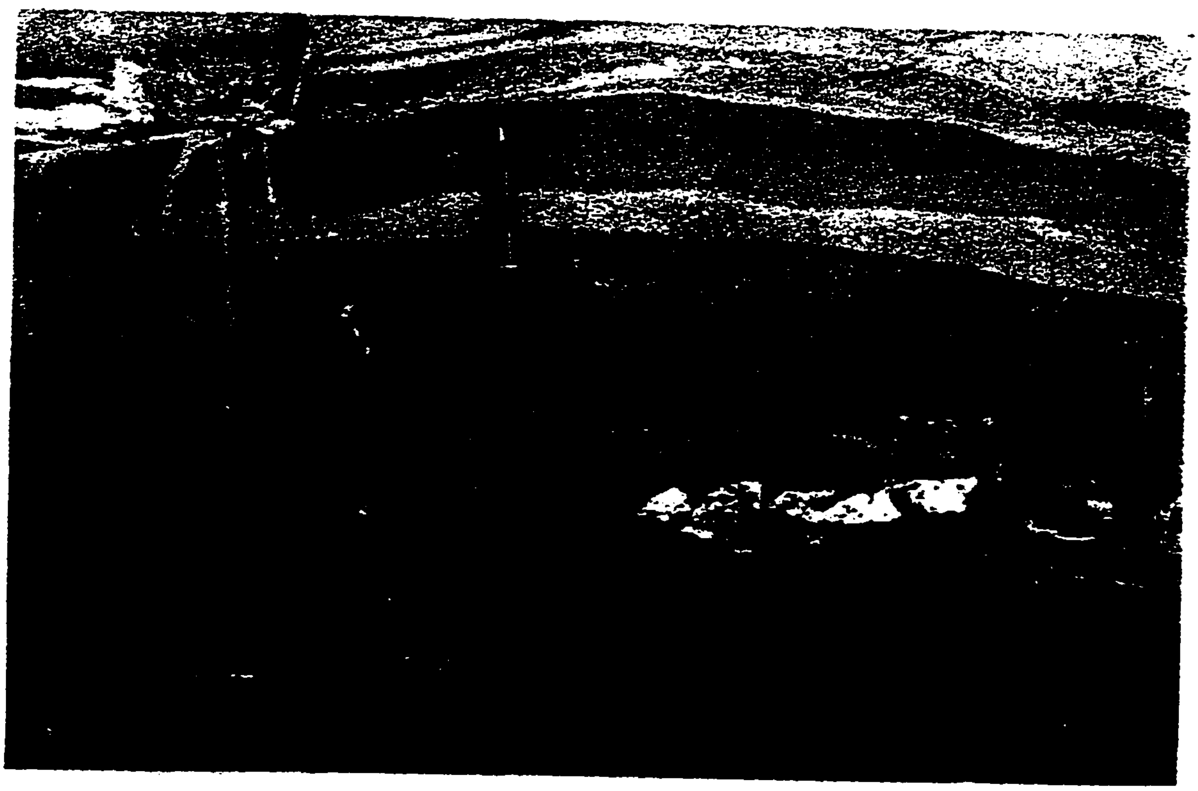
Parallel Laminated Sandstone Beds

Both graded and nongraded parallel laminated sandstone beds are present (Figure

FIGURE 4-1 Graded, parallel laminated sandstone beds. The most distinctive laminated bed is overlain by a massive sandstone bed.

FIGURE 4-2 Parallel laminated sandstone bed in centre of photograph.





4-1). Grainsize varies from medium- to fine-grained sand. Rarely, coarse-grained sandstone beds are also present. The coarse-grained sand tends to form thin basal layers to many of the medium- to fine-grained beds. The graded beds usually undergo a size reduction from a medium- to coarse-grained sandstone base upwards into either a fine- to very fine-grained siltstone or mudstone top. Occasionally, the siltstone or mudstone tops are massive, others are parallel laminated. Individual bed thicknesses range from 1.0 to 26.5 centimetres, the averaging 7.5 centimetres.

Individual laminae in all beds are composed of very fine-grained sandstone, and can range in thickness from 0.05 to 0.5 centimetres (Figure 4-2). In places the parallel lamination is very faint and somewhat indistinguishable. This is partly due to the thin and faint nature of the laminae in many sections of the sequence. Within individual beds, a change from thick, distinctive laminae upwards into thin, faint laminae commonly occurs. In many of the beds, especially higher in the section, the laminae have a wavy or undulating appearance. This type of parallel laminated sandstone bed is similar to quasi-planar laminated sandstone beds described by Arnott (1993), from the Lower Cretaceous Bootlegger Member of Montana.

Lateral variations exist in some of the parallel laminated sandstone beds. Many of the beds thin and thicken laterally, others exhibit greater variations. For example, a bed consisting of parallel laminated medium-grained sands laterally becomes more wavy, or hummocky-like in appearance. The wavy, or hummocky-like, laminated portion subsequently is laterally truncated from above, the cut filled with a massive siltstone layer. Many of the beds, laterally pass from parallel lamination into lamination which is slightly wavy.

Within many non-graded and graded very fine- to fine-grained sandstone beds, laterally discontinuous layers (0.5 cm wide) of very fine-grained silt are present. These layers are somewhat contorted in appearance. Other beds also contain isolated, discontinuous layers of siltstone or mudstone. Sporadic, rare, isolated lenses are also present in a small number of beds. Lenses filled with very coarse-grained sandstone are rarely present at the base of sandstone beds. One bed contains mud drapes over ripples in its upper 2.0 centimetres.

Many boundaries between beds are erosive and irregular. Scours into the tops of beds are usually filled with material from the overlying bed. At some contacts the material infilling the scours is massive, at others it appears parallel laminated. Load casting is also very common, especially when a medium - to coarse-grained basal portion of a bed is involved.

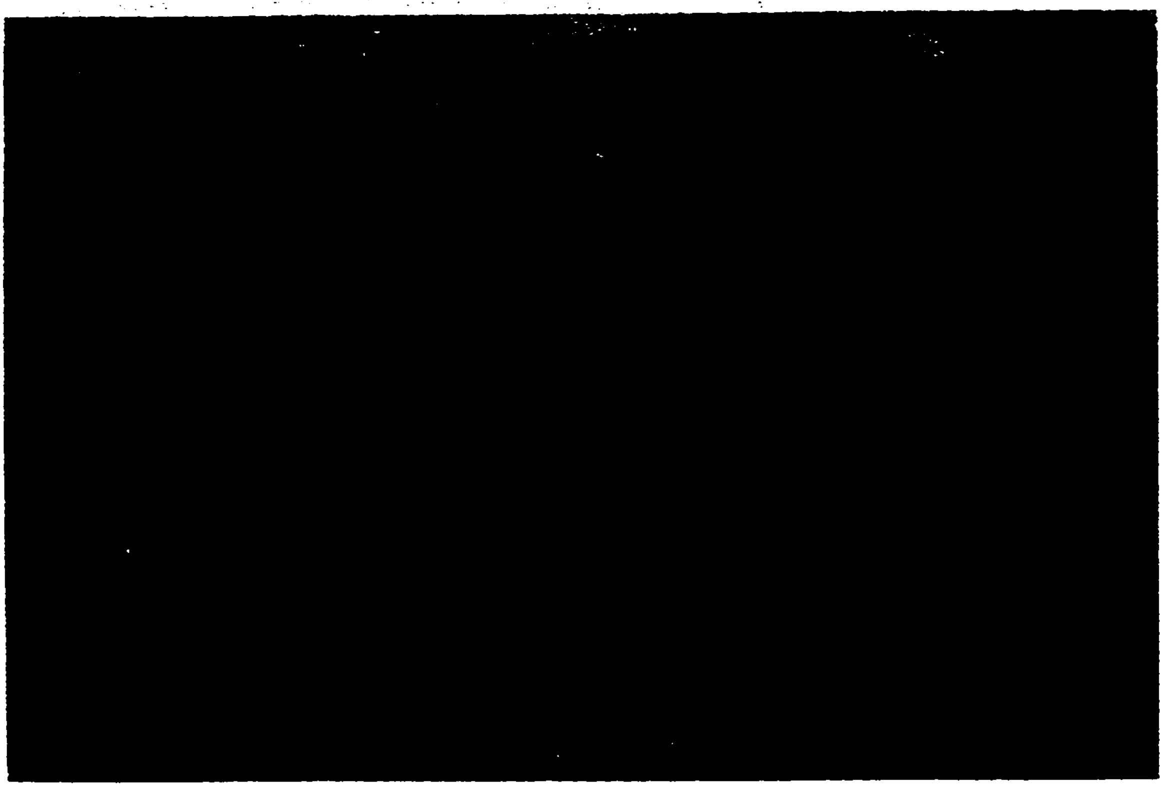
One of the non-graded parallel laminated sandstone beds passes upwards into an interlayered sequence of coarse-grained and fine-grained layers. The coarser-grained layers dominated, and average 0.5 centimetres in thickness. Another bed is topped by a series of vertically stacked troughs, infilled with medium-grained sandstone. The transition from the parallel laminated fine-grained sandstone base of the bed to the top dominated by troughs is erosively scoured. A 8.5 centimetre thick very fine-grained sandstone bed grades upwards into a thin, massive siltstone top. The transition from the parallel laminated portion of the bed into the massive top is marked by a number of small scours, infilled by the massive siltstone. The presence of internal scours between the parallel laminated sandstone base and siltstone top is present in a small number of beds.

A 15.0 centimetre thick bed is composed of a massive medium-grained sandstone base, which passes upwards into a portion which is parallel laminated. The abundance and thickness of individual laminae increase upwards within the parallel laminated portion. At the transition between the massive and parallel laminated portions, small isolate mud flasers are present. The entire bed is topped by a 1.5 centimetre thick massive siltstone layer, containing discontinuous coarse-grained sand laminae. This is repeated in two other beds, 10.5 and 14.0 centimetres in thickness. The 10.5 centimetre thick bed also contains isolated lenses filled with coarse-grained sand at its top. Lateral transitions are present in the 14.0 centimetre thick bed. In this bed, there is a lateral change from a massive base into a parallel laminated base.

Massive Sandstone Beds

Massive graded and nongraded sandstone beds vary in thickness from 1.5 to 15.5 centimetres, with an average of 6.0 centimetres (Figures 4-1 & 4-3). As with the parallel laminated sandstone beds, grainsize ranges from coarse- to very fine-grained sand. Medium-grained sandstone appears to dominate. The graded beds fine

FIGURE 4-3 Massive, nongraded sandstone bed, overlain by a faintly parallel laminated sandstone bed - lower portion of photograph.



upwards from a coarse-grained base into a very thin, massive fine-grained siltstone or mudstone top. One bed contains mud rip-ups in its bottom two centimetres. In some of the beds, the coarse-grained base was observed to thin and thicken laterally. Rarely beds have a very coarse-grained base.

Similar to the parallel laminated beds, the massive sandstone beds exhibit lateral variations. Some beds thicken or thin laterally, but others exhibit more complex lateral changes. Two very fine-grained sandstone beds widen laterally into thicker lenticular bedded units overlain by massive siltstones. The lenticular bedding then passes laterally into a ripple laminated sandstone overlain by siltstone. Occasionally, other beds will laterally pass into a finer-grained, thinly parallel laminated portion. Near the base of the sequence, there are two massive fine-grained sandstone beds that show lateral transitions into lenticular bedding.

Irregular contacts between massive sandstone beds and adjacent beds are common. Usually the irregular contacts simply consist of load casting. In the remaining beds which show no irregular contacts, there are sharp and distinctive contacts between beds.

Isolated lens are also commonly present in the massive sandstone beds. Lenses are typically filled with coarse-grained sand. Discontinuous layers of fine-grained siltstone or mudstone are common. These layers average 0.3 to 0.5 centimetres in thickness. Rarely, the thicker non-graded beds will be cut by numerous laterally discontinuous layers of fine-grained to medium-grained siltstone, averaging 0.5 centimetres in thickness. Internal scours infilled with parallel laminated fine- to medium-grained sandstone are rarely present.

Hummocky Cross-Stratified Sandstone Beds

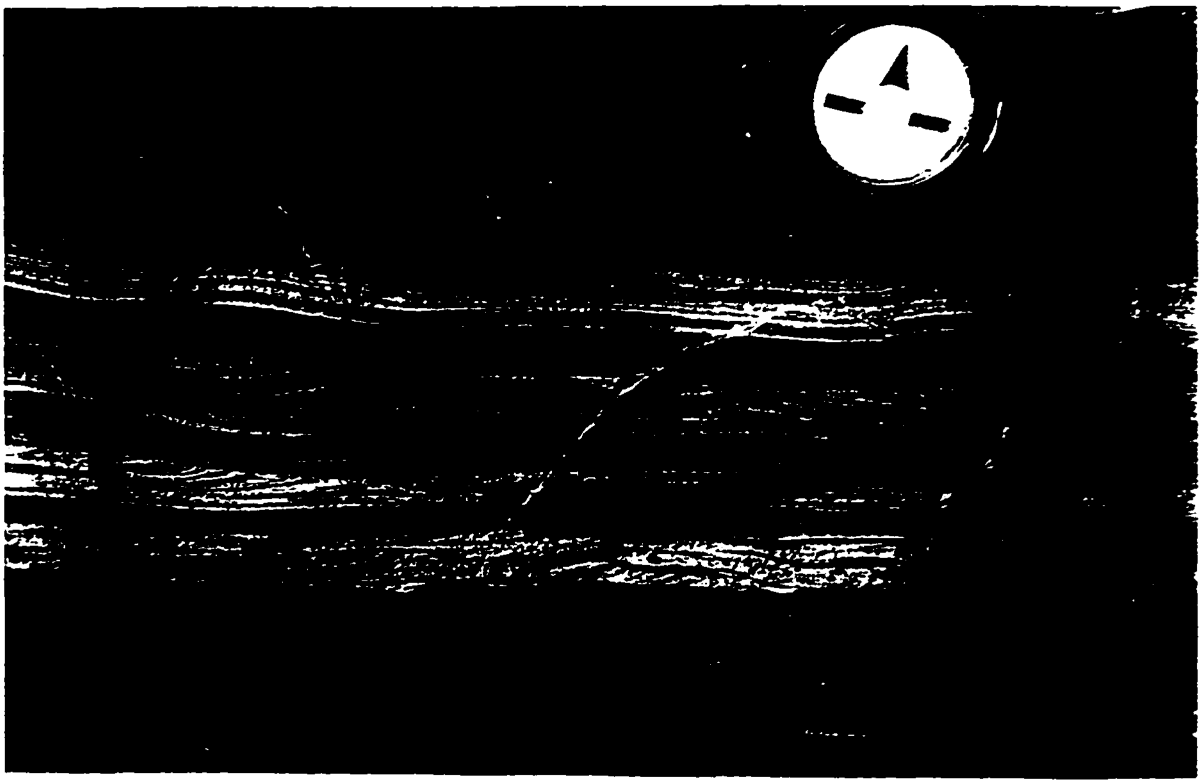
The upper portions of the offshore sequence are characterized by the presence of hummocky cross-stratification within individual beds (Figures 4-4 & 4-5). Hummocky cross-stratification (HCS) was first named and described by Harms *et. al.* (1975) and consists of antiformal hummocks and synformal swales defined by randomly oriented, even lamination with dip angles and truncation angles of $< 15°$ (Dott and Bourgeois, 1982).

An idealized hummocky sequence (Figure 4-6) has been proposed by Dott and Bourgeois (1982), and includes the following zones; a hummocky zone, flat laminae zone, cross laminae zone, and mudstone zone. A number of deviations from this idealized sequence have also been described by Dott and Bourgeois (1982), and are illustrated in Figure 4-6. Less common variations include units that commence with flat-lamination (Dott and Bourgeois, 1982).

Walker *et. al.*, (1983) have presented a modified idealized hummocky cross-stratified sequence (Figure 4-7). This sequence contains the following divisions: B -

FIGURE 4-4 Hummocky cross-stratification interbedded with massive, siltstone layers.

FIGURE 4-5 Close-up view of hummocky cross-stratification from the study area.


A

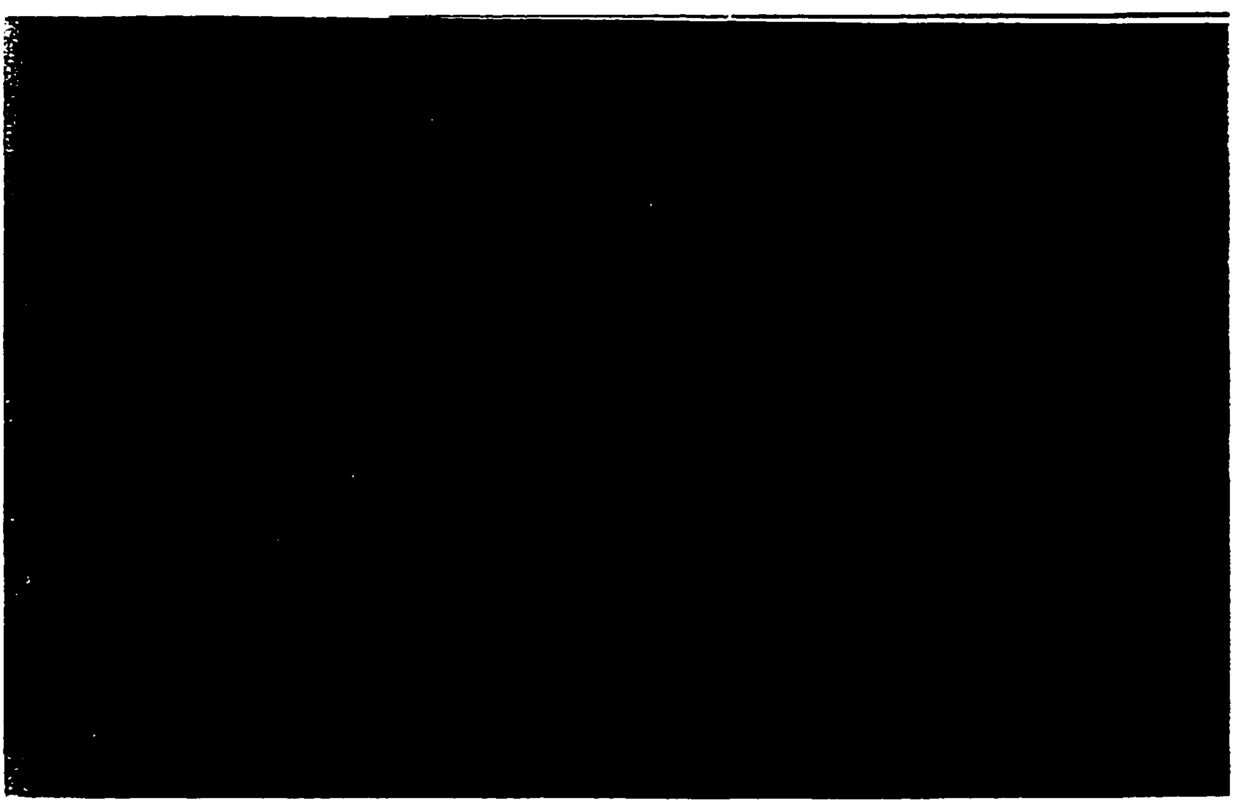
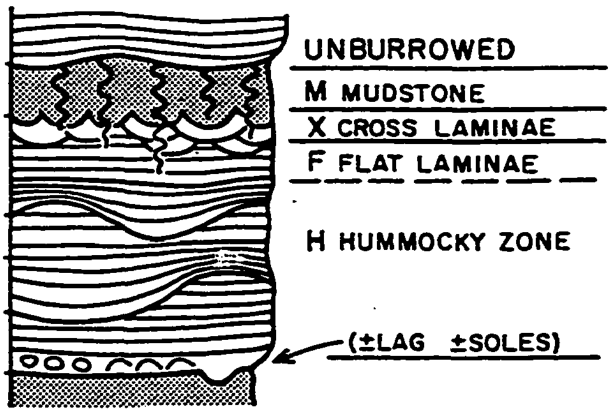
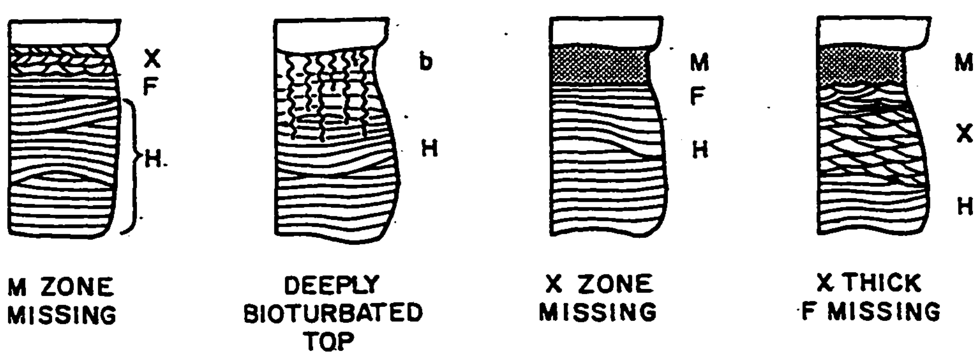


FIGURE 4-6 Idealized sequence of hummocky stratification from Dott and Bourgeois (1982), with common variations.

H - hummocky zone
F - flat laminae zone
X - cross laminae zone
M- mudstone zone.

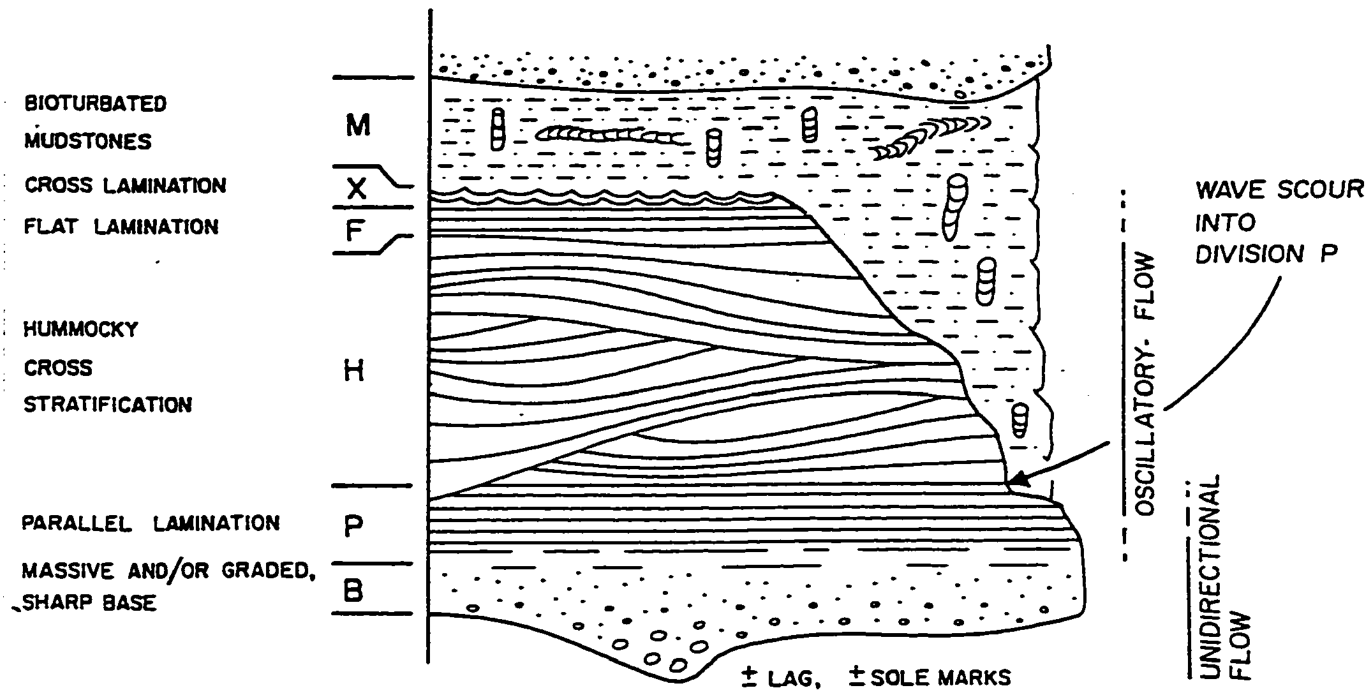


COMMON VARIATIONS



Dott and Bourgeois (1982)

FIGURE 4-7 Modified hummocky cross-stratified sequence from Walker *et. al.* (1983).
M - mudstone
X - ripple cross lamination
F - 'flat' lamination
H - hummocky cross-stratification
P - planar parallel lamination
B - basal division



Walker *et. al.* (1983)

basal division, P - planar parallel lamination, H - hummocky cross-stratification, F - 'flat' lamination, X - ripple cross lamination, and M - mudstone. As with Dott and Bourgeois' (1982) sequence, the modified sequence of Walker *et. al.*, (1983) commonly has missing divisions, such as the absence of the flat laminated (F) and ripple cross laminated (X) divisions. The hummocky cross-stratified sequences in the current study will be compared to the idealized and modified sequences of Dott and Bourgeois (1982) and Walker *et. al.*, (1983).

Thicknesses of hummocky cross-stratified beds ranges from 3.5 to 22.0 centimetre, with an average of 8.5 centimetres (Figure 4-8). The beds present in the study area consists of packages of thin layers of HCS interlayered with massive and parallel laminated siltstone and sandstone layers (Figure 4-9). Grainsize within the hummocky cross-stratified layers varies from very fine- to fine-grained sandstones. Individual laminae within the hummocky cross-stratified layers are thin, becoming even thinner over hummocks and thicker within the swales. Beds containing hummocky cross-stratification are laterally persistent for the width of the outcrop (2 metres).

The interlayered packages of layers of hummocky cross-stratification with layers of siltstone and sandstone, forms the following three sequences;

top: massive siltstones and mudstones
middle: hummocky cross stratification
bottom: parallel laminated sandstones

top: massive siltstones and mudstones
bottom: hummocky cross stratification

FIGURE 4-8 Hummocky cross-stratification

FIGURE 4-9 Interlayered association of very thin hummocky cross-stratified units with massive and parallel laminated sandstone and siltstone layers.

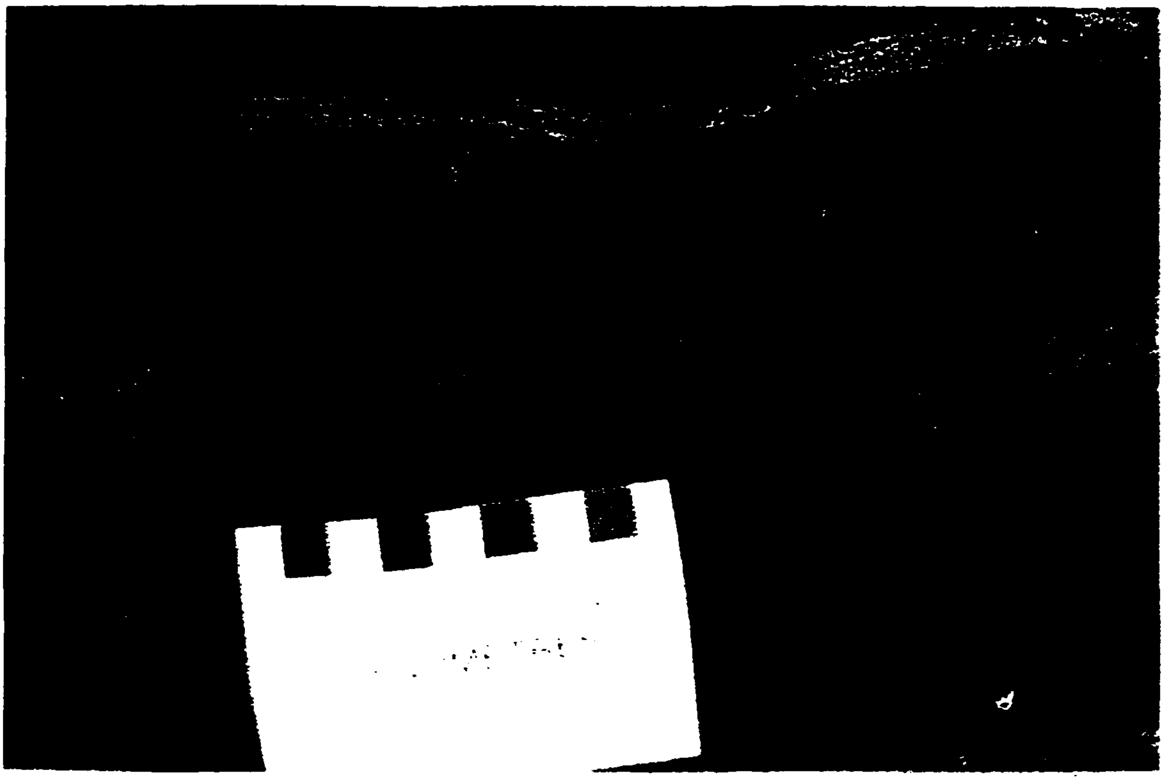
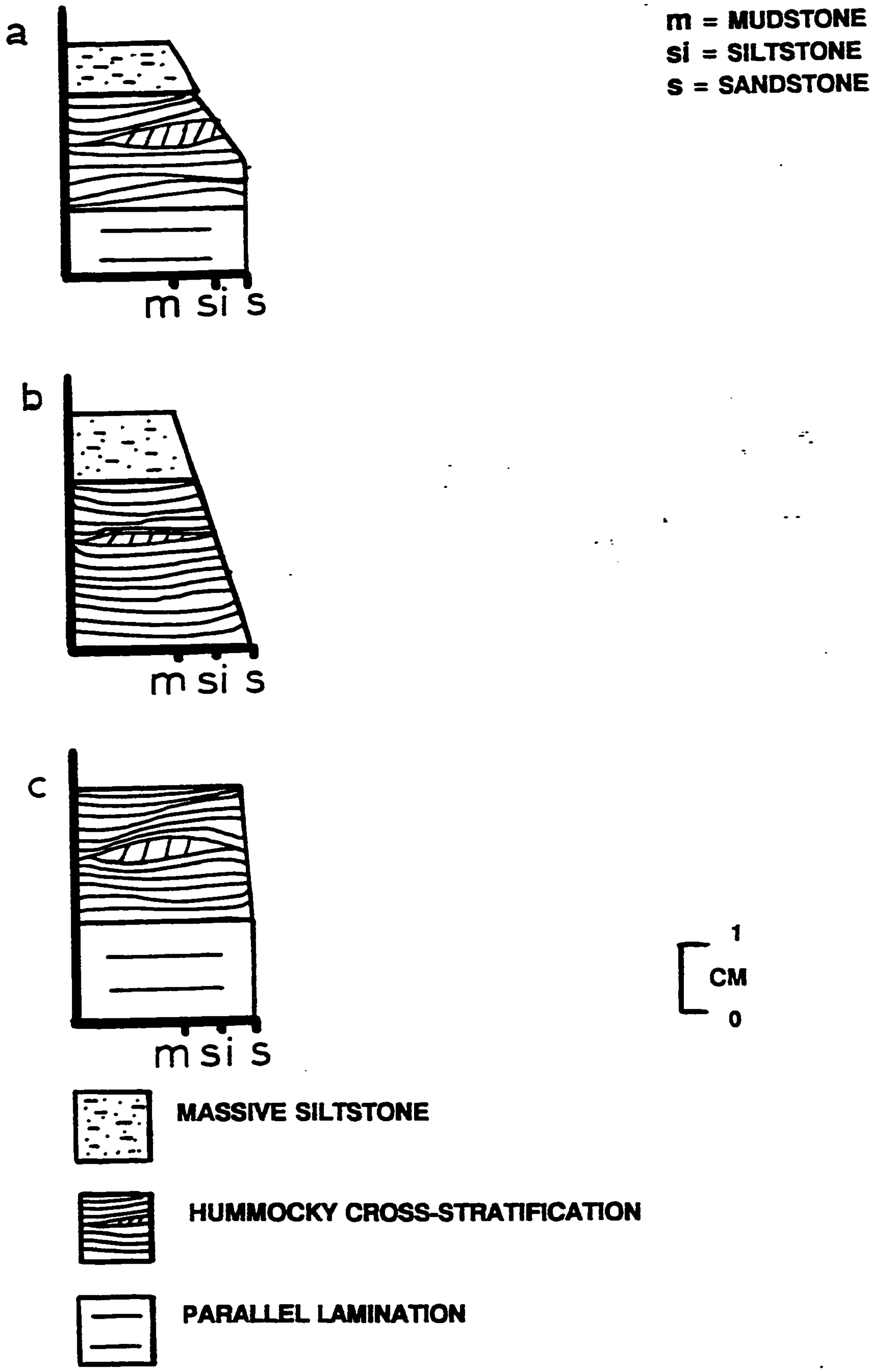


FIGURE 4-10 Generalized depiction of the three interlayered sequences of hummocky cross-stratification typically found in the study area.


m = MUDSTONE
si = SILTSTONE
s = SANDSTONE
a
m si s
b
m si s
c
m si s
1
CM
0
MASSIVE SILTSTONE
HUMMOCKY CROSS-STRATIFICATION
PARALLEL LAMINATION

top: hummocky cross stratification
bottom: parallel laminated sandstones

Almost all hummocky cross-stratified beds in the study area are composed of one of these three sequences. Figure 4-10a,b,c illustrates the three sequences. The parallel laminated layers contain laminae that are between 0.1 - 0.4 centimetres in thickness. Laminae tend to become thinner and fainter when moving up through the bed. The massive layers are typically graded. At times, the massive layers also appear very faintly and thinly laminated. The lamination in the massive layer tends to be discontinuous and isolated. An overall fining upwards trend is usually present in the hummocky cross-stratified beds.

The three sequences resemble those described by Dott and Bourgeois (1982) and Walker *et. al.*, (1983). The sequence shown in Figure 4-10b, is somewhat similar to Dott's and Bourgeois' (1982) sequence (Figure 4-6) with the X zone missing. The other two sequences with parallel lamination at the base resemble variations of the modified idealized sequence of Walker *et. al.*, (1983) (Figure 4-7).

Many of the transitions between the underlying layers of parallel laminated sandstones and the layers of hummocky cross-stratification, and overlying layers of massive siltstone are smooth and gradual. In one bed, the layer of hummocky cross-stratification is abruptly truncated and overlain by a draping, discontinuous layer of mudstone. In two beds, at the transition between the hummocky cross-stratified layer and the overlying massive layer, small scours are present. The scours are infilled by thinly laminated medium- to coarse-grained siltstone.

The basal portion of the hummocky cross-stratified beds are typically composed of very fine- to fine-grained sandstone. This portion may be parallel laminated. There is generally a decrease in grainsize upwards, especially when the layer of hummocky cross-stratification is topped by a layer of massive fine-grained siltstone or mudstone.

One of the stratigraphically lower hummocky cross-stratified beds contains mud rip-up clasts in its basal 2.0 centimetres. An 8.0 centimetre thick bed contains mud rip-ups at its top which are overlain by a very thin layer of massive fine-grained siltstone.

The hummocky cross-stratified beds are usually interbedded with massive and parallel laminated siltstone and mudstone and sandstone beds. Boundaries between hummocky cross-stratified beds and other beds are typically sharp and distinct. Occasionally, load casting can be found at both the top and bottom of hummocky cross-stratified beds.

A small number (2) of hummocky cross-stratified beds do not exhibit the three previously described sequences. These beds appear to be entirely hummocky cross-stratified. There are no massive siltstone layers overlying the hummocky cross-stratified layer within the bed. Parallel laminated fine-grained sandstone layers that compose the base are also not present. The two beds average 2.0 centimetres in thickness. One bed immediately overlies the other bed. The contact between the two beds is sharp.

SILTSTONE AND MUDSTONE LITHOFACIES

Parallel Laminated Siltstone and Mudstone Beds

Parallel laminated siltstone and mudstone beds appear to increase in abundance towards the top of the section (Figure 4-11). Bed thickness vary from 2.0 to 19.0 centimetres, with an average thickness of 6.0 centimetres. Grainsizes range from coarse-grained siltstone to mudstone and beds may be either graded or non-graded. Many of the graded beds fine upwards from a coarse- or medium-grained siltstone base into a mudstone top. In a small number of beds there is a thin fine-grained sandstone base which may thin and thicken laterally. The mudstone top is generally massive.

As with the parallel laminated sandstone beds, in places the laminae are very faint and thin. Laminae are 0.1 to 0.2 centimetres thick. In many of the beds, the laminae will appear somewhat wavy, again similar to some parallel laminated sandstone beds. Rarely, laminae will increase in abundance towards the top of the bed, or become discontinuous and localized.

FIGURE 4-11 Interbedded association of massive and parallel laminated siltstone and mudstone beds.

Small scours are found at the top of a small percentage of beds. These scours are filled with a fine-grained sandstone at their base, which fines upwards into a mudstone. Isolated lenses filled with fine- to coarse-grained sandstone are found in many of the beds. Load casting is also found along the top and the bottom of a single bed.

Lateral and vertical transitions within individual beds are uncommon. Vertically, a bedmay pass from a thin, massive, coarse-grained siltstone base into a parallel laminated siltstone middle, and back into a massive fine-grained siltstone top. A few beds show an upwards transition into a small series of interlayered fine- and coarse-grained layers near their top. There is also very little lateral variation within beds. The beds that do show lateral variations only thicken and thin laterally.

Massive Siltstone and Mudstone Beds

The massive siltstone and mudstone beds are dominated by fine- to coarse-grained siltstone (Figure 4-12). Bed thicknesses range from 1.5 to 22.0 centimetres. The average thickness is 5.8 centimetres. The vast majority of beds are non-graded, with only twelve of the beds exhibit grading. The graded beds fine upwards from a coarse-grained siltstone base into a mudstone top.

Lateral variations within beds exist. One bed passes laterally into a series of small, vertically stacked troughs. The troughs are filled with a massive, non-graded, fine-

Figure 4-12 Massive very-fine grained siltstone beds interbedded with hummocky cross-stratification.

grained sandstone. In another example, the coarse-grained base of a bed pinches out laterally and is replaced by the finer-grained top portion of the bed. The top 2.0 centimetres of another bed passes laterally into parallel laminated fine-grained siltstone.

Many of the beds contain isolated lenses of fine-grained sandstone to coarse-grained siltstone. The lenses are concentrated in either the top or bottom portion of beds and are commonly parallel laminated. Rarely, lenses will be found scattered randomlythroughout an entire bed. One bed contains a string of elongate lenses near its base. These lenses are internally parallel laminated. Laterally, the lenses consolidate, forming a continuous parallel laminated layer. In a 6.0 centimetre non-graded bed, a string of cross-laminated lenses along the base of the bed resembles asymmetrical ripples. Laterally discontinuous layers of very fine- to fine-grained sandstone are also common. One bed contains small internal scours filled with medium-grained sandstone. The scours are truncated laterally and the cut filled by massive mudstone. Internal scours infilled with very fine-grained sandstone are rarely present.

Boundaries between the massive siltstone beds and sandstone beds are usually sharp and distinct. Occasionally though, load casting into the uppermost portion of the siltstone bed will occur. Infilled scours are also present at the top of individual beds.

Thin beds of massive mudstone are also present, interbedded with the slightly coarser-grained massive siltstone beds. The mudstone beds average 1.75 centimetres in thickness.

CHAPTER FIVE -- OFFSHORE ENVIRONMENT - LITHOFACIES ASSOCIATIONS

The presence of an offshore depositional environment within the Shebandowan Group was discussed by Rezka (1987), Fralick and Barrett (1991), and Eriksson *et. al.* (1994). Lithofacies associations within the offshore environment are simple. The vast majority of the environment consists of interbedded hummocky cross-stratified, parallel laminated and massive sandstone, and parallel laminated and massive siltstone. The succession exhibits a fining upwards trend from abundant parallel laminated and massive sandstone beds in the lower portion of the sequence compared with the dominance of siltstone beds in higher portions.

Figure 5-1 shows the relative positions of the sections illustrated in Figures 5-2, 5-3, and 5-4. The transition from predominantly sandstone beds in the proximal portion to siltstone beds in the distal portion is also discernable in Figure 5-1.

The transition into the offshore sequence and approximately the first 3.0 metres of this sequence is shown in Figure 5-2. This represents a portion of the transition zone from the shoreface to the offshore environment and is dominated by parallel laminated, wavy laminated and massive sandstone beds. Wavy laminated beds increase in abundance upsection and medium-grained sandstone beds present in the lower portion of the section become finer-grained towards the top of the section. The massive and parallel laminated sandstone beds are randomly interbedded with each other. The transition out of the shoreface sequence is marked by interbedded

FIGURE 5-1 Generalized stratigraphic section depicting the relative positions and average grain size of the offshore, tidal, and shoreface depositional environments. Positions of detailed stratigraphic sections (Figures 5-2 - 5-4) from the offshore environment are indicated. All sections are from outcrop 1.

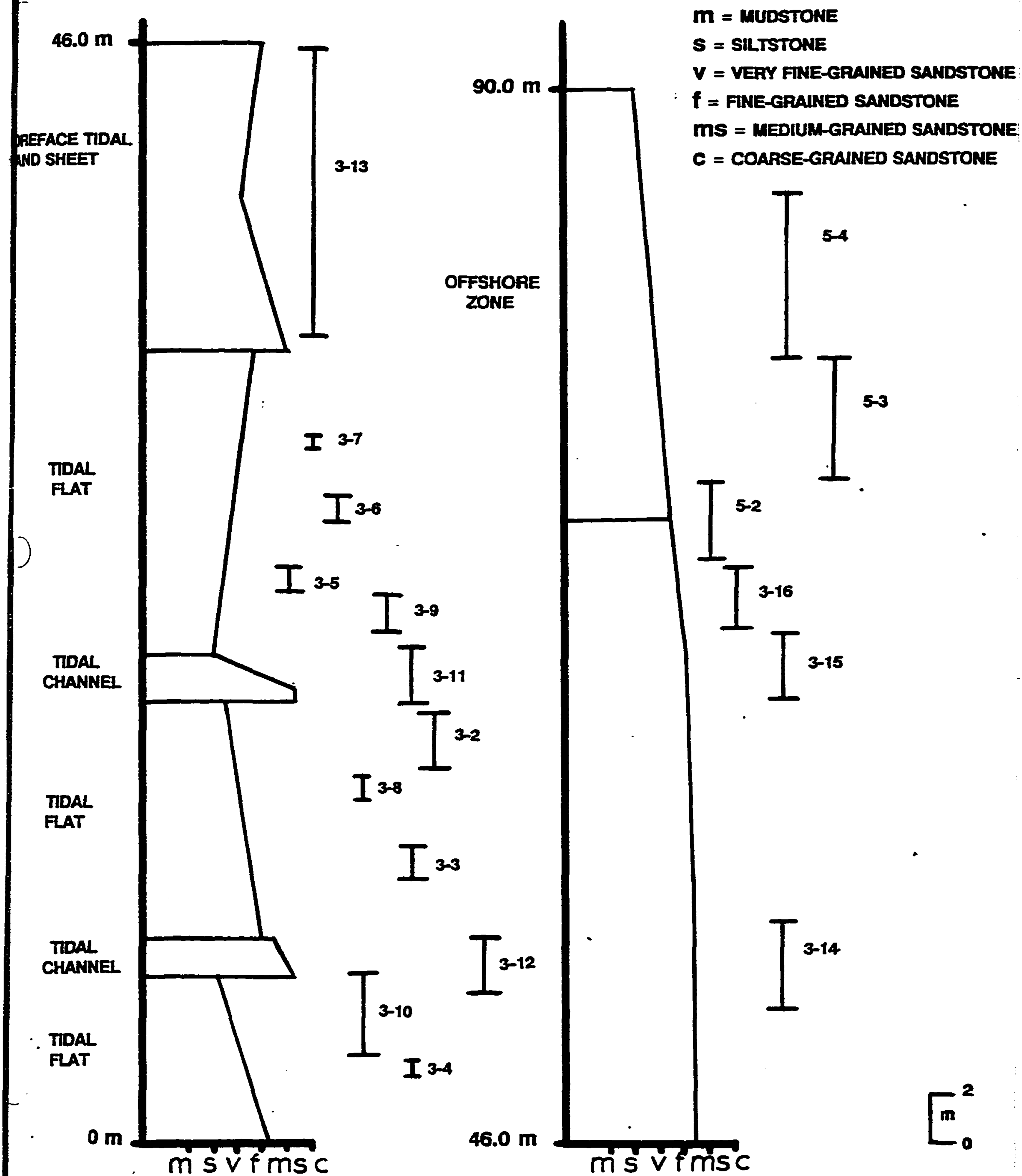

m = MUDSTONE
S = SILTSTONE
V = VERY FINE-GRAINED SANDSTONE
f = FINE-GRAINED SANDSTONE
ms = MEDIUM-GRAINED SANDSTONE
C = COARSE-GRAINED SANDSTONE
46.0 m
REFACE TIDAL
ND SHEET
3-13
TIDAL
FLAT
3-7
3-6
3-5
3-9
TIDAL
CHANNEL
3-11
3-2
TIDAL
FLAT
3-8
3-3
TIDAL
CHANNEL
3-12
3-10
TIDAL
FLAT
3-4
0 m
m s v f ms c
90.0 m
OFFSHORE
ZONE
5-4
5-3
5-2
3-16
3-15
3-14
46.0 m
m s v f ms c
2
m
0

FIGURE 5-2 Shoreface to offshore transition zone and proximal offshore environment.

MASSIVE SANDSTONE

CONVOLUTE BEDDING

MASSIVE SILTSTONE

WAVY LAMINATION

PARALLEL LAMINATION

HUMMOCKY CROSS-STRATIFICATION

HERRINGBONE CROSS-STRATIFICATION

SCOURS

LENSES

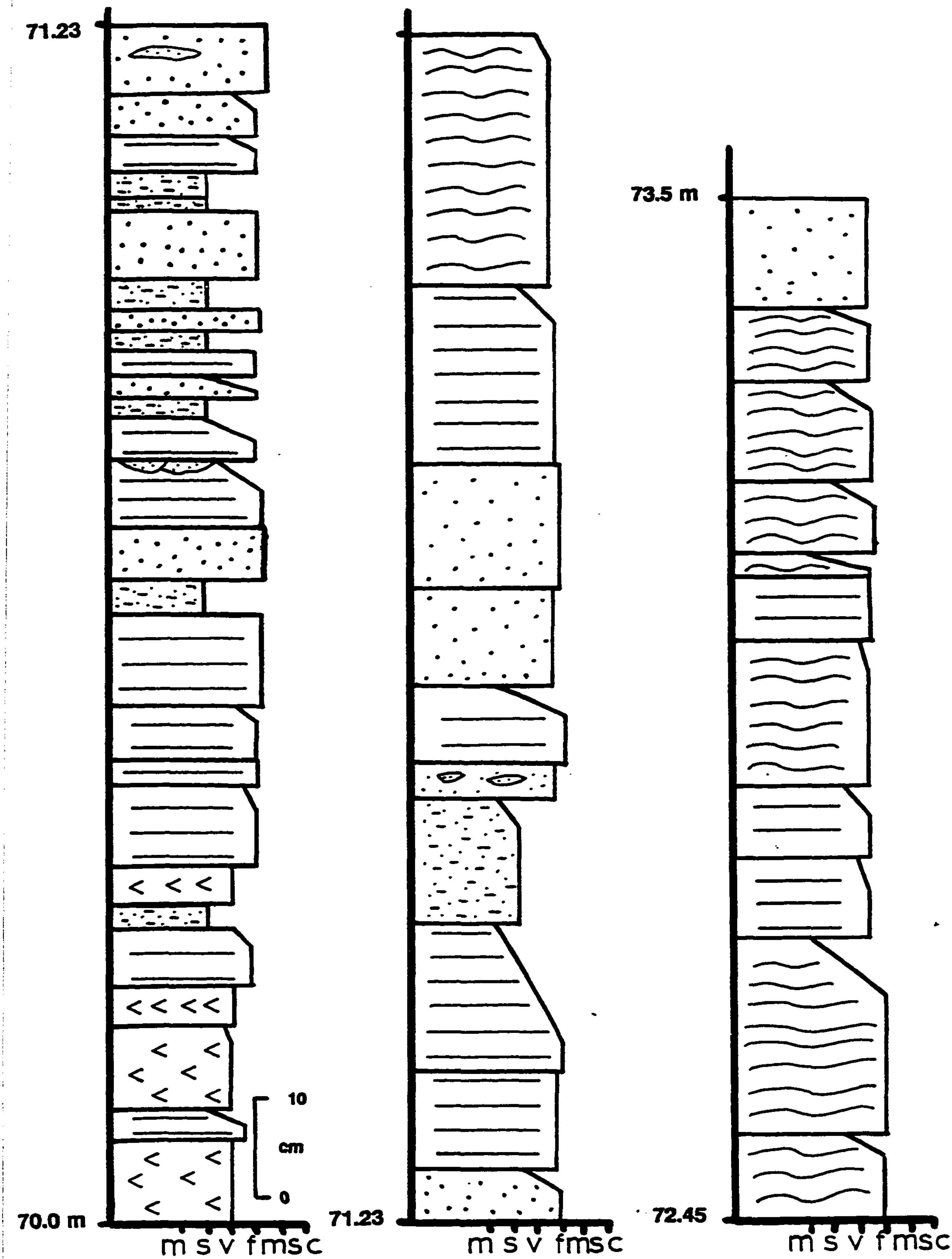
FIGURES 5-2 & 5-3

m = MUDSTONE
s = SILTSTONE
v = VERY FINE-GRAINED SANDSTONE
f = FINE-GRAINED SANDSTONE
ms = MEDIUM-GRAINED SANDSTONE
c = COARSE-GRAINED SANDSTONE

FIGURE 5-4

m = MUDSTONE
fi = FINE-GRAINED SILTSTONE
mi = MEDIUM-GRAINED SILTSTONE
ci = COARSE-GRAINED SILTSTONE
v = VERY FINE-GRAINED SANDSTONE

FIGURE 5-2

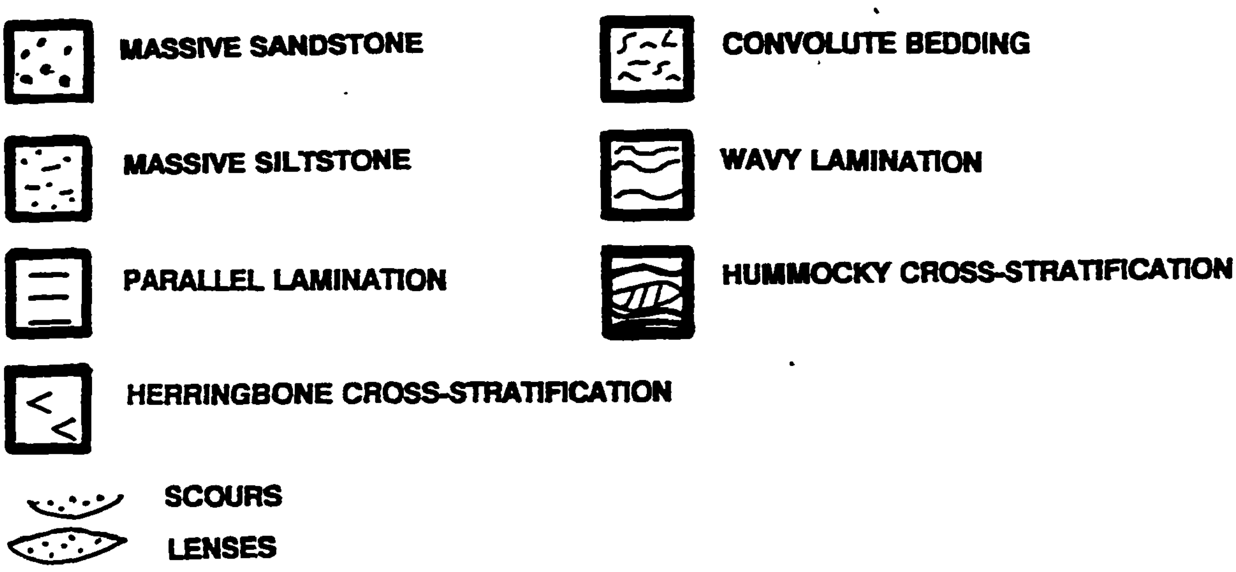


herringbone cross-stratified and parallel laminated sandstone beds. The number of parallel laminated beds increases when moving upwards through this transition. Immediately above this transition, is a small number of massive siltstone and mudstone beds interbedded with the sandstone beds. This association dominates the lower 0.5 metres of the offshore sequence.

Figure 5-3 is a continuation of Figure 5-2, and is higher up in the offshore succession. This 5.3 metre section depicts the transition from a sequence dominated by fine-grained sandstone beds, into one that is dominated by massive and parallel laminated siltstone and mudstone beds. As with the 3.5 metres depicted in Figure 5-2, there is an overall fining upwards trend. The amount and grainsize of sandstone beds decreases upwards through the section. Inversely, the amount of siltstone/mudstone beds increases upwards. Again, the parallel laminated and massive sandstone beds and the siltstone/mudstone beds are randomly interbedded.

The 7.0 metre section shown in Figure 5-4 contains the majority of the hummocky cross-stratified beds that are present in the offshore environment. These beds are randomly interbedded with the siltstone and sandstone beds that comprise the remainder of the section. The majority of hummocky cross-stratified beds are present between 83.0 to 84.0 metres. In this small interval, there is very little interbedding of the HCS beds and the sandstone and siltstone beds. Instead, beds containing hummocky cross-stratification are vertically stacked on top of one another. Following the 84.0 metre mark, only one more hummocky cross-stratified bed is present within

FIGURE 5-3 Offshore environment.



FIGURES 5-2 & 5-3

m = MUDSTONE
s = SILTSTONE
v = VERY FINE-GRAINED SANDSTONE
f = FINE-GRAINED SANDSTONE
ms = MEDIUM-GRAINED SANDSTONE
c = COARSE-GRAINED SANDSTONE

FIGURE 5-4

m = MUDSTONE
fi = FINE-GRAINED SILTSTONE
mi = MEDIUM-GRAINED SILTSTONE
ci = COARSE-GRAINED SILTSTONE
v = VERY FINE-GRAINED SANDSTONE

FIGURE 5-3

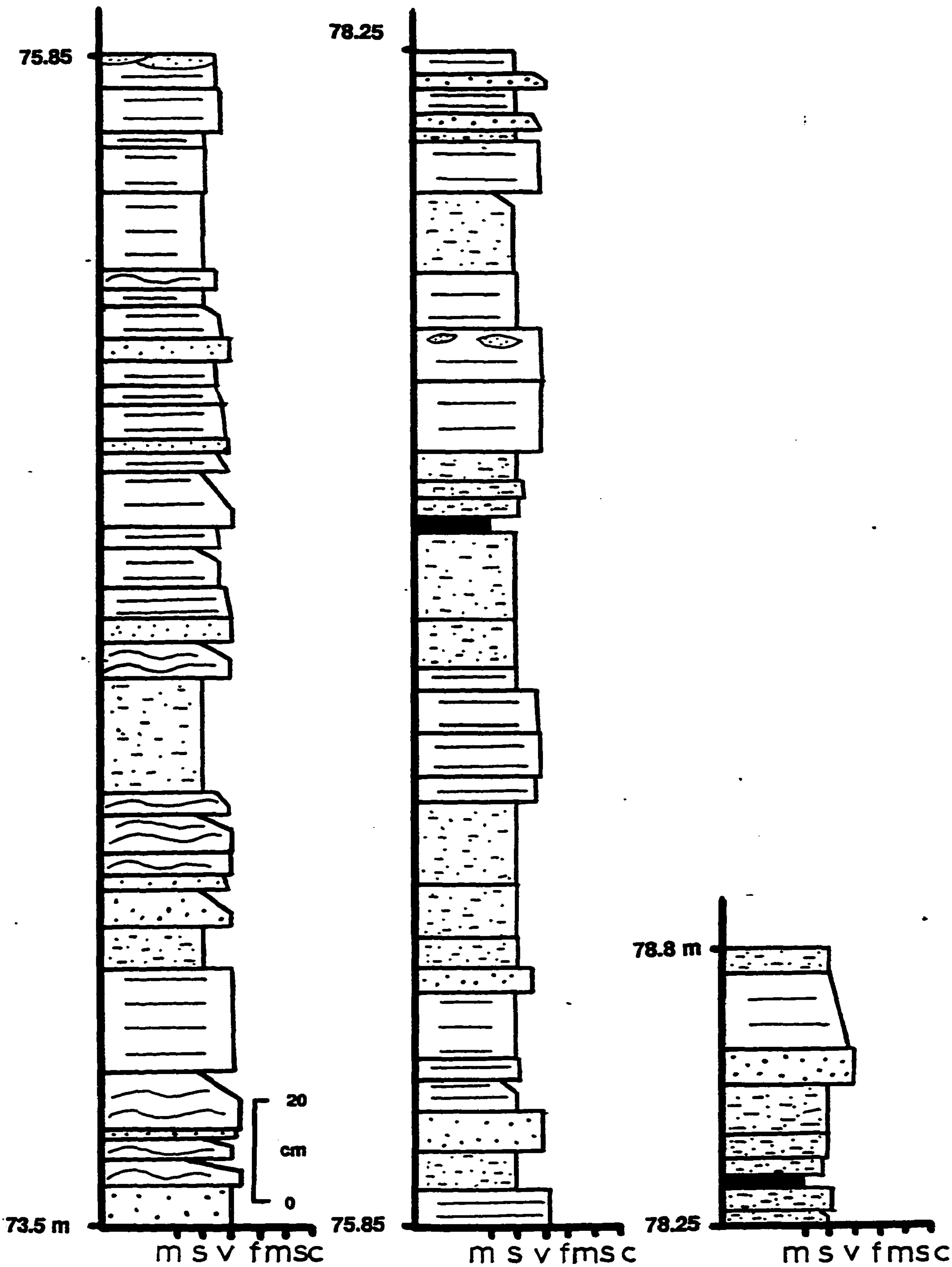
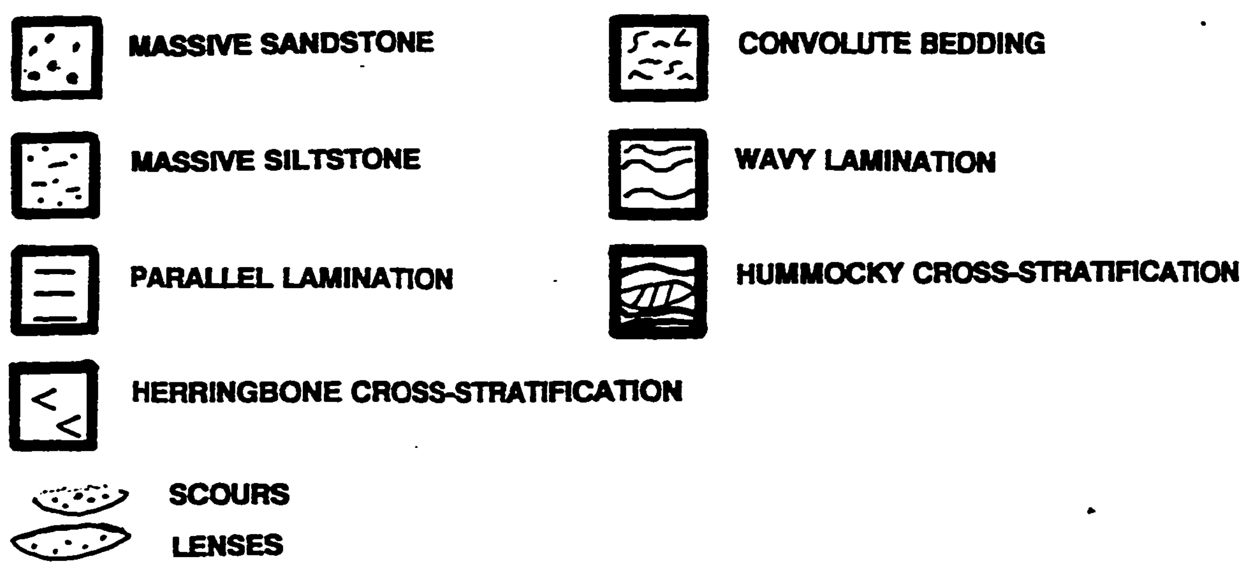

75.85
73.5 m
20
cm
0
m s v f m s c
78.25
75.85
m s v f m s c
78.8 m
78.25
m s v f m s c

FIGURE 5-4 Distal offshore environment.



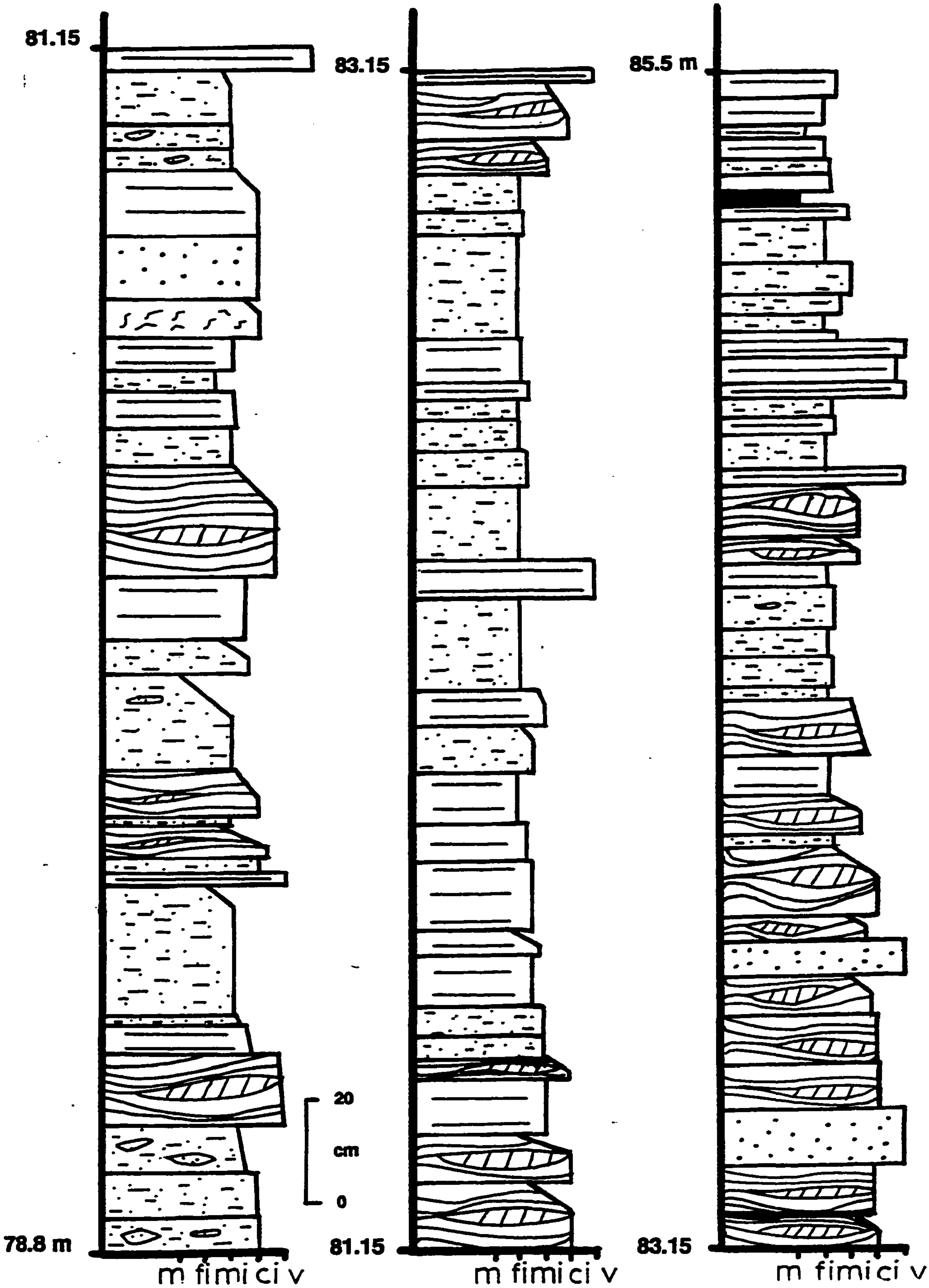
FIGURES 5-2 & 5-3

m = MUDSTONE
s = SILTSTONE
v = VERY FINE-GRAINED SANDSTONE
f = FINE-GRAINED SANDSTONE
ms = MEDIUM-GRAINED SANDSTONE
c = COARSE-GRAINED SANDSTONE

FIGURE 5-4

m = MUDSTONE
fi = FINE-GRAINED SILTSTONE
mi = MEDIUM-GRAINED SILTSTONE
ci = COARSE-GRAINED SILTSTONE
v = VERY FINE-GRAINED SANDSTONE

FIGURE 5-4


81.15
78.8 m
m fi mi ci v
83.15
81.15
m fi mi ci v
85.5 m
83.15
m fi mi ci v
20
cm
0

the section (Figure 5-4).

Massive and parallel laminated mudstone, siltstone and sandstone beds are, interbedded with the hummocky cross-stratified beds. The siltstone beds dominate over the rarer sandstone beds. A decrease in the grainsize of the siltstone beds occurs from the bottom of the section to the top. Coarse--grained siltstone beds dominate in the bottom portion of the section and are transitional upwards into medium- to fine-grained siltstone beds near the top.

CHAPTER SIX – DISCUSSION

INTRODUCTION

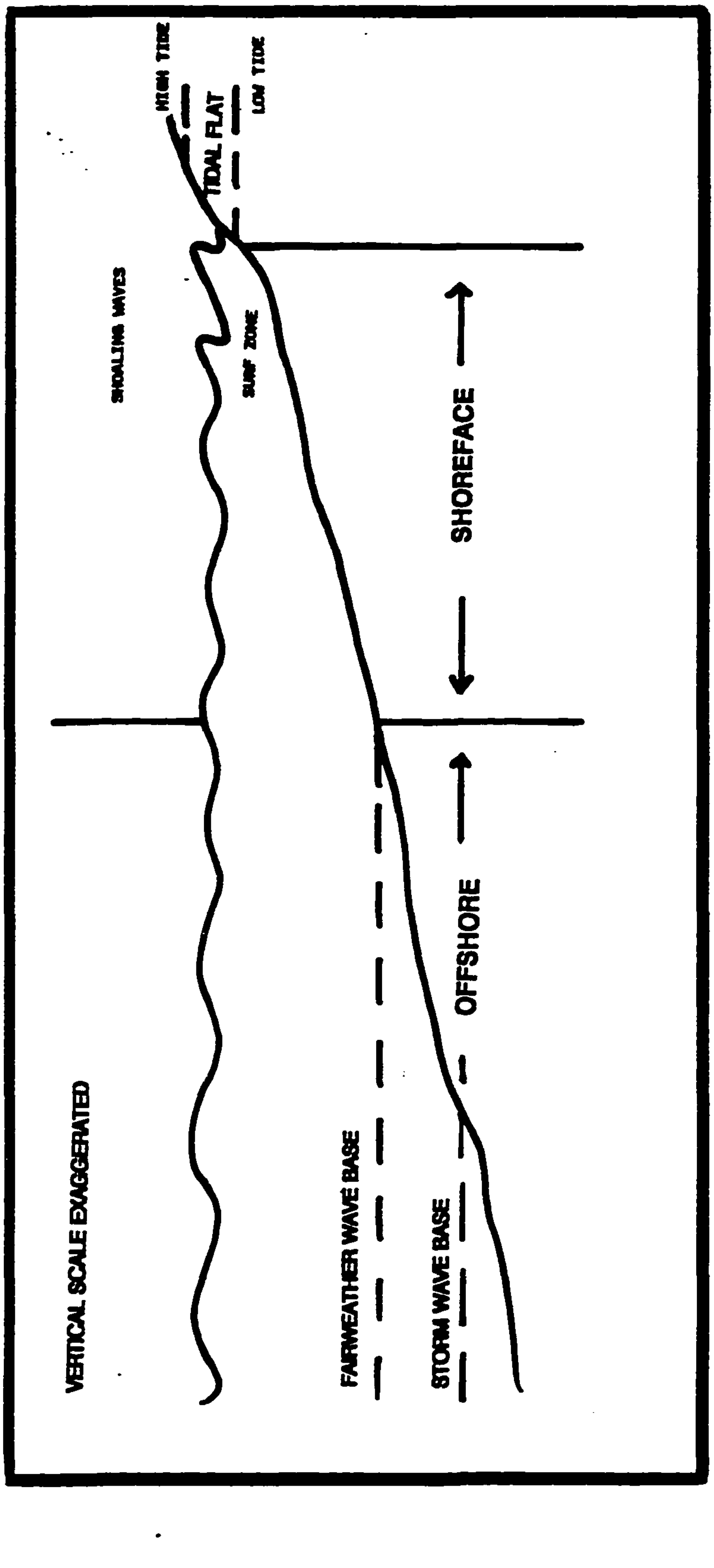
The study area represents an unique opportunity to reconstruct the processes active on a Neoarchean tidal flat and its adjacent storm-dominated, offshore area. It also facilitates investigation of a shoreline under both a strong tidal and storm-wave influence. Similar changes in influences affecting depositional conditions have been described by Soegaard and Eriksson (1985), Simpson and Eriksson (1990), and Colquhuon (1995), while other authors have documented the transition from the tidal to offshore environment (Simpson, 1991; Hein, 1987).

Figure 6-1 represents a typical cross-section of the environments under consideration. The following discussion of depositional controls and processes will involve all of the environments present in a transect from the tidal environment to the storm-dominated offshore environment.

TIDAL ENVIRONMENT

The nature of deposition in the tidal environment is intimately related to the activity and processes of tides and tidal currents. Tides are periodic and predictable fluctuations in water level along a coastline. They are generated by the gravitational attraction between the earth, the moon and the sun. This section will briefly discuss the generation of tides and tidal currents, but detailed and excellent discussions can be found in: Komar (1976), Open University Course Team (1989), Nio and Yang (1991), Dalrymple (1992), and Friedman *et. al.* (1992).

FIGURE 6-1 Cross-section illustrating the positions of the three depositional environments present in the current study. The three environments are; tidal,
shoreface, and
offshore.
The locations of Figures 6-4, and 6-5 are also indicated.



(modified from Walker, 1984)

On the earth, water bulges form as a result of the gravitational attraction between the earth, the moon, and the sun. Since the moon is considerably closer to the earth than the sun it exerts the greater gravitational influence even though its mass is less. Two water bulges are present, on opposite sides of the earth. As the earth rotates, the bulges appear to travel around the earth as two distinct 'tidal waves', which cause water levels to rise and fall regularly. The rising of water levels is known as the flood tide, the falling of water level is the ebb tide. Between episodes of flood and ebb tides are periods of water stand-still, known respectively as the flood (high-water) and ebb (low-water) stand-stills. This cycle of rising and falling water gives rise to the tidal currents responsible for sediment transport and generation of sedimentary structures commonly associated with a tidally-influenced coastline. The difference between mean low water and mean high water is known as the tidal range.

The relative positions of the sun, the moon, and the earth during the lunar cycle produce predictable differences in the range of tidal fluctuations with the periodicity of a lunar month (Davis, 1992). At the new and full moon, the three celestial bodies are in syzygy, and tidal ranges are at their greatest, this is a spring tide. When the moon is at right angles to the sun and earth, the tidal range is at its lowest, and is a neap tide. The period from a neap to spring tide is known as the neap - spring tidal cycle. There are fluctuations in tidal current velocities that are associated with the neap - spring tidal cycle.

Storm Tides (Storm Surge)

Occasionally water levels will fluctuate from predicted levels. These fluctuations are generally related to weather events causing higher, and rarely lower, than normal water levels. If a storm surge, storm tide comes during the high-tide portion of the tidal cycle, especially during a spring tide, considerable sediment movement can occur as velocities are abnormally high. This results in a change in the nature of depositional features already present in the environment.

In general, many of the bedforms that are produced by tidal activity are similar to those that are produced by unidirectional flows. A key difference though is the reversing nature of tidal currents, and the alternating periods of strong current activity and slack water which will result in the production of bedforms and structures that are not typical of other depositional environments. This is observed in the sedimentary structures and features that are present in the study area resulting in the interpretation that the shoreline was dominated by tidal current activity. This activity, coupled with the storm activity which was also prevalent in the area, has resulted in the formation of distinctive lithofacies.

Tidal Flat Sub-Environment

Sedimentation in the tidal flat sub-environment is governed by changes in both current velocity strength and direction during a single, tide and neap - spring tidal cycles. Over a single tidal cycle, there are two stages of high current velocities associated with the incoming flood and outgoing ebb tides, with subsequent episodes of water stand-still. Changes in current direction and strength are responsible for the deposition of lithofacies considered characteristic of the tidal flat sub-environment. These lithofacies are; flaser, wavy, and lenticular bedding, as well as coarsely interlayered bedding. All lithofacies are interbedded with each other within the tidal flats. The origin of these lithofacies can be related to variations in current velocity strength, such as conditions of tidal current activity depositing sand-rich lithofacies (high-energy), alternating with slack water (low energy/quiescence) conditions when mud-rich lithofacies are deposited (Reineck and Singh, 1975). The sequence in which lithofacies are deposited can also reflect changing current velocities associated with the neap - spring tidal cycle. Availability of sediment also plays an important role in the origin of these lithofacies. Deposition in the tidal flat sub-environment will be discussed in relation to these changes in velocity strength. A continuum of lithofacies from high to low velocity conditions would be as follows: massive and parallel laminated sandstones → flaser bedding → wavy bedding → lenticular bedding → coarsely interlayered bedding → parallel laminated and massive siltstones → mudstones. All of the listed lithofacies will be discussed, but not necessarily in this order.

The conditions required for the genesis of flaser, wavy, and lenticular bedding are adequately described and illustrated by Reineck and Singh (1975). Generation of these lithofacies can be treated as a continuum from flaser to wavy to lenticular bedding; dependant upon the availability of either sand or mud, and current velocities. Flaser bedding forms when conditions are more favourable for the deposition and preservation of sand than mud, and current velocities are high. The genesis of wavy bedding requires conditions where the deposition and preservation of both sand and mud are possible (Reineck and Singh, 1975). Lenticular bedding is produced under conditions more favourable for the deposition and preservation of mud than for sand and when current velocities are low.

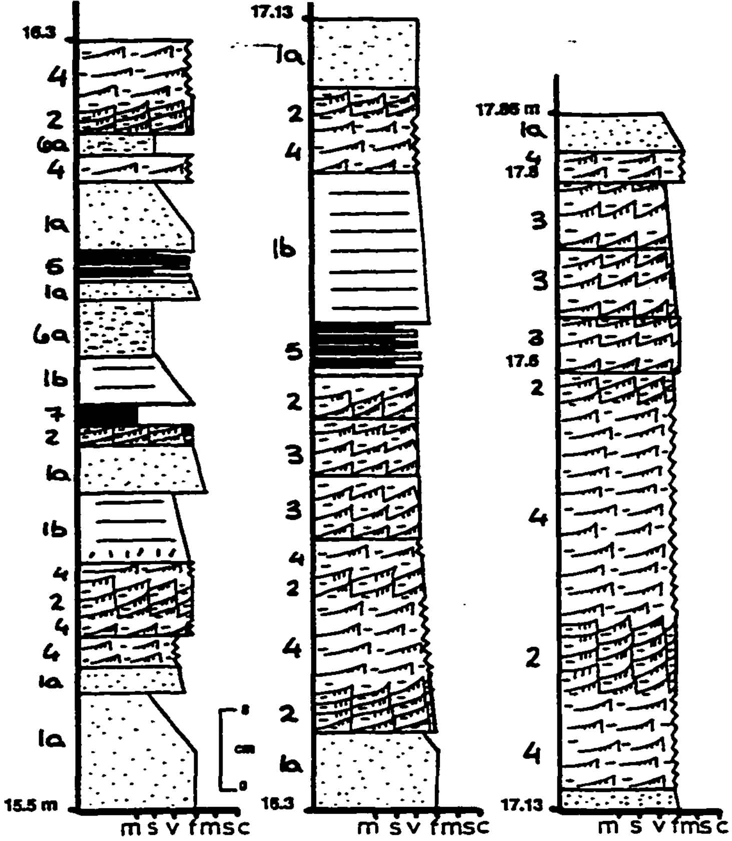
Statistical analyses of transitions in vertical sequences (explained in Appendix 1) were performed on stratigraphic sections from the three tidal flat sub-environments. This method of statistical analysis is similar to Markovian-chain analysis and is discussed by Schenk (1975). The end result of this statisitcal analysis was the determination of high positive values for transitions between lenticular, flaser, and wavy bedded units (values are shown in the random and non-random transition matrix). These values indicate that transitions between the three bed types are not random, but in fact are related to changing current velocities, as well as the availability of either sand or mud. Figure 6-2 depicts a vertical sequence in one of the tidal flats. Statistical analysis of this vertical sequence is also shown. In Figure 6-2, a number of transitions between flaser, wavy, and lenticular bedding are shown. Transitions from lenticular into wavy bedding were brought on by increasing current velocity related to either the flood or ebb tidal currents. Associated with the increasing current velocity was the ability of the current to transport sand, resulting in the formation of wavy bedding instead of lenticular bedding. Likewise, a change from wavy bedding

FIGURE 6-2 Vertical sequence through a portion of the tidal flat sub-environment. The lithofacies are;

1a) massive sandstone,
1b) parallel laminated sandstone,
2) flaser bedding,
3) wavy bedding,
4) lenticular bedding,
5) coarsely interlayered bedding,
6a) massive siltstone,
6b) parallel laminated siltstone,
7) mudstone.

Statistical analyses of transitions between the lithofacies are also shown. The three matrices are;

1) upward transition matrix,
2) predicted random transition matrix,
3) matrix showing transitions which occur more or less commonly then if random;
   positive value - common, non-random
   negative value - random.



3) RANDOM AND NON-RANDOM TRANSITION MATRIX

	1a	1b	2	3	4	5	6a	6b	7	
1a	-.23	-.53	.42	-.88	1.07	.65	-.35	0	-.18	
1b	.47	-.23	-.68	-.38	.17	-.15	.85	0	-.08	
2	-.58	-.68	-2.03	-.13	2.57	.55	-.45	0	.77	
3	-.83	-.38	-.13	2.37	-.58	-.25	-.25	0	-.13	
4	.07	.17	2.57	-.38	-2.08	-.55	.45	0	-.28	
5	.65	.85	-.45	-.25	-.55	-.1	-.1	0	-.08	
6a	.65	-.15	.55	-.25	-.55	-.1	-.1	0	-.05	
6b	0	0	0	0	0	0	0	0	0	
7	-.18	.92	-.23	-.13	-.28	-.05	-.05	0	-.08	

1) UPWARD TRANSITION MATRIX

	1a	1b	2	3	4	5	6a	6b	7	
1a	1	0	2	0	3	1	0	0	0	7
1b	1	0	0	0	1	0	1	0	0	3
2	1	0	0	1	5	1	0	0	1	9
3	0	0	1	3	1	0	0	0	0	5
4	2	1	5	1	1	0	1	0	0	11
5	1	1	0	0	0	0	0	0	0	2
6a	1	0	1	0	0	0	0	0	0	2
6b	0	0	0	0	0	0	0	0	0	0
7	0	1	0	0	0	0	0	0	0	1
	7	3	9	5	11	2	2	0	1	40

2) PREDICTED RANDOM TRANSITION MATRIX

	1a	1b	2	3	4	5	6a	6b	7	
1a	1.23	.53	1.58	.88	1.93	.35	.35	0	.18	7
1b	.53	.23	.68	.38	.83	.15	.15	0	.08	3
2	1.58	.68	2.03	1.13	2.48	.45	.45	0	.23	9
3	.83	.38	1.13	.63	1.38	.25	.25	0	.13	5
4	1.93	.83	2.48	1.38	3.03	.55	.55	0	.28	11
5	.35	.15	.45	.25	.55	.1	.1	0	.05	2
6a	.35	.15	.45	.25	.55	.1	.1	0	.05	2
6b	0	0	0	0	0	0	0	0	0	[illegible]
7	.18	.08	.23	.13	.28	.05	.05	0	.08	1
	7	3	9	5	11	2	2	0	1	40

into flaser bedding is generated by a similar situation. In this case, the current velocities were sufficient to transport large amounts of sand, erode away the majority of mud and deposit a predominantly sand-rich layer.

Transitions between beds brought on by a decrease in tidal current velocities are also present in the sequence depicted in Figure 6-2. Flaser bedding passing upwards into lenticular bedding is a reflection of waning current velocities. Associated with diminishing tidal current velocities is the ability of the current to transport sand. As a result, there is also a decrease in supply of sand to the system resulting in the formation of sand-poor lithofacies such as lenticular bedding.

As depicted in Figure 6-2, as well as in many figures in Chapter 3, transitions between flaser and lenticular bedding are abundant. These transitions can either be from flaser into lenticular bedding or inversely, lenticular into flaser bedding. In the statistical analysis, these transitions consistently had the highest positive values in all three tidal flats, indicating that transitions between the two types of bedding are non-random and very common. This reflects that velocity changes in the tidal flat sub-environments of the study area most likely result in the formation of lenticular bedding if flaser bedding has formed and current velocity and sediment supply has decreased. Similarly, the odds are greater for flaser bedding to form if lenticular bedding has been deposited and velocity and sediment supply is increasing.

Occasionally there will be a series of vertically stacked beds all consisting of the same bed type. Such a series occurs near the top of Figure 6-2, where three wavy bedded units are vertically stacked. In cases such as this, there has been no or very limited changes in either sediment supply and maximum current velocities have remained consistent during deposition of these beds.

Interbedded with the flaser, wavy, and lenticular beds are units of coarsely interlayered bedding. This type of bedding is formed by the alternation of tidal current bedload transport with suspension settling during slack water periods. The sand layers were deposited during periods of either flood and ebb current activity. The mud was deposited during stand-still phases of the flood and ebb tides. As with wavy bedding, coarsely interlayered bedding requires conditions in which the deposition and preservation of both sand and mud are possible. In the case of coarsely interlayered bedding though, flow conditions are not sufficient for the formation of ripples. Dalrymple (1992) has stated that tidal currents which are too slow to produce ripples may still deposit thin sand layers from suspension that alternate with mud laminae. In Figure 6-2, an upward passage from flaser bedding into coarsely interlayered bedding reflects this decrease in current velocity. Statistical analysis has also shown that transitions between lenticular, flaser, and wavy bedding and coarsely interlayered bedding are non-random events.

Also present in the tidal environment are numerous massive and parallel laminated mudstone, siltstone and sandstone beds. These lithofacies are interbedded with the flaser, wavy, lenticular, and coarsely interlayered bedding. The presence of thin fine-grained siltstone to mudstone layers overlying many of these lithofacies represents periods of quiescence and low current energy, when the fine-grained material held in suspension settled out.

The presence of sandstone and siltstone beds interbedded with other lithofacies has been observed by other authors (Klein, 1975; Driese *et. al.*, 1981; Terwindt, 1988) in a number of tidal environments, but especially the mixed flat or intertidal zone. Although interbedded sandstone and siltstone sequences have been observed by numerous authors, there is still no definitive answer concerning their genesis in the tidal environment. A few suggestions may be made regarding their formation: 1) they represent end-members in the depositional continuum from flaser to coarsely interlayered bedding. The parallel laminated and massive sandstone beds are the next stage of deposition with increasing current velocity after flaser bedding; in this case, presence of a mud layer is eroded out by either the flood or ebb tide, so that not even small mud flasers are left as evidence of deposition from suspension processes. The opposite occurs in the formation of the parallel laminated or massive mudstone and siltstone beds, which represent the lowest velocity stage after the formation of coarsely interlayered bedding. It could also be postulated that the presence of either the mudstone and siltstone beds, or the sandstone beds represents periods of limited sand or silt supply to the overall depositional system. This possibility also explains the presence of gradational boundaries between flaser, lenticular, wavy and coarsely interlayered bedding, and the mudstone, siltstone and sandstone beds; 2) individual beds represent storm deposits, this possibility will be discussed in the section on storm processes; 3) the beds formed as levee-like deposits.

The parallel laminated and massive sandstones represent the highest velocity conditions on the tidal flat. Stronger current strengths were required to move the very fine- to medium-grained sands that comprise these beds. Statistical analysis has shown that beds are usually randomly interbedded with flaser, wavy, lenticular, and coarsely interlayered bedding. This is highly suggestive of chaotic emplacement of these beds, probably related to radical environmental changes such as storm activity, although there appears to be no cyclicity to the occurrence of storm-emplaced sandstone beds. The parallel lamination and grading reflects deposition in the upper flow regime and during waning flow respectively. Other beds, as described in the previous paragraph probably were deposited as a result of increasing current velocities with the flood or ebb tides.

Parallel laminated and massive siltstone beds were generally deposited under conditions when current velocities of the ebb and flood phases of the tidal cycle were almost at their lowest. In fact, only lower flow velocity conditions are represented by the presence of sporadic massive mudstone beds. The deposition of these beds represents periods of high- and low-water stand-stills associated with both the ebb and flood tides.

Interbedded massive beds may be the result of liquefaction brought on by rapid deposition. Liquefaction of deposited sediment is also responsible for the formation of the sporadic convolute beds. During subaerial exposure of the sediment surface at low tide, compaction of sediment from the expulsion of water produces local liquefaction of sediment, which results in the development of convolutions (Reineck and Singh, 1975). Convolute beds formed by liquefaction have been observed on the steeper slopes of sand bars in tidal environments (Wunderlich, 1970). Liquefaction has also probably resulted in the formation of convolute bedding in the tidal environment of the study area.

Although many of the boundaries between beds are sharp and distinct, there are also gradational boundaries present. Gradual passages between lithofacies are another indicator of the importance that varying flow conditions play in the development of the tidal flat sub-environment. The gradual transitions are indicative of changes in flow velocities and availability of either sand or mud during deposition of individual beds. For example, the gradual transition from coarsely interlayered bedding into flaser bedding may indicate an increase in availability of sand within the environment and higher current velocities. Similarly, the gradual transition from flaser to lenticular bedding signifies that the amount of available sand and current velocities have decreased.

Klein (1975) has noted that different associations of bedforms and lithofacies occur, depending on the relative concentration of sand or mud and the relative duration of the bedload or suspension style of deposition. These differing lithofacies associations can be clearly seen in Figures 3-2 to 3-8 Chapter 3, which are representative of tidal flat sequences. In these associations, flaser, lenticular and wavy bedding are interbedded and interlayered, demonstrating variability in the concentrations of sand and mud in the environment; as well as degrees of current activity. The presence of the interbedded and interlayered sequences of lenticular, flaser, wavy, and coarsely interlayered bedding indicates that deposition occurred in the intertidal zone of the tidal flat, otherwise referred to as the mixed tidal flat (Davis, 1992) or the mid-tidal flat of Klein (1975). Klein (1975) described the mid-tidal flat as an area containing coarser sediment with careful segregation of nearly equal volumes of mud and sand arranged into lenticular, flaser, wavy, and tidal bedding, and goes on to state that there is an equal amount of bedload and suspension deposition. These associations record quickly changing depositional conditions.

Most importantly, the interbedding of lithofacies reflects that deposition in the tidal flat sub-environment was dominated by tidal current activity with fluctuating velocities throughout the neap-spring tidal cycle, giving rise to the myriad of sedimentary structures and features present. Velocities changed rapidly over a short period of time on the tidal flat, and these rapid changes are reflected in the distribution of lithofacies present in the tidal flat sub-environment.

As stated, the effects of fluctuating current velocities during an individual neap-spring tidal cycle are reflected in the vertical distribution of lithofacies on the tidal flat as it grows. Changing current velocities result in a somewhat predictable vertical sequence of lithofacies deposited on the tidal flat. As the current increased in velocity during the neap - spring cycle towards the spring tide, lithofacies that reflected increasing current velocities were deposited. One example of this is the progression from lenticular to wavy to flaser bedding at the base of the sequence mimicking a similar increase in current velocity. Then as the cycle progressed towards the neap tide, a decrease in current velocities occurred, which was matched by deposition of lithofacies associated with progressively decreasing velocities. This is shown at the top of the sequence, where there is an orderly progression from flaser to wavy into lenticular bedding. The cyclical nature present in the vertical sequence of lithofacies from the tidal flat sub-environment can be expected of and is characteristic of deposition in the tidal environment.

Changes in the vertical distribution of lithofacies are also related to sediment supply. The amount of sediment supplied to the system may reflect seasonal changes which result in either a decreased or increased sediment supply to the depositional environment. Sediment supply may possibly have also been associated with volcanic activity in the area. During periods of active volcanism, sediment supply ware greater, while during inactive periods there was a decreased amount of sediment present in the system. Further work is needed to study these possibilities.

Tidal Flat and Tidal Channel Sub-Environment Transitions

Transitions into and out of the two tidal channels are marked by sequences of interbedded massive and parallel laminated mudstone, siltstone and sandstone. Many of the sandstone beds exhibit normal grading, indicative of the effects of waning current activity. The interbedded sequences represent possible levee-like deposits, with the sandstone beds transported as bedload material and deposited during episodes of high current activity, and the siltstone beds deposited during periods of quiescence from fine-grained material held in suspension. Interbedded sequences similar to those from the study area have been described by a number of authors. George (1994) has reported the presence of parallel laminated sandstone beds in channel-margin deposits of tidal channels. Driese *et. al.* (1981) recorded the presence of horizontally laminated sandstone, siltstone, and shale, and stated that this represented deposition on tidal flats adjacent to tidal channels. Klein (1975) has also stated that interbedding of sandstones and mudstones is a common feature of tidal flat environments, particularly where intertidal fill consists of sands. In the study area it is also possible that the interbedded sequences adjacent to the tidal channels represents infilling of an abandoned channel, but this is speculative. A third possibility is that the interbedded sequences of sandstone and siltstone beds reflect deposition in small depressions adjacent to the tidal channels during high water episodes.

Tidal Channel Sub-Environment

Deposition in the tidal channel sub-environment is predominantly controlled by the tidal cycle and the variable flow conditions associated with this cycle. With the incoming flood tide dunes or sandwaves on the channel floor migrate in the same direction, depositing flood-oriented foreset laminae. With the outgoing ebb tide, dune migration occurs in the ebb direction, and foreset laminae are now oriented in this direction. The bimodal nature of the tidal cycle results in the generation of herringbone cross-stratification, and is reflected in the tidal channel sub-environment of the study area.

The two tidal channels present in the study area exhibit an overall fining-upwards trend and are dominated by herringbone cross-stratified sandstones. The channels will be specifically referred to as the lower and upper tidal channels. The abundance of herringbone cross-stratification indicates that the depositional system was governed by an apparent lack of tidal asymmetry. Occasionally, the herringbone cross-stratification is interbedded with beds of planar cross-stratified sandstone. This interbedded association indicates periods of bimodal tidal current activity alternating with rarer episodes of unimodal tidal current activity which is dominant in either the flood or ebb current directions. Such an association most likely formed as the result of episodic storm activity in the area. The herringbone cross-stratified beds formed during normal fairweather conditions. The beds of planar cross-stratification formed from onshore-directed flows associated with storm activity. These flows would have moved water through the tidal channels. The presence of mud rip-ups at the base of some of the planar cross-stratified beds further indicates that these beds were emplaced by storm processes. A cessation of storm activity, and a resumption of normal fairweather processes saw the formation and deposition of herringbone cross-stratified beds once again.

Moving towards the top of the tidal channels, there is an increase in the number of beds of massive and parallel laminated siltstone. This overall fining-upwards trend in the channels is the result of channel abandonment and coincident infilling. The fining-upwards trend is caused by waning and restricted current flows which result in the settling of mud and silt out of suspension. The infilling of the channels indicates that the channel mouths have become partially or completely blocked. As a result, water is restricted in its flow, or is no longer able to actively flow into the channels, transporting and depositing sediment. Massive amounts of sediment moved by storm activity is most likely responsible for the blocking of tidal channel mouths.

Small erosive scours are found at the top of both fining-upwards tidal channel sequences. These scours are filled with massive sandstone and siltstone. Both scours provide evidence for the reactivation of infilled channels following channel abandonment. The channels did not fill with sediment to the same level as the surrounding tidal flats, leaving small depressions on top of the channels. During periods of high-water, rivulets formed in these depressions. These small channels or depressions that the rivulets of water flowed in were eventually cut off from water brought by the incoming tide and filled with sediment. One scour contains mud rip-ups and chips at its base. The mud chips were transported by tidal currents during the inundation of tidal flats by high water and were redeposited in the tidal channel in a manner similar to that described by von Brunn and Hobday (1976) in the Early Precambrian Pongola Supergroup of South Africa.

Both channels lack many of the features of the classical meandering and braided stream models. Most notably is the almost complete absence of point bar sequences found in meandering streams. Traditionally, tidal channels described in the literature for the Recent, Phanerozoic and Precambrian are meandering in nature. With the exception of one small, limited sequence of epsilon cross-bedding in one of the tidal channels, there is no evidence of point bar development in the tidal channels of the study area.

This small sequence of point bar development is found in the upper tidal channel (see Figure 3-11, Chapter 3). In this channel, planar cross-stratified beds are bounded by epsilon cross-bedded surfaces. This is evidence of limited point bar development on a curved reach of the tidal channel, and illustrates that there was slight meandering in one of the tidal channels.

As already pointed out though, the presence of point bar sequences is not the norm in the two tidal channels of the study area. In fact it is the lack of point bars; or the abrupt vertical changes typical of braided streams, that characterize the two tidal channels. The lack of point bar development, or any evidence of lateral accretion indicates that the tidal channels were relatively straight. In many respects the sedimentary structures of the tidal channels resemble those of the Nubia strata in southwestern Egypt. These strata also contain sequences which cannot be easily interpreted in terms of the classical meandering or braided stream models (Klitzsch *et. al.,* 1979). The lower parts of the sequences are composed of medium- to coarse-grained sandstone with planar cross-stratification which has been interpreted as fluvial in origin (Klitzsch *et. al.*, 1979). Although the sequences in the Nubia strata record unidirectional current flows, comparisons made with the tidal channel sediments of this study are valid. In both the Nubia strata and the current study, one is still looking at flow in channels which lack features of meandering or braided streams. Klitzsch *et. al.* (1979) have interpreted the channel fill deposits in the Nubia strata as having formed when sandwaves deposited planar cross-stratified sets in a channel with low sinuosity. Similarly, tidal channels in the study area represent bedform migration in both the ebb and flood directions along the floors of relatively straight tidal channels. Unidirectional fluvial sequences described by Fralick and Miall (1989) also have similar characteristics. The point bar sequence observed in the upper tidal channel represents a curved reach in that tidal channel.

It is also possible that the tidal channels represent portions of tidal inlet sequences. One problem though is the lack of sedimentary structures and textures that would have been created by the lateral migration of a tidal inlet. There is also no evidence of any development of spit and spit-platform sequences that are commonly found in tidal inlet sedimentary deposits.

There is some similarity between units described by Kumar and Sanders (1974) for the Fire Island Inlet, and the channels in the current study. Structures described for the deep and shallow channels of the Fire Island Inlet consisted of cross-stratification and parallel lamination respectively. The channelized portion of the inlet sequence is referred to as the inlet proper by Kumar and Sanders (1974) This sequence of structures is observed in both tidal channels of the study area, where herringbone cross-stratified sandstones pass upwards into parallel laminated, and massive, siltstones and sandstones. It is possible that the two tidal channels represent the inlet proper of a tidal inlet, and exhibit no development of spits and spit-platforms in the upper reaches of the inlet.

Two possible depositional situations are indicated by the tidal channels of the study area. Firstly, the tidal channels could represent deposition in the inlet proper of tidal inlet sequences. This possibility does not seem very likely though, when one considers the almost total absence of lateral accretion deposits in both of the tidal channels. Secondly, the two tidal channels simply represent relatively straight channels similar to those in the Nubia strata of Egypt, with the occasional curved reach. This second possibility is the most likely.

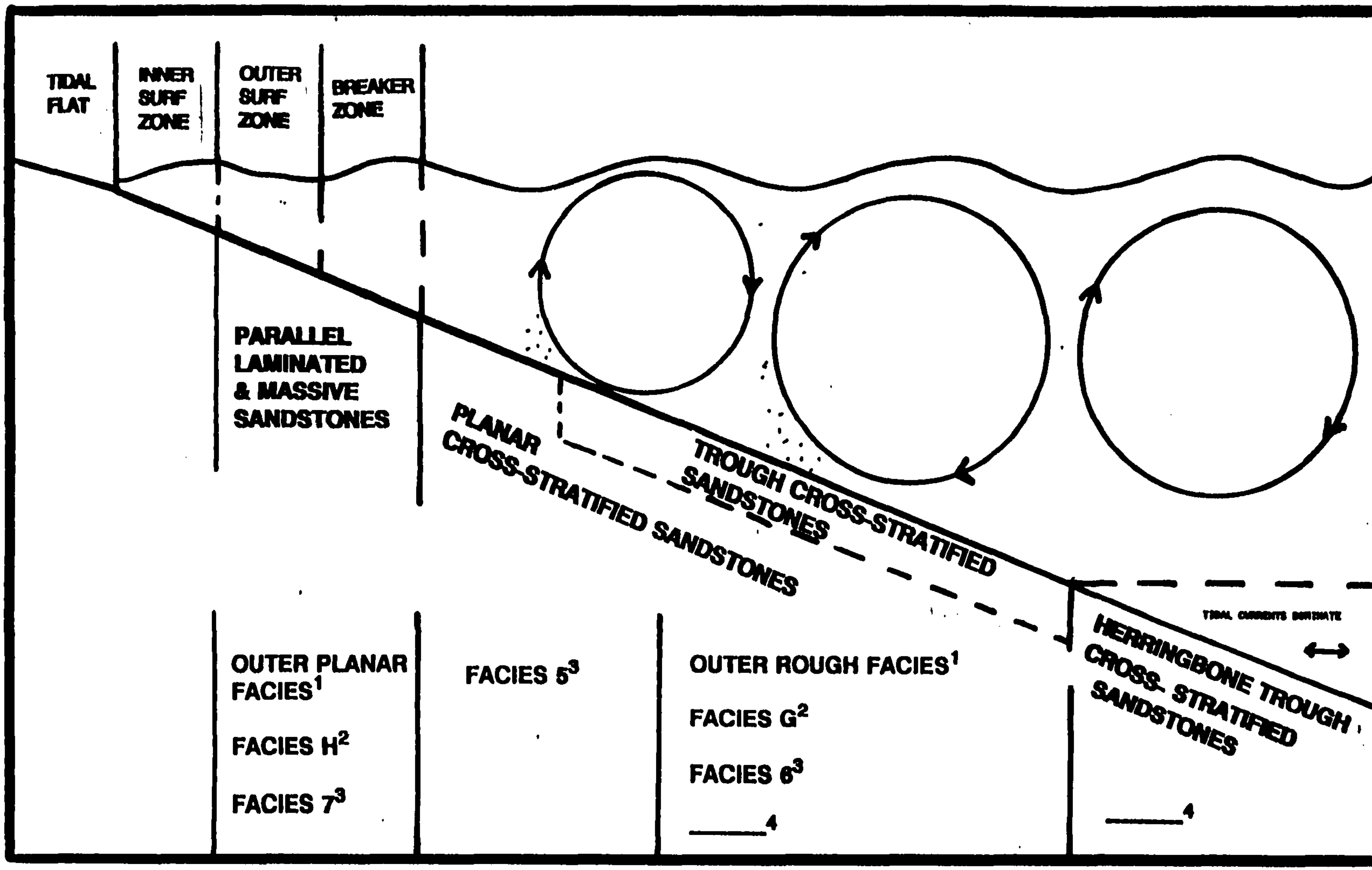
PALEOTIDAL RANGE

The excellent preservation of sedimentary structures allowed for the determination of a minimal paleotidal range. To do this, methods outline by Klein (1971), and Terwindt (1988) were utilized. Klein (1971) suggests to measure the distance from the base of herringbone cross-stratification, up through tidal bedding (interlayered sands and muds) to a muddy top (supratidal). In this case, since the supratidal is not well developed in the study area, a measurement from the base of herringbone cross-stratification filling a tidal channel to the boundary between the fine-grained top of a tidal flat and the coarse-grained base of the overlying tidal channel was made. This gave minimal tidal ranges of 3.5 and 3.3 metres for each tidal channel - tidal flat sequence. The average minimal tidal range was 3.4 metres, which indicates a mesotidal environment. Mesotidal environments include those with tidal ranges that vary between two and four metres.

SHOREFACE TIDAL SAND BODY

Bedload transport processes dominate in the shoreface tidal sand body which is depicted in Figure 6-3. This area is analogous to the subtidal zone. The presence of planar and trough cross-stratification in the shoreface zone has been noted by several authors (Driese *et. al.*, 1981; Hein, 1987; Soegaard and Eriksson, 1985; Simpson and Eriksson, 1990; Simpson, 1991; and Colquhuon, 1995). The formation of these depositional features has been attributed to the migration of dunes and sandwaves in the subtidal zone (Driese *et. al.*, 1981). Simpson (1991) stated that the bedforms are generated by relatively high current velocities during onshore-directed flow produced during initial coastal setup, or after cessation of storm conditions by the fair-weather wave spectrum. The bedforms and depositional processes responsible for their formation are similar to those described by Hein (1987) for the Gog Group of the southern Rocky Mountains; and Colquhuon (1995) for the Early Devonian Roxburgh Formation of southeastern Australia.

FIGURE 6-3 Cross-section of the shoreface tidal sand body showing the distribution of bedforms. References are also given for similar bedforms and facies in the shoreface environment described in the literature. Note that while unidirectional wave orbitals affect the bottom close to shore, in deeper water the orbitals no longer touch the bottom, allowing bidirectional tidal currents to dominate.



(modified from Clifton *et. al.*, 1971)

[1] Clifton *et. al.* (1971)
[2] Colquhuon (1995)
[3] Hein (1987)
[4] Soegaard and Eriksson (1985)

The parallel laminated, fine- to medium-grained sandstone beds in the proximal portion of the sand body (Figure 6-3) are similar to the parallel laminated sandstone facies (Facies H) of Colquhuon (1995) who interpreted it as representing wave swash in a relatively flat beach foreshore zone. However, the parallel laminated sandstones of the shoreface environment in the study area lack many of the features typical of beach sedimentation such as heavy mineral enriched laminae and truncated parallel lamination which dips seaward. Instead, the parallel laminated sandstones were deposited by high energy shoaling waves in the outer surf and breaker zones during fairweather conditions. This corresponds to the outer planar facies of Clifton *et. al.*, (1971), and are similar to laminated sandstones described by Hein (1987) who interpreted them as forming in the surf zone from shoaling waves. The parallel laminated beds in the shoreface, especially if they are graded, may also be the products of high-energy storm activity. Storm-generated parallel laminated sandstones have been found in a number of shoreface environments described in the literature (see Elliott, 1986).

The massive, structureless sandstones interlayered with the parallel laminated sandstones possibly formed as the result of bedload transport by high-energy shoaling waves, or the reworking of parallel laminated sandstones into massive sandstones by storm activity. Post-depositional fluid escape or liquefaction from rapidly deposited sediments probably have obliterated any original sedimentary structures present in the sandstone beds.

The lower portions if the shoreface sequence records the movement of tidal sand bodies in this environment, as well as the upper offshore. The sequence of planar cross-stratified beds (Figure 6-3) interbedded with siltstone to fine-grained sandstone beds chronicles the migration of sandwaves across the bottom. Hein (1987) felt that the planar cross-stratified sandstones may represent deposits of larger-scale bedforms, such as sandwave complexes. This process occurs slightly above the fairweather base, with the presence of the massive and parallel laminated siltstone beds indicating suspension deposition. Parallel laminated sandstone beds were most likely deposited as the result of storm activity. The formation of the migrating sandwaves is not influenced by the prevailing tidal currents in the area, but instead is affected by wave-induced currents, and the interaction of the bases of wave orbitals with the bottom (see Figure 6-3). Another possibility is that the sandwaves formed and migrated as the result of storm activity . This probability will be discussed in the section on storm processes.

The presence of trough cross-bedding on top of the interbedded cross-stratified and siltstone beds may represent migration of smaller dune fields on top of the larger sandwaves that make up the planar cross-stratified zone (Figure 6-3). Similar trough cross-bedding has been described by: 1) Hein (1987) who observed the presence of trough cross-stratification in the shoreface zone, and has attributed vertical stacking of these beds to a field of migrating ripples or dunes, and 2) Colquhuon (1995) who describes the presence of trough cross-bedded sandstones (Facies F) in the Roxburgh Fm., and attributed their formation to the migration of numerous small- to medium-scale lunate megaripples in onshore and lesser longshore and oblique offshore directions. The trough cross-stratified beds observed in the shoreface environment of the present study are analogous to Clifton *et. al.* (1971) outer rough facies, which they interpret as forming from the migration of lunate megaripples.

Evidence of prevailing bidirectional tidal current activity is overprinted by asymmetrical wave activity in this zone. The wave orbitals are able to touch and interact with the bottom surface, transporting sediment and resulting in an unidirectional component to the generated sedimentary structures. Soegaard and Eriksson (1985) have commented on the presence of dunes superimposed on larger sandwaves in the inner shelf facies of the Ortega Gp. of New Mexico. Here, they attributed the generation of the superimposed dune structures to offshore-directed storm currents (Soegaard and Eriksson, 1985). Considering the high-energy stormy conditions common in rocks of the study area, this is also a plausible scenario for the formation of trough cross-stratified beds.

The herringbone trough cross-stratified sandstone beds higher in the shoreface zone formed in deeper water then the trough cross-stratified beds (Figure 6-3). When moving into deeper water, sedimentation and deposition is once again affected by prevailing tidal currents in the area. At this point, the asymmetrical fairweather wave orbitals have lost contact with the bottom. Sediment is no longer moved by wave activity, but instead is transported by bidirectional tidal currents. Migration of sandwaves or dunes now occurs in both the ebb and flood current directions. The presence of rare wavy and coarsely interlayered bedding interbedded with the units of herringbone cross-stratification is also indicative of a tidal influence. Soegaard and Eriksson (1985) have also observed the presence of herringbone cross-stratification which formed as the result of symmetrical tidal flow.

STORM PROCESSES

There has been modification of sedimentary structures and features in the tidal environment and the shoreface tidal sand body by storm activity. The effects of storms are especially noticeable in the tidal flat sub-environment; where numerous beds of massive and parallel laminated graded sandstone are present. As stated previously, many of the sandstone beds formed as the result of bedload and suspension tidal depositional processes, but others are representative of storm activity. This is especially apparent in the beds which contain numerous mud rip-ups at their base. At the base of two of the storm-generated beds, scours have been cut into the top of the underlying bed. Driese *et. al.* (1981) have reported the presence of scours exhibiting channel-like morphology and states that they indicate erosion due to storm-generated currents. George (1994) has also noted the presence of granular layers which attest to sporadic conditions of higher energy induced by storms, floods, or spring tides; and later state that the presence of coarser-grained sandstone beds, which are either massive or parallel laminated, interbedded with other features is most likely the result of storm activity. The presence of the massive coarse-grained sands are probably the result of liquefaction.

Swift *et. al.* (1979) have reported the migration of ripples, megaripples, and sandwaves along the Atlantic shelf as a result of storm activity. Along the Atlantic shelf, there are rippled zones which are present from the shoreline to the shelf edge. The ripples have formed from current activity during peak storm flows. In slightly deeper water, megaripples and sandwaves form during the winter storm months. It is possible that the shoreface sequence of the study area records the activity of seasonal storms interspersed with everyday fairweather conditions resulting in the movement of smaller ripples over the top of the main sand body.

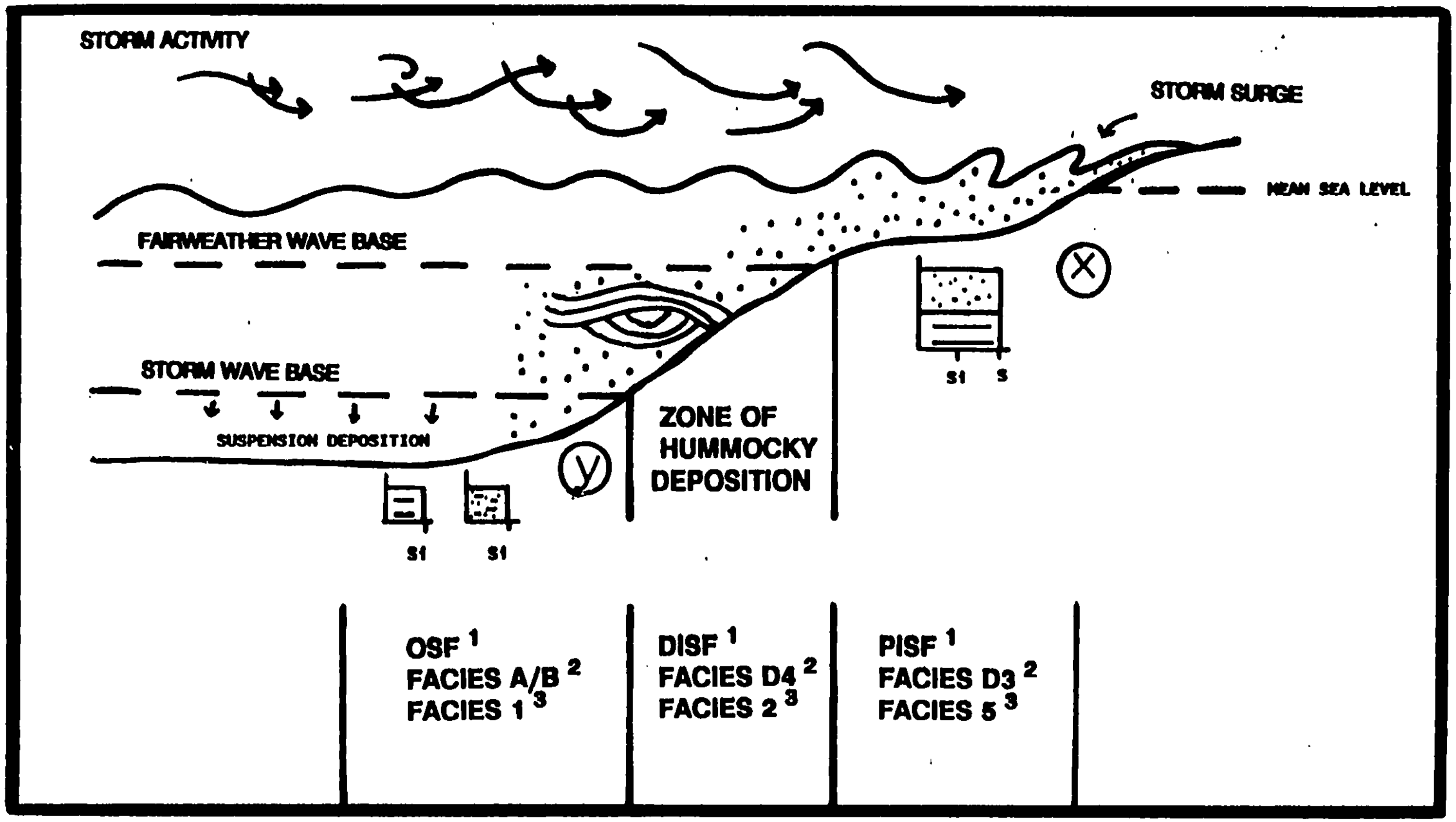
OFFSHORE ENVIRONMENT

The sedimentary structures and features present in the offshore environment reflect short-lived, episodic, high-energy conditions, storms, which alternated with longer periods of lower energy, fairweather, conditions. These conditions are responsible for the generation and deposition of the sandstone, siltstone, and hummocky cross-stratified beds.

Figure 6-4 illustrates the distribution of sandstone, siltstone and mudstone and hummocky cross-stratified beds within the offshore environment. The majority of parallel laminated and massive sandstone beds are deposited shore - proximal to the zone of hummocky deposition, marking the transition zone from the shoreface into the offshore. The bulk of the hummocky cross-stratified beds are deposited within this zone, where potential for the preservation of these beds is the greatest (Dott and

FIGURE 6-4 Cross-section of the offshore environment showing the distribution of the sandstone and siltstone and mudstone lithofacies. Deposition of the majority of massive and parallel laminated sandstone beds occurs at **X**, while the bulk of massive and parallel laminated siltstone and mudstone beds are deposited at **Y**. The zone of hummocky deposition is also shown. References to similar offshore environments are also given.

S = sandstone
Si = siltstone



[1] Simpson and Eriksson (1990) (modified from Dott & Bourgeois, 1982; and Walker, 1984)
[2] Cloquhuon (1995)
[3] Duke *et. a1.* (1991)

Bourgeois, 1982). Finally, the majority of parallel laminated and massive siltstone and mudstone beds are deposited shore - distal to the zone of hummocky deposition.

Zone above hummocky deposition/Transition Zone

The individual parallel laminated and massive sandstone beds above the zone of hummocky deposition (Figure 6-4) were deposited rapidly, possibly over periods of a few hours to several days. The sandstone beds and rare interbedded siltstone beds represent the transition from the shoreface into the storm-dominated offshore environment. The presence of parallel laminated and massive sandstone beds in shallower water depths than the zone of hummocky cross-stratification have been reported by Reineck and Singh (1972), Kumar and Sanders (1976), Simpson and Eriksson (1990), Arnott (1993), and Colquhuon (1995), among others.

The parallel laminated and massive sandstone beds that comprise the transition zone from the shoreface to offshore environments of the study area are similar to those belonging to the proximal inner shelf facies of Simpson and Eriksson (1990). Simpson and Eriksson (1990) state that the sandstone beds which form the bulk of this facies are the result of rapid sedimentation from suspension. Similar beds have been described by Kumar and Sanders (1976) who attribute their production to the interaction of rapid suspension fallout and tractional processes as a result of storm events. Colquhuon (1995) has also reported on the presence of sandstone beds with parallel lamination or gently undulating lamination, similar to the wavy-like lamination present in the sandstone beds of the study area. These beds, as previously stated, resemble the quasi-planar laminated sandstone beds described by Arnott (1993) which are present in lower shoreface to shallow-shelf deposits. Colquhuon (1995) attributed the presence of the sandstone beds to the same formational processes as described by Arnott (1993).

Arnott and Southard (1990) showed that in a combined flow characterized by a long-period, moderate to strong oscillatory component, addition of a unidirectional component causes topographically positive bed forms to develop a strong downstream asymmetry and eventually to be washed out to a quasi-planar bed surface. This bed configuration is stable with increasing unidirectional speed and over a wide range of high-energy, combined flow conditions. Further offshore the unidirectional component is lessened, reducing substantially the upper limit of flow strength for the existence of large-amplitude bed forms needed for hummocky cross-stratification (Arnott and Southard, 1990). Duke (1985) stated that these unidirectional currents overwhelm wave-generated oscillatory or multidirectional flows and inhibit formation of hummocky cross-stratification.

When the above is considered, it is possible to hypothesize that the following processes are occurring in the transition zone. In association with onshore storm surges, there is a return flow (sometimes referred to as the storm surge ebb current), out towards the offshore environment. This seaward flow, which was first suggested by Hayes (1967), creates a bottom current capable of transporting sand below fairweather wave base. The bottom current has a strong unidirectional component. This unidirectional current dominates over the oscillatory or multidirectional flows responsible for the formation of hummocky cross-stratification, and as a result there is very little formation of hummocky cross-stratification within the transition zone. Eventually, the strength of the unidirectional current wanes, and hummocky cross-stratification forms.

Another possibility is that hummocky cross-stratification has formed in the transition zone. Any evidence of hummocky cross-stratification though, is wiped out by the next high-energy (storm) event, leaving only the bottom parallel laminated division of Walker *et. al's.*, (1983) idealized sequence. In this case, the strong returning flow is responsible for the erasure of hummocky cross-stratification.

The parallel laminated, graded sandstone beds are also similar to laminated sand and graded rhythmites described by Reineck and Singh (1972) and may have formed by a similar process. The genesis of these beds, also called storm-sand layers by Reineck and Singh (1972), begins with an increase in water turbulence associated with storm activity. The water is so turbulent that sand is able to be kept in suspension, and is transported from the coastline to the offshore environment by the turbulent water flowing away from the coast. As the storm wanes, and energy decreases, the material (such as the sand) which was carried in suspension by the turbulent water begins to settle out. Initially, only sand in the form of parallel laminae is deposited, producing laminated sand. With subsequent decreases in wave energy, fine-grained sediments (silts) are deposited. The sand laminae become thinner upwards, whereas mud laminae becomes thicker, producing a graded rhythmite (Reineck and Singh, 1972). This decrease in the thickness of laminae has been observed in the parallel laminated sandstone beds of the offshore environment of the study area. The processes and mechanisms that Reineck and Singh (1972) invoke for the formation of the storm-sand layers are similar to the storm surge ebb currents first described by Hayes (1967). The interbedded massive siltstone beds were deposited from suspension during fairweather conditions.

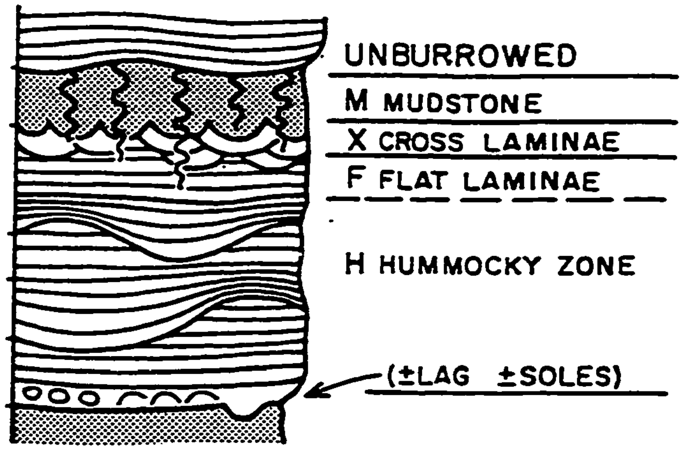
Zone of Hummocky Deposition

The presence of interbedded sandstone and hummocky cross-stratified beds with siltstone and mudstone beds (Figure 6-4) in the shallower, proximal portion of the offshore environment has been reported by many authors including; Hamblin and Walker (1979), Duke (1985), McCroy and Walker (1986), Duke *et. al.*, (1991), and Colquhuon (1995). This association reflects the alternation of slow fairweather sedimentation processes depositing mudstone and siltstone beds, with storm-induced or enhanced processes depositing hummocky cross-stratified beds between the fairweather and storm-wave base. Rezka (1987) has previously reported on the presence of hummocky cross-stratification in sediments of the Shebandowan Group. The hummocky cross-stratification described by Rezka (1987) is very similar to that present in the current study area.

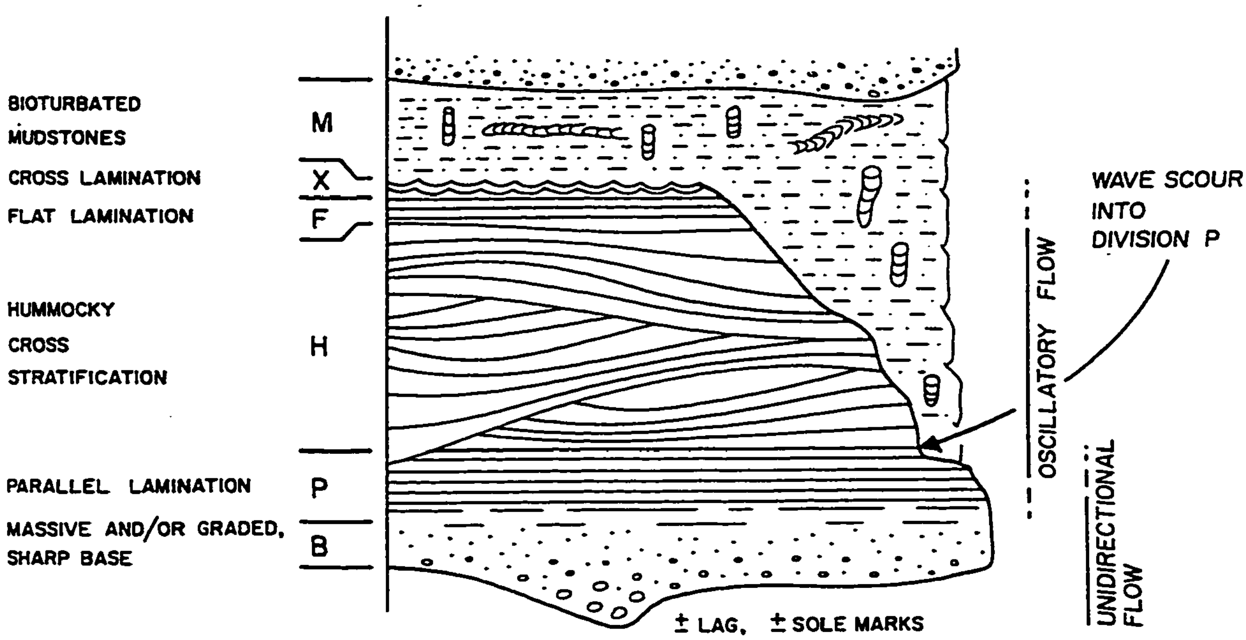
FIGURE 6-5 Idealized sequences of hummocky cross-stratification from Dott and Bourgeois (1982), and Walker *et. al.*, (1983).

a) H - hummocky zone
F - flat laminae zone
X - cross laminae zone
M- mudstone zone.

b) M - mudstone
X - ripple cross lamination
F - 'flat' lamination
H - hummocky cross-stratification
P - planar parallel lamination .
B - basal division.



Dott and Bourgeois (1982)

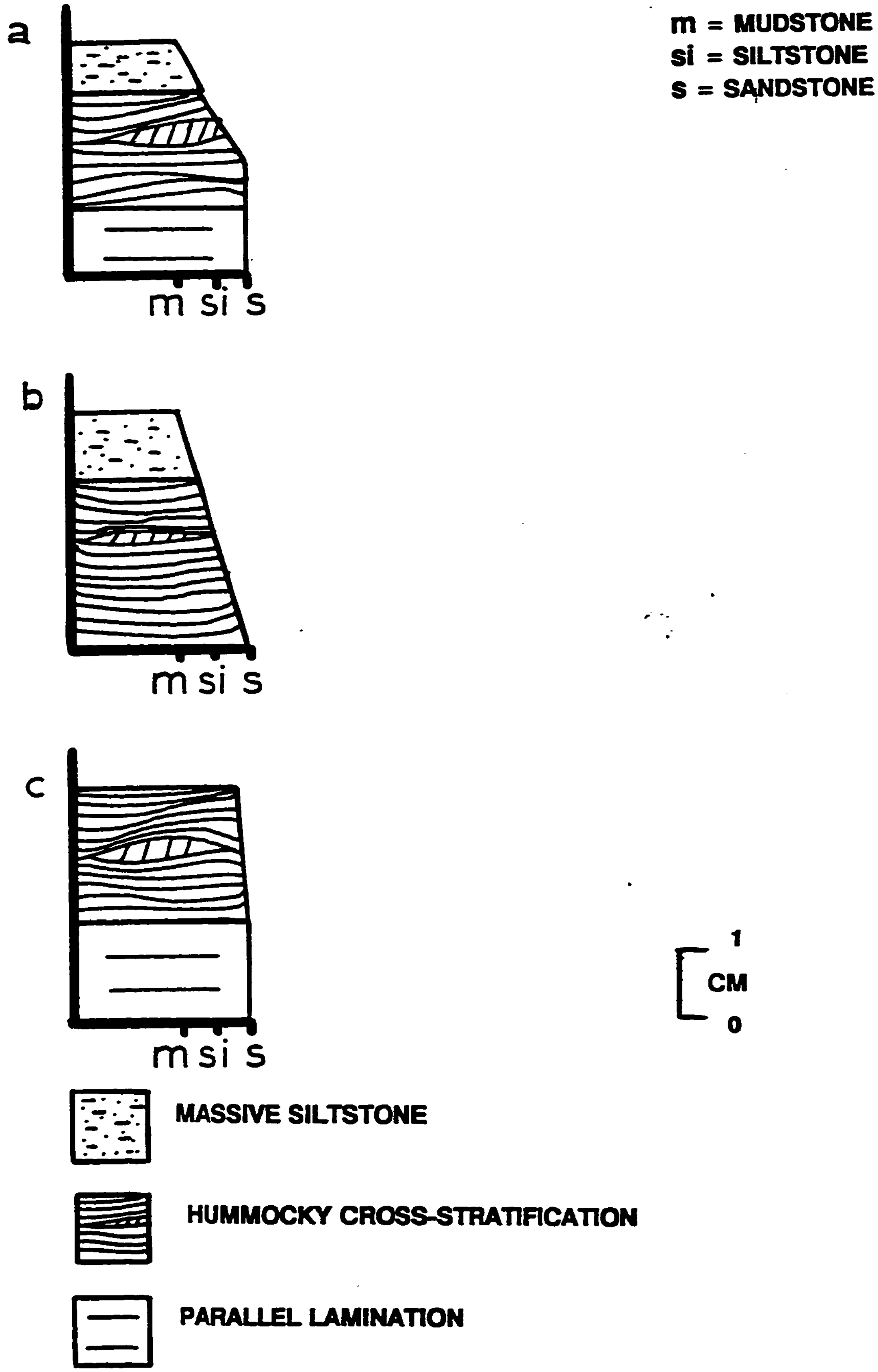


Walker *et. al.* (1983)

Hummocky cross-stratification has been interpreted as a wave induced bedform which is produced in the offshore environment by intense wave activity during storm events; formation by strong surges that are generated by the action of relatively large storm waves. Although there has been some debate over the origin and formation of hummocky cross-stratification; most authors and workers now infer an origin due to powerful oscillatory-dominant or multidirectional flows (from Duke, 1985). Dott and Bourgeois (1982) describe hummocky cross-stratification as forming most commonly by redeposition below normal fair-weather wave base with the deposition involving both fallout from suspension and lateral tractive flow due to wave oscillation.

To discuss the formation of the hummocky cross-stratified beds; one will have to again consider the idealized hummocky sequence of Dott and Bourgeois (1982) and the modified sequence of Walker *et. al.*, (1983). These sequences (from Chapter 4), which reflect waning of storm waves followed by fairweather deposition, are once again shown in Figures 6-5 a,b. Variations in the ideal sequence can indicate coincident variations in flow conditions (Dott and Bourgeois, 1982). This means that at certain times, wave oscillation is operating while at other times unidirectional flow is dominant, resulting in the deposition of certain subdivisions of the idealized hummocky cross-stratified sequences. Variability of flow conditions is reflected in the three sequences (Figure 6-6a,b,c) of hummocky cross-stratification present in the current study area. These three sequences exhibit none of the common variations described by Dott and Bourgeois (1982).

FIGURE 6-6 Generalized depiction of the three interlayered sequences of hummocky cross-stratification typically found in the study area.


a
m = MUDSTONE
si = SILTSTONE
s = SANDSTONE
m si s
b
m si s
c
1
CM
0
m si s
MASSIVE SILTSTONE
HUMMOCKY CROSS-STRATIFICATION
PARALLEL LAMINATION

The cross-laminated (X) and flat-laminated (F) divisions are missing in all hummocky cross-stratified sequences of the study area (Figure 6-6). The F division is produced by thickness changes in laminae over hummocks and swales, resulting in a flattening upwards of the laminae. The X division is produced by a temporary reworking at low flow intensity of the top of a bed by wave oscillation as a storm waned (Dott and Bourgeois, 1982). The absence of the F and X divisions in the study area provides evidence of flow conditions during deposition of the various hummocky cross-stratified beds. Flow conditions at the time of formation of the hummocky cross-stratified beds did not allow for the formation of these two divisions during deposition. The cross-laminated (X) division will not always form if there is a rapid and abrupt cessation of storm conditions. The absence of the X division also indicates that storm activity in the area ceased abruptly.

The formation of the parallel laminated divisions present at the base of two of the hummocky cross-stratified sequences (Figure 6-6a,c) in the study area have been discussed by Walker *et. al.,* (1983), who state that this division has formed as the result of two processes. The first process is deposition from powerful unidirectional flows. The second process is deposition from powerful oscillatory flows. Walker *et. al.* (1983) state that the two processes leave indistinguishable types of parallel lamination, therefore it is impossible to determine which process is responsible for the formation of parallel lamination at the base of hummocky cross-stratified beds. They also cite a third process, during which deposition from unidirectional flows grades into deposition from oscillatory flow; the rate of deposition from the unidirectional flow decreases as oscillatory wave motion become more important (Walker *et. al.*, 1983). The third process seems the most likely for the formation of parallel laminated divisions which form the base to hummocky cross-stratified beds of the study area. Initial deposition of the sequences in the study area begins with a powerful unidirectional current depositing the P division; with slowing of the unidirectional current, the H division is formed by oscillatory dominant flow. The parallel laminated basal division is absent in one of the hummocky cross-stratified sequences of the study area (Figure 6-6b). The absence of this division indicates complete reworking of the parallel laminated division by the oscillatory wave motion during the formation of hummocky cross-stratification.

The massive mudstone or siltstone layer at the top of all of the hummocky cross-stratified sequences in the study area (Figure 6-6) allows for the differentiation of major depositional events. Dott and Bourgeois (1982) feel that these layers are representative of both waning-storm and normal fairweather sedimentation. The massive fine-grained siltstone to mudstone layers that are present at the top of hummocky cross-stratified sequences were deposited from waning storm activity. Individual siltstone beds that are interbedded with the hummocky cross-stratified beds, and sometimes overly the hummocky beds in the study area, reflect normal fairweather sedimentary processes. In both cases, the layers are deposited as a result of material (mud to fine-grained silt) settling out of suspension.

The hummocky cross-stratified beds in the study area have a range of thicknesses that extends from 3.5 to 22.0 centimetres. This range contains thicknesses that are considerably less then those commonly reported in the literature, where a range of 20 to 80 centimetres (Dott and Bourgeois, 1982) in thickness is common. This difference in thickness ranges also provides evidence of flow conditions in operation at the time of deposition of hummocky cross-stratification in the study area. The thickness of hummocky cross-stratification in the study area indicates a limited sediment supply to the offshore environment. The sediment supply is controlled by the bottom return flow (unidirectional current). The return flow may only be of limited strength or duration and is only able to transport a restricted supply of sediment to the offshore. This indicates that storm conditions in the study area were of limited strength and duration.

The trends in the distribution of hummocky cross-stratified beds in Chapter 5, can be explained with the aid of Figure 6-4. The rare hummocky cross-stratified beds that are present in the lower portions of the transgressive offshore sequence of outcrop 1 were deposited above the zone of hummocky deposition. The concentration of hummocky cross-stratified beds between 83.0 - 85.0 metres (Figure 5-4, Chapter 5) represents the generation and formation of these beds within the zone of hummocky deposition. Finally, the small number of hummocky cross-stratified beds towards the top of the sequence were deposited slightly deeper than the main zone of hummocky deposition.

Below the Zone of Hummocky Deposition

The upper portion of Figure 5-4 in Chapter 5 shows the interbedded association of parallel laminated and massive siltstone and mudstone and rare sandstone beds. This interbedded association which is present in the uppermost part of the transgressive sequence of outcrop 1 is similar to Facies A of Colquhuon (1995), and Facies 1 of Duke *et. al.* (1991). Facies A of Colquhuon (1995) consists of mudstone to very fine silty sandstone with rare interbeds of fine- to medium-grained sandstone; while Facies 1 of Duke et. al. (1991) is composed of intervals dominated by siltstone and mudstone locally interbedded with very thin beds of coarse-grained siltstone to fine-grained sandstone. The interbedded association, Colquhuon's (1995) Facies A and Duke *et. al.'s* (1991) Facies 1, are all indicative of low-energy suspension sedimentation on a shelf that was generally below storm wave base. This corresponds to the area below the zone of hummocky deposition in Figure 6-4, and indicates that the majority of massive siltstone and mudstone beds of the offshore environment in the study area were deposited under similar conditions. The rare sandstone beds present in the distal offshore environment are similar to the laminated sandstone beds of Reineck and Singh (1972) and formed in the same manner.

Colquhuon (1995) has also reported on the presence of thinly interbedded sandstone and siltstone/mudstone beds (Facies A and B) in the storm-dominated offshore environment. The sandstone beds have sharp scoured bases, normal grading and parallel lamination (Colquhuon, 1995). A similar association of siltstone and sandstone beds is also present in the offshore environment of the current study area.

Colquhuon (1995) attributes their formation to deposition of thin, graded sandstone beds from waning storm-generated suspension currents, interbedded with fairweather suspension deposited mudstones, and it is these formational processes that also resulted in the presence of sandstone beds in the current study. Similar interbedded associations in other ancient storm-dominated shelves have been recorded by Hamblin and Walker (1979), Walker (1984) and Swift *et. al.* (1987). Once again, this association represents sedimentation below the zone of hummocky deposition in the study area (Figure 6-4).

CHAPTER SEVEN -- TIDAL RHYTHMITES

Sedimentary rocks can record the activity of tides, providing a picture of depositional, environmental, and astronomical conditions at the time of sedimentation. The current study provides a rare window onto such conditions during the Neoarchean of the Canadian Shield. A close examination of tidally-deposited sediments in the study area yields limited information concerning the nature of tidal activity at the time of deposition.

Rare occurrences of finely rhythmically parallel laminated beds are present in the Shebandowan Group. This type of bedding consists of alternating laminae, ranging from 0.1 to 6.5 centimetres in thickness, of fine- and coarse-grained sediments which are rhythmically repetitive. The fine-grained sediments are composed of mudstone and appear to cap the coarser-grained sediments. The coarse-grained sediments consists of very fine-grained sandstone which fine upwards into a coarse-grained siltstone. The laminae appear to thin and thicken systematically through a vertical sequence. The repetitive nature of the laminae has resulted in the term tidal rhythmites being assigned to this type of bedding (Reineck and Singh, 1975). Such rhythmicity can be related to neap-spring tidal cycles and current velocity fluctuations that are associated with such a cycle. An individual sandstone laminae overlain by a mudstone laminae is similar to sand-mud couplets described by Dalrymple *et. al.*, (1991) on mud flats in the Cobequid Bay - Salmon River estuary of the Bay of Fundy.

The presence of individual laminae can be interpreted as the products of diurnal, mixed or semidiurnal tidal activity. Varying laminae thicknesses reflect semimonthly (neap to spring) fluctuations in tidal current activity. Lunar months are defined by two peaks (spring deposits) and two troughs (neap deposits) (Brown *et. al.*, 1990). This means that a two week period is represented by the laminae between two peaks or two troughs. Interpretation is based on methods outlined by Kvale *et. al.* (1989), Brown *et. al.* (1990), and Kvale and Archer (1991), in which sequential sandstone (or mudstone) laminae are numbered and plotted against their thickness on a histogram. The number of sandstone or mudstone laminae per cycle can then be counted between laminae maxima or minima. In the present case, the number of sandstone laminae between zones of laminae maxima were counted. Using methods from Archer *et. al.* (1995), successive laminae thicknesses are plotted against each other (**n vs. n + 1**) was plotted on a scattergram to determine if the laminae were deposited in a semidiurnal or diurnal setting. The following two sections describe and discuss the results of the histogram and scattergram plots.

RHYTHMIC UNIT A

When sequential sandstone laminae from rhythmic unit A (Figure 7-1) are plotted against their thickness, the result is two sinusoidal curves exhibiting periodicities of 22 and 28 laminae (Figure 7-2). Similar, but more extensive curves have been generated by Kvale *et. al.*, (1989), and Kvale and Archer (1991) for the Hindostan Whetstone beds and Abbott sandstone in the Illinois Basin, and by Brown *et. al.* (1990) for the Salem Limestone,. These curves have been interpreted as representing a semidiurnal to mixed tidal cycle of a half-lunar month (Kvale *et. al.*, 1989; Brown

FIGURE 7-1 Photomicrograph of Rhythmic Unit A

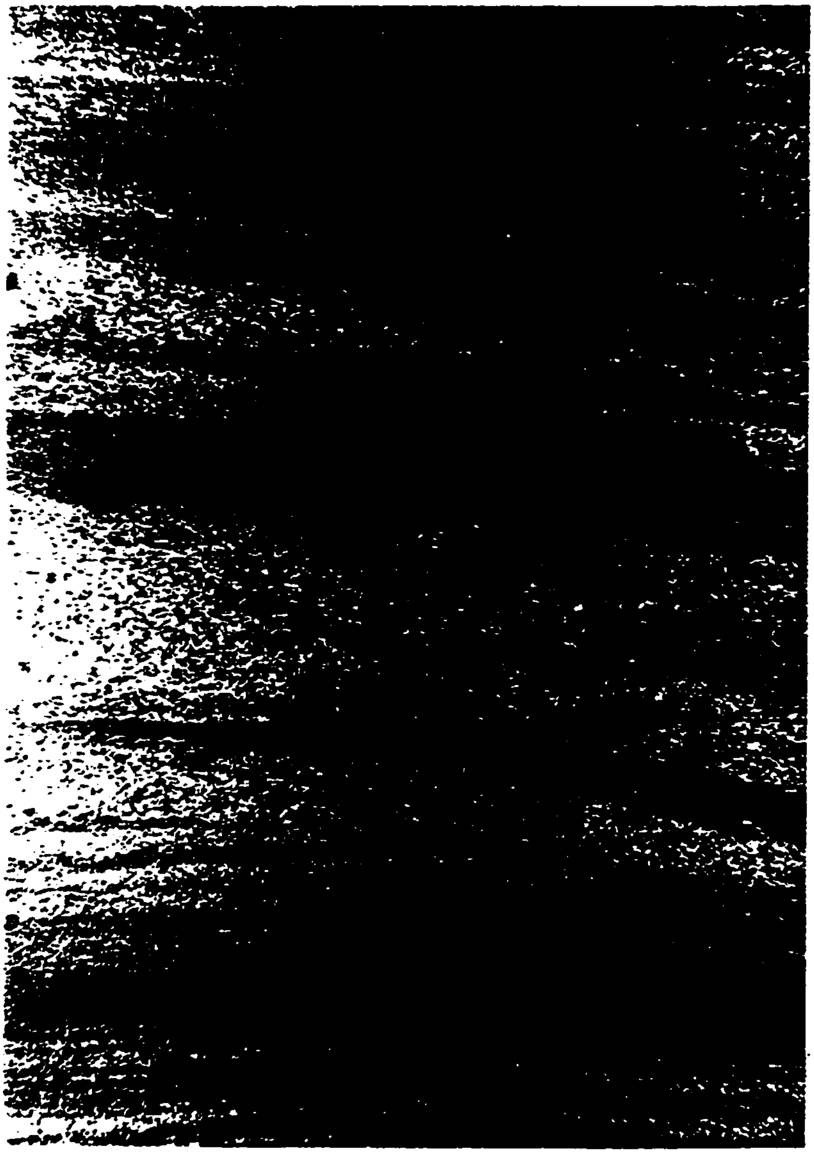
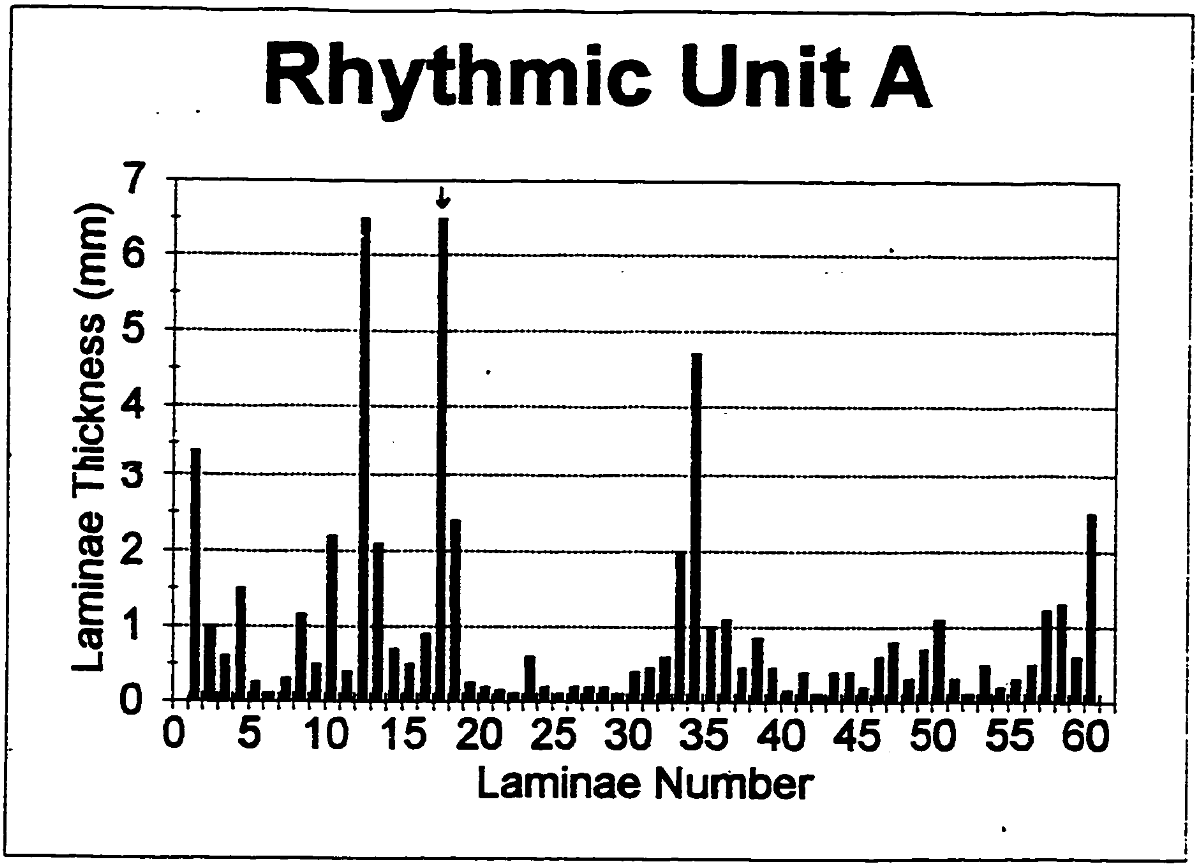
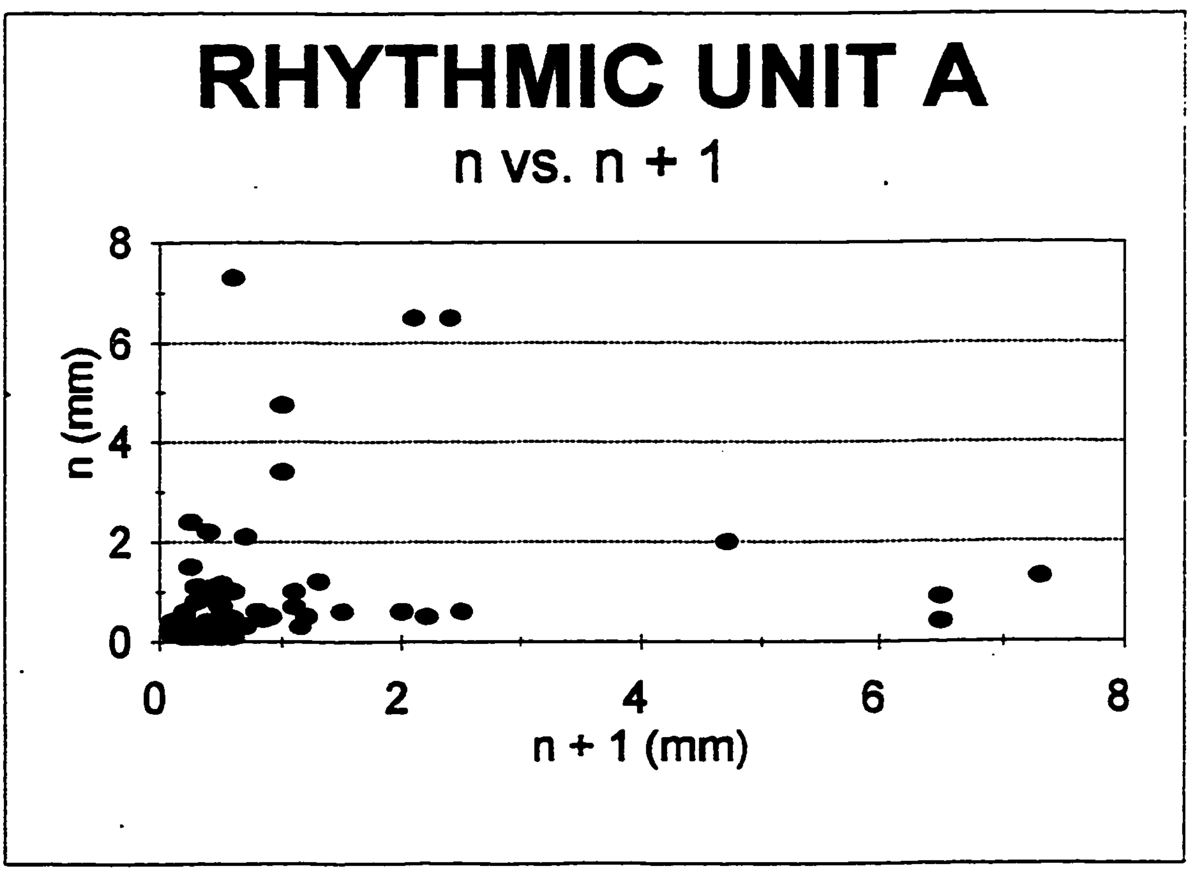


FIGURE 7-2 Plot of sequential sandstone laminae against laminae thickness in Rhythmic Unit A.

FIGURE 7-3 Plot of successive laminae thicknesses (n vs. n + 1) for sandstone laminae in Rhythmic Unit A.


Rhythmic Unit A
Laminae Thickness (mm)
0
1
2
3
4
5
6
7
0
5
10
15
20
25
30
35
40
45
50
55
60
Laminae Number


RHYTHMIC UNIT A
n vs. n + 1
n (mm)
0
2
4
6
8
n + 1 (mm)

et. al., 1990; Kvale and Archer, 1991). This is reflective of two flood-ebb events per day during two fourteen day periods between successive spring tides, depositing a series of 22 and 28 sandstone laminae respectively.

Further confirmation that the laminae were deposited in a semidiurnal tidal setting are present in a plot of successive laminae thicknesses (**n vs. n + 1**), for the sandstone laminae (Figure 7-3). In this plot, the wide scatter of data points is probably indicative of a semidiurnal setting. This plot is similar to scattergrams of successive-laminae thicknesses for Carboniferous rhythmites and modern-day semidiurnal systems generated by Archer *et. al.* (1995).

The first curve of 22 laminae, also contains an anomalously thick laminae (↓ in Figure 7-2), equal in thickness to one generated by the possible spring tide. When one considers both the low number of laminae (22) and the presence of the anomalously thick sandstone laminae, it is evident that non-astronomical controls have played a role in the deposition of the laminae. It is possible that the first curve reflects the effects of storm activity during the time of deposition replacing tidal processes as the dominant control over deposition. The anomalous laminae may represent sediment deposited during the storm.

DISCUSSION

The number of laminae present in both curves of Unit A yield a minimal value of

22 days for the length of a lunar month, and a maximum value of 28 days; values which are less then that of 29.6 days for the present-day lunar month associated with semidiurnal tidal systems. The length of a possible lunar month determined for Unit A (2692 Ma) is considerably less then the value of 30.5 (±1.5) days determined by Williams (1989, 1991) for the late Precambrian (650 Ma) Elatina formation of Australia; although there is some question concerning the validity of this value. Comparing the determined lengths for the late Precambrian (30.5 ±1.5 days), and the modern-day synodical (29.6 days) month it is apparent that a complete record of tidal activity has probably not been preserved in Unit A.

There are two possible reasons for the incomplete tidal record of Unit A. As previously discussed, the semidiurnal tidal cycles of Unit A may have been overprinted as the result of episodic storm activity. Archer (1995) and Kvale *et. al.* (1995) have discussed how wave and storm influences can create random components that significantly overprint astronomically generated tidal periodicities. Williams (1989, 1991) has also stated that the record of tidal rhythms might be overprinted by episodic or seasonal patterns caused by storminess or changes in the rate of sediment supply. This possibility is strengthened by the observed presence of parallel laminated sandstone beds deposited by storm activity and hummocky cross-stratification at other locations in the study area.

Storm activity though, cannot solely explain the absence of laminae within the generated cycle for Unit A. In the current study, it was determined that tidal deposition occurred predominantly in the intertidal zone. Dalrymple et. al., (1991) has observed that sand-mud couplets deposited on the intertidal zone do not always produce curves with obvious tidal periodicities. The intertidal zone is periodically inundated by water during the flood - ebb tidal cycle. It is possible that at certain times, especially during periods of low neap tide, the water did not reach high enough up on the intertidal flat to deposit any material, therefore leaving no laminae behind as a record of that particular tide.

As previously stated, the non-deposition of laminae on the intertidal flat can be related to periods of low neap tides. DeBoer *et. al.* (1989) have suggested that a cessation of sand transport around the time of a neap tide will result in a less than 'ideal' number of neap laminae being deposited. Williams (1989, 1991) has also written that laminae can be missing from laminae cycles through non-deposition at times of low tidal ranges. Laminae in the cycle of Unit A may be absent as a result of non-deposition during periods of low neap tides. Non-depositional events are also related to periods during which the current velocity of either the flood or ebb tide was not high enough to transport sediment to be deposited. Truncation of the tidal cycles may have occurred in a manner similar to that discussed by Tessier (1993),

It is probable that tidal periodicities are preserved in the rocks of the Neoarchean Shebandowan Group. The information obtained in this study provides a very brief and limited glimpse of conditions in operation during this time. Only limited interpretations concerning the nature of the tidal system and the length of the lunar month can be made from the data obtained in the this study. Further investigation of the sediments of the Shebandowan Group may lead to increased knowledge of the dynamics of the earth-moon system, and astronomical 'conditions' during the Neoarchean.

CHAPTER EIGHT -- CONCLUSIONS

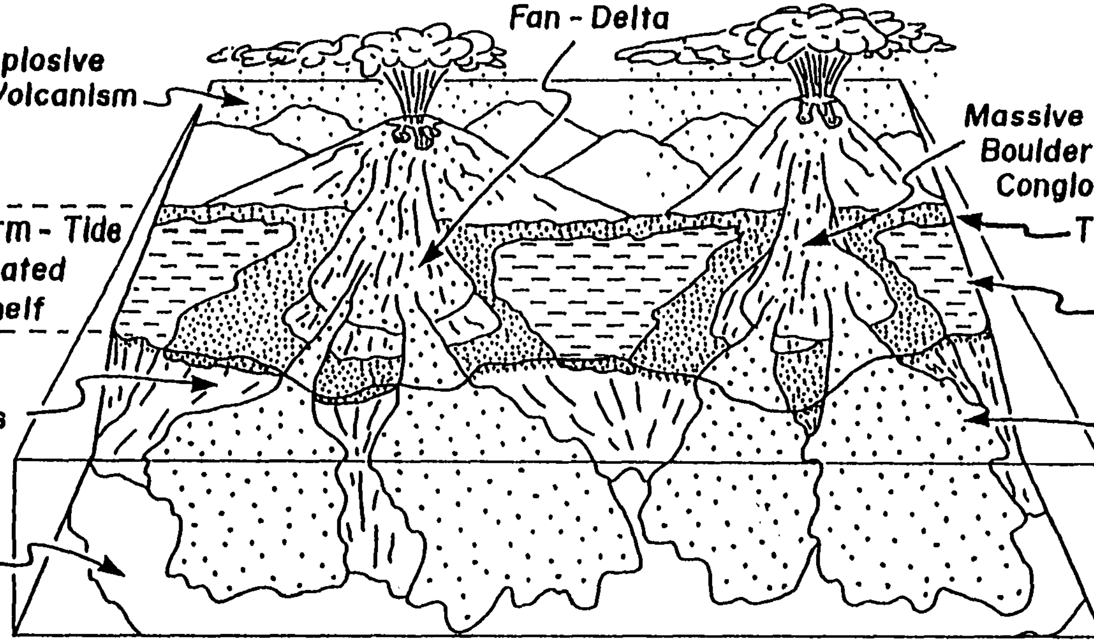
INTRODUCTION

The present study of the Shebandowan Group has looked at a rare example of three shallow-water environments from the Neoarchean of the Canadian Shield. They are the tidal, shoreface, and offshore environments, and depositional processes in the three environments were under the influence of tidal, wave, and storm processes. The excellent preservation of sedimentary structures and depositional features within the sedimentary rocks of the Shebandowan Group has allowed for a detailed examination of depositional processes active in the three environments.

The environments formed part of a larger depositional system described by Rezka (1987); Fralick and Barrett (1991); and Eriksson *et. al.* (1994). This depositional system is shown in Figure 8-1; and contains the entire transition between the two depositional facies that typify the depositional history of the Archean Canadian Shield. The presence of the tidal to offshore depositional environments, which typify shallow-water shelf settings demonstrates that there was development of shelves in the Archean, contrary to the popular and widely held belief that there was very little, if any shallow shelf development. Further, the environments indicate the presence of a stable area around a small oceanic island on which extensive reworking of the tidal to offshore sandstones and siltstones could occur (Figure 8-2).

FIGURE 8-1 The larger depositional system described by Rezka (1987); Fralick and Barrett (1991); and Eriksson *et. al.* (1994) present in the Wawa subprovince. The current study is located on the storm - tide dominated shelf.

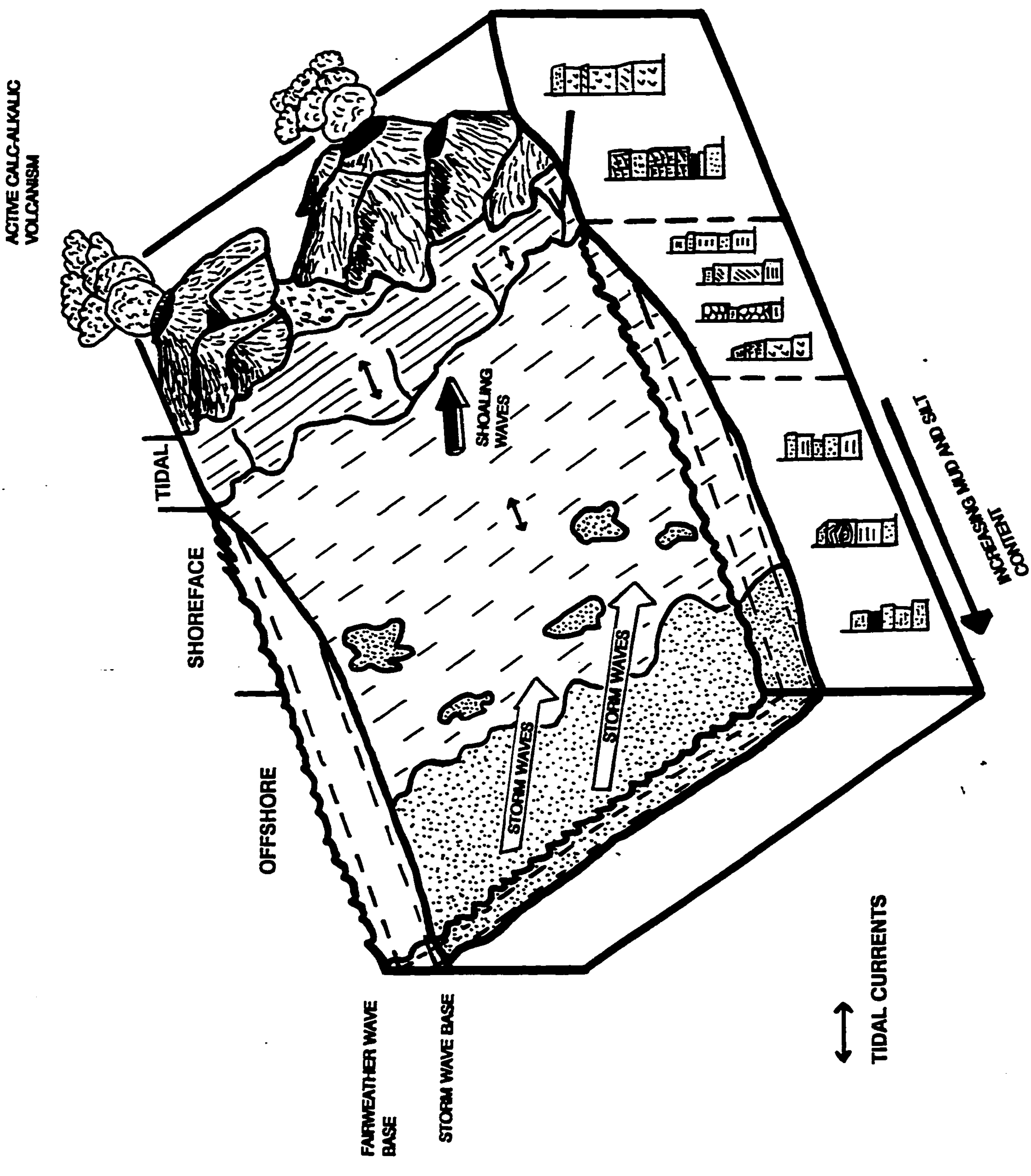
DEPOSITIONAL MODEL



VERTICAL SCALE EXAGGERATED 1000 X

(Eriksson *et. al.*, 1994)

FIGURE 8-2 Block diagram summarizing the depositional environments and processes present in the Shebandowan Group. All three environments described in this study are present, and represent coastal sedimentation along the shorelines of active volcanic islands. Small sections along the base of the block diagram depict beds and lithofacies common in the three environments.



ACTIVE CALC-ALKALIC VOLCANISM
TIDAL
SHOREFACE
OFFSHORE
FAIRWEATHER WAVE BASE
STORM WAVE BASE
SHOALING WAVES
STORM WAVES
STORM WAVES
INCREASING MUD AND SILT CONTENT
TIDAL CURRENTS

TIDAL ENVIRONMENT

Observations of the tidal environment in the current study area have revealed that the physical depositional processes in operation during the Archean were remarkably similar to those operating in the Phanerozoic and present-day environments. The only notable difference in the lack of bioturbation. Depositional processes in both the tidal flat and tidal channel sub-environments were controlled by the bidirectional nature of tidal currents (Figure 8-2) and fluctuating current velocities related to both the daily tidal cycle and the biweekly neap - spring cycles. The amount of sediment supplied to the depositional setting also played a role in the generation and formation of lithofacies in both sub-environments, especially the tidal flat.

The fluctuations in tidal current velocity during the daily tidal cycle resulted in the formation of lithofacies considered characteristic of the tidal environment. These lithofacies include flaser, lenticular, and wavy bedding, as well as coarsely interlayered bedding. Transitions between these lithofacies within vertical sequences throughout the tidal flats reflect changing current velocities associated with the neap - spring tidal cycles. Statistical analysis similar to Markov chain analysis performed on tidal flat sequences has shown that transitions between these four types of bedding are non-random occurrences. This further illustrates that the deposition of different lithofacies on the tidal flats were controlled by processes such as changing current velocities. Another control on the type of bedding generated during a tidal cycle; either daily or neap - spring, is the amount of sediment available. Sediment supply may be controlled by seasonal variations or associated with volcanic activity present in the area.

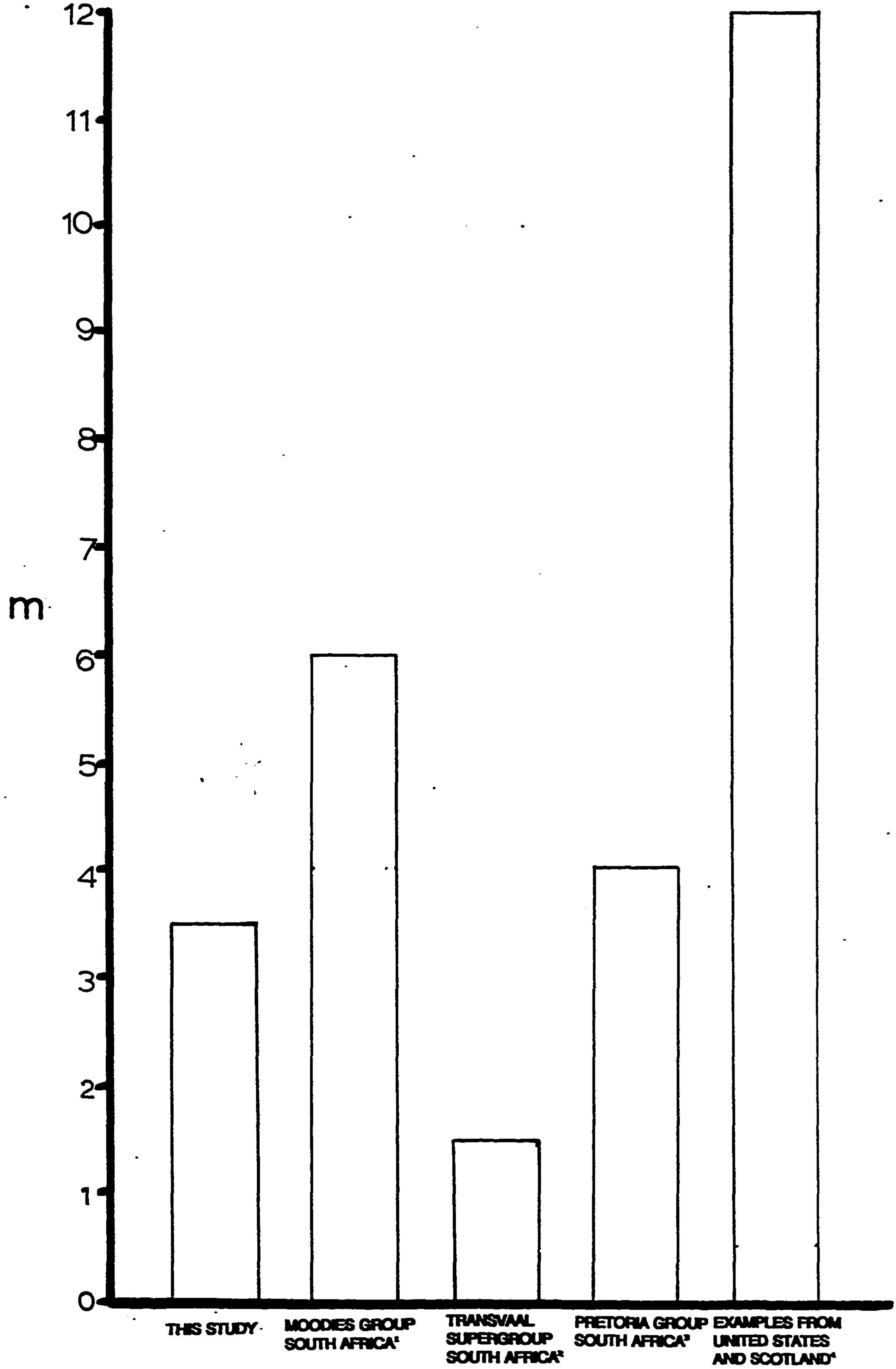
The tidal channel sub-environment represents an unique situation. The vast majority of tidal channels described in the literature are meandering in nature, with extensive point bar development. The tidal channels of the current study though lack many of the attributes of meandering stream or even of braided stream models. In this respect, the tidal channels of the study area are similar to channel sequences found in the Nubia strata of southwestern Egypt (Klitzsch *et. al.,* 1979), which exhibit low sinuosity.

It is fairly obvious that tidally-influenced processes dominated in this environment, transporting and depositing sediment in both the tidal flats and channels. Occasionally tidal processes were superseded by episodic, high-energy storm activity. The storm activity overprinted evidence of tidal processes, and usually resulted in the deposition of numerous, graded and parallel laminated sandstone beds.

A minimal, average tidal range of 3.4 metres was calculated for the tidal environment present in the study area. This is indicative of a mesotidal environment. In comparison to tidal ranges determined for many other Precambrian tidal environments, this value is slightly less (Figure 8-3). Many of the Precambrian tidal ranges reported in the literature, and shown in Figure 8-3 are meso- to macrotidal. The differences in tidal ranges could be attributed to such factors as variable shelf widths and coastline morphology.

FIGURE 8-3 Bar graph depicting paleo-tidal ranges from a number of Precambrian tidal environments described in the literature. The tidal range for the current study is shown on the far left for comparison.

[1] Eriksson, 1977
[2] Beukes, 1977
[3] Button and Vos, 1977
[4] Klein, 1977



PRECAMBRIAN TIDAL RANGES

SHOREFACE ENVIRONMENT

The shoreface environment exhibits many of the features of a high-energy, non-barred shoreline, although there is no evidence of the presence of beach deposits (see Clifton *et. al.*, 1971). Deposition in this environment predominantly shows an influence from unidirectional wave-induced current activity, which overprints bidirectional tidal current activity (Figure 8-2). The deposition of sediments is controlled by unidirectional processes such as the migration of dunes and ripples along the bottom surface of the shoreface environment. Throughout much of the shoreface environment, the depth from sea level to the bottom is shallow enough that fairweather wave orbitals affect the substrate, transporting and depositing sediment. The action of the wave orbitals associated with unidirectional wave current activity overprints or masks a tidal influence on deposition. Towards the distal edge of the sand body, there is a resumption of tidally-influenced depositional processes (Figure 8-2). This represents the point at which fairweather wave orbitals are no longer affecting the bottom, and bidirectional tidal currents dominate.

The migration of dunes and ripples in the shoreface environment may also possibly be the result of asymmetrical tidal currents, with either the flood or ebb current directions dominating. This is unlikely when considering the presence of herringbone cross-stratification in both the tidal channels and shoreface. The presence of this type of cross-stratification indicates that the ebb and flood tidal currents were nearly equal in strength the majority of the time. Storm activity also influenced sedimentation in the shoreface environment. Unidirectional offshore flows caused by storm activity resulted in the formation of some of the sandstone beds.

OFFSHORE ENVIRONMENT

Deposition in the offshore environment was dominated by alternating periods of storm activity and fairweather suspensional processes (Figure 8-2). There is no longer any evidence of the tidal processes that operated in the foreshore and shoreface environments. Periods of storm activity resulted in the formation of distinctive beds of hummocky cross-stratification. The transition into this environment is marked by a change from dominantly unidirectional flows depositing parallel and 'wavy' laminated sandstones into multidirectional or oscillatory flows responsible for the generation of hummocky cross-stratification.

Although the distribution of the sandstone and siltstone lithofacies in the offshore environment are similar to distributions described in the literature, there are several differences with regard to the hummocky cross-stratified units. First, the average thickness of hummocky cross-stratification in the study area is considerably less then those commonly reported in the literature (Dott and Bourgeois, 1982). This difference in thickness indicates a sediment supply controlled by the bottom return flow (unidirectional current) to the offshore environment and the lack of biota capable of disrupting the thin storm layers. Second, the hummocky cross-stratified units in the study area do not contain a number of division that are present in idealized hummocky cross-stratified sequences. The absence of these divisions is also related to low flow velocities during storm activity, and short duration of storms.

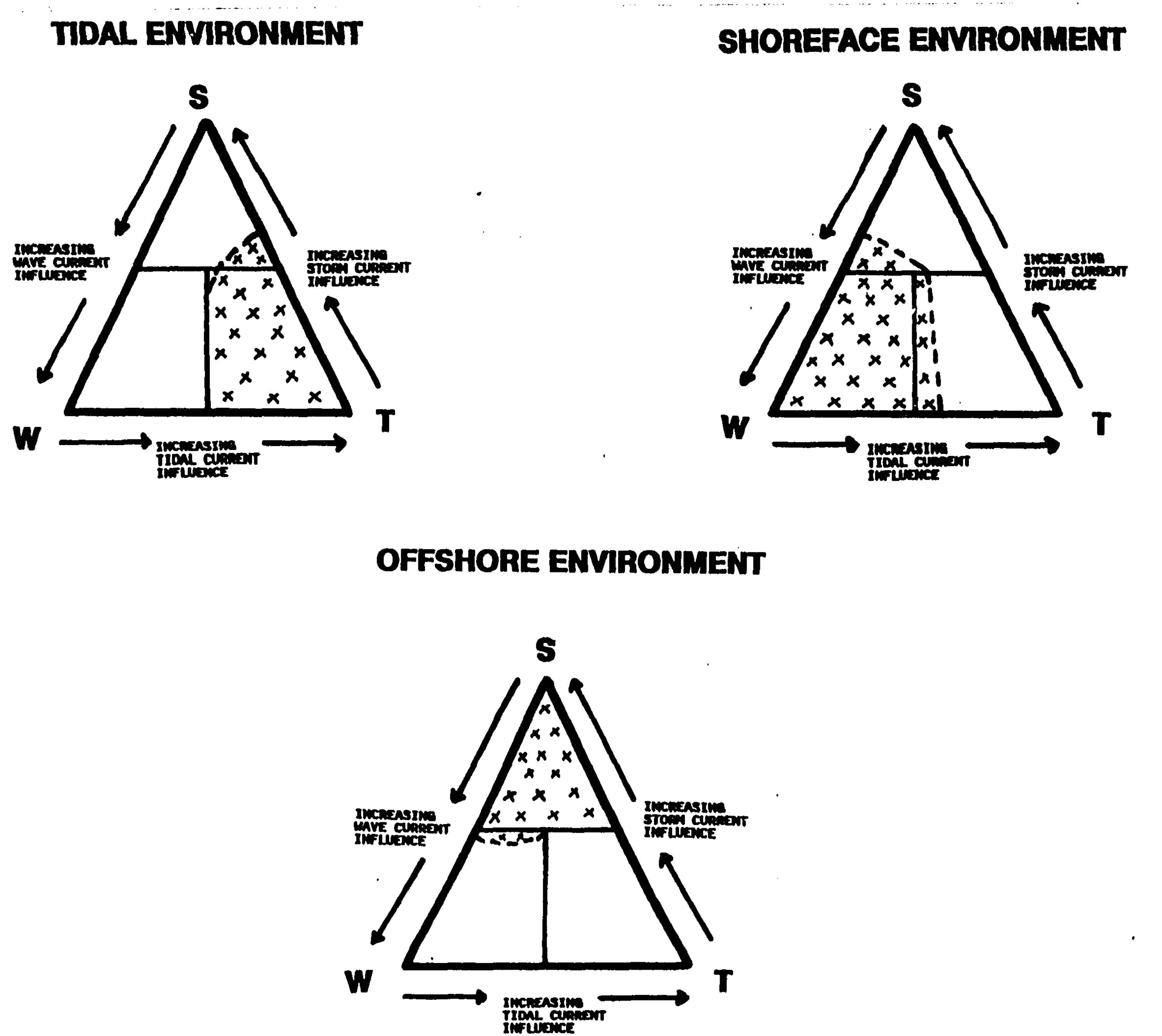
The presence of hummocky cross-stratification in the study area in addition to Rezka's (1987) observations also provides unrefutable evidence for the development of shallow-water shelves in the Archean. The mere existence of hummocky cross-stratified beds within the Shebandowan Group allows an interesting observation to be made concerning paleo-environmental conditions prevalent during the deposition and formation of these beds. It is widely recognized that hummocky cross-stratification forms as a result of intense storm activity; usually attributed to hurricanes or intense winter storms. Duke (1985) has found in a study of 107 known examples of hummocky cross-stratification that 75% of these examples formed as a result of tropical hurricane activity. It could be hypothesized, that the hummocky cross-stratified beds were probably deposited in a paleo-environment with climatic conditions similar to those found in present day tropical environments.

The hypothesis that the hummocky cross-stratified beds were deposited in an environment similar to the present-day tropics allows inferences regarding paleo-latitude to be made. Hurricanes are latitudinally restricted in the modern world (Duke, 1985), and it stands to reason that this would be true of the Archean. Hayes (1967) has also suggested that hurricane deposits may be useful as paleo-latitude indicators. Duke (1985) has determined that hurricane deposits such as hummocky cross-stratification can be expected from paleo-latitudes of about 10° to 45°. Using this determination, a broad generalization can be made about the position of the land mass along which the tidal to storm-dominated offshore Lithofacies were deposited. Basically, the land mass was located between 10° to 45° latitude either north or south of the equator. Further study may lead to more accurate determinations being made concerning the position of the land mass, although the fact that the atmosphere was probably denser during the Archean may have serious implications for this hypothesis.

Attention should be briefly turned to the transition zones between the three major environments present in the study area. These transitions all appear to be very gradational, and probably indicate a slow and gradual rise in sea level in the area. The transition zones are marked most notably by the following features: vertical changes in overall grain size and changes in depositional processes which produce changes (laterally and vertically) in both lithofacies and lithofacies associations.

The current study has shown that deposition in the three environments was affected by different current processes (Figure 8-4). When moving offshore through the three environments, there is a progression from an environment controlled by bidirectional currents into one that is dominated by unidirectional and multidirectional currents (see Figure 8-2). The tidal environment, which contains both the tidal flat and tidal channel sub-environments was dominated by tidal currents (Figure 8-4), with minor input from storm activity. Bidirectional tidal currents were also present in the shoreface environment, but many of the effects of this activity was overprinted by the

FIGURE 8-4 The three depositional environments present in the current study area are represented by one of the three triangles. The x'ed area in each triangle indicates which currents dominated and controlled deposition in that particular environment.



S = STORM - INDUCED CURRENTS
W = WAVE - INDUCED CURRENTS
T = TIDAL - INDUCED CURRENTS

action of unidirectional wave-induced currents (Figure 8-4). There is also evidence of deposition from storm currents in this environment. Finally, deposition in the offshore environment was controlled by storm current activity (Figure 8-4).

EARTH - MOON SYSTEM

The development and presence of tidally deposited sediments offers evidence for the existance of the earth-moon system. Tidal deposits from older rocks have already indicated the existence of such a system, but this is the first time that Archean rocks in Canada have provided such evidence. The presence of a sequence of tidal rhythmites in the study area has provided possible evidence of semidiurnal tidal system. From this sequence, it was possible to determine a minimal duration of the lunar month during the Archean. From Rhthymic Unit A, an approximate duration of 28 days was determined. This value is only slightly less then that for the present day synodical lunar month (29.6 days), as well as those determined for Phanerozoic examples (see Chapter 7).

REFERENCES

Archer, A.W., 1995, Modelling of cyclic tidal rhythmites based on a range of diurnal to semidiurnal tidal-station data, Marine Geology, v.123, p.1-10.

Archer, A.W., Kuecher, G.J., and Kvale, E.P., 1995, The role of tidal-velocity asymmetries in the deposition of silty tidal rhythmites (Carboniferous, eastern Interior Coal Basin, U.S.A.), Journal of Sedimentary Research, v.A65, p.408-416.

Archer, P., Dimroth, E., and Gobeil, A., 1982, Volcanism and sedimentation of the Archean Blondeau Formation, Chibougamau, Quebec: Geological Association of Canada, Programs with Abstracts, v.7, p.36.

Arnott, R.W.C., 1993, Quasi-planar-laminated sandstone beds of the Lower Cretaceous Bootlegger Member, North-Central Montana: Evidence of combined-flow sedimentation: Journal of Sedimentary Petrology, v.63, p. 488-494.

Arnott, R.W.C., and Southard, J.B., 1990, Exploratory flow-duct experiments on combined flow bed configurations, and some implications for interpreting storm-event stratification: Journal of Sedimentary Petrology, v.60, p.211-219.

Beukes, N.J., 1977, Transition from siliciclastic to carbonate sedimentation near the base of the Transvaal Supergroup, northern Cape Province, South Africa: Sedimentary Geology, v.18, p.201-221.

Borradaile, G., and Brown, G.H., 1987, The Shebandowan Group: "Timiskaming-like" Archean rocks in northwestern Ontario: Canadian Journal of Earth Sciences, v.24, p.185-188.

Blatt, H., Middleton, G., and Murray, R., 1980, Origin of Sedimentary Rocks 2[ed]: Prentice-Hall Inc., New Jersey, 782 p.

Brown, G.H., 1985a, A Structural and Stratigraphic Study of the Keewatin-type and Shebandowan-type rocks west of Thunder Bay, Ontario: unpublished MSc thesis. Lakehead University, Thunder Bay, Ontario.

Brown, G.H., 1985b, A Re-examination of some mineral occurrences in the Shebandowan greenstone belt, northwestern Ontario in Summary of Field Work and Other Activities, Ontario Geological Survey, Misc. Paper 126, p.222-228.

Brown, G.H., 1992, Geology and mineral potential of Oliver Township, District of Thunder Bay: in Summary of Field Work and Other Activities, Ontario Geological Survey, Misc. Paper 160, p. 237-241.

Brown, G.H, and Fogal, R.I., 1993, Geology and mineral potential of Ware Township, District of Thunder Bay in Summary of Field Work and Other Activities, Ontario Geological Survey, Misc. Paper 162, p.231-236.

Brown, M.A., Archer, A.W., and Kvale, E.P., 1990, Neap-spring tidal cyclicity in laminated carbonate channel-fill deposits and its implications: Salem Limestone (Mississippian) south-central Indiana, U.S.A.: Journal of Sedimentary Petrology, v.60, p.152-159.

Button, A. and Vos, R.G., 1977, Subtidal and intertidal clastic and carbonate sedimentation in a microtidal environment; an example from the Lower Proterozoic of South Africa: Sedimentary Geology, v.18, p.175-200.

Carter, M.W., 1984, Goldie and Horne Townships, District of Thunder Bay: in Summary of Field Work, Ontario Geological Survey, Misc Paper 119, p.

Carter, M.W., 1985, Forbes and Conmee Townships, District of Thunder Bay in Summary of Field Work and Other Activities, Ontario Geological Survey, Misc. Paper 126, p.60-66.

Carter, M.W., 1988, Alkalic Rocks of the Thunder Bay area in Summary of Field Work and Other Activities, Ontario Geological Survey, Misc. Paper 141, p.179-184.

Carter, M.W., 1990, Geology of Forbes and Conmee Townships: Ontario Geological Survey, Open File Report 5726, 188 p.

Chorlton, L.B., and Brown, G.H., 1984, Gold mineralization in the Shebandowan area: in Summary of Field Work, Ontario Geological Survey, Misc. Paper 106, p. 201-207.

Clifton, H.E., Hunter, R.E., and Phillips, R.L., 1971, Depositional structures and processes in the non-barred high-energy nearshore: Journal of Sedimentary Petrology, v.41, p. 651-676.

Colquhuon, G.P., 1995, Siliciclastic sedimentation on a storm- and tide-influenced shelf and shoreline: the early Devonian Roxburgh Formation, NE Lachlan fold belt southeastern Australia: Sedimentary Geology, v.97, p.69-98.

Cooke, D.L and Moorhouse, W.W., 1969, Timiskaming volcanism in the Kirkland Lake area, Ontario, Canada: Canadian Journal of Earth Sciences, v.6, p. 117-132

Corfu, F., and Stott, G.M., 1986, U-Pb ages for late magmatism and regional deformation in the Shebandowan Belt, Superior Province, Canada: Canadian Journal of Earth Sciences, v.23, p.1075-1082.

Corfu, F., and Stott, G.M., 1995, U-Pb geochronology of the Shebandowan greenstone belt, Superior Province, Ontario [abst]: Institute on Lake Superior Geology, 41st Annual Meeting, Marathon, Ontario, v.41, part 1, p. 6.

Corfu, F., Jackson, S.L., and Sutcliffe, R.H., 1991, U-Pb ages and tectonic significance of late Archean alkalic magmatism and nonmarine sedimentation: Timiskaming Group, southern Abitibi Belt, Ontario: Canadian Journal of Earth Sciences, v.28, p.489-503.

Dalrymple, R.W., Makino, Y., and Zaitlin, B.A., 1991, Temporal and spatial patterns of rhythmite deposition on mud flats in the macrotidal Cobequid Bay - Salmon River estuary, Bay of Fundy, Canada in Smith, D.G., Reinson, G.E., Zaitlin, B.A., and Rahmani, R.A., eds, Clastic Tidal Sedimentology: Canadian Society of Petroleum Geologists, Memoir 16, p.137-160.

Dalrymple, R.W., 1992, Tidal Depositional Systems, in Walker, R.G., and James N.P., eds., Facies Models - Response to Sea Level Change: Geological Association of Canada, p.195-218.

Davis, R.A. Jr., 1992, Depositional Systems - An Introduction to Sedimentology and Stratigraphy 2ed: Prentice-Hall Inc., New Jersey, 604p.

De Boer, P.L, Oost, A.P., and Visser, M.J., 1989, The diural inequality of the tides as a parameter for recognizing tidal influences, Journal of Sedimentary Petrology, v.59, p.912-921.

Dimroth, E., Muller, W., Archer, P., Gobeil, A. and Allard, G.O., 1982, Evidence for extensive shallow marine sedimentation in the Chibougamau area, Quebec: Geological Survey of Canada Paper 82-1A, p.29-36.

Dott, R.H. Jr., and Bourgeois, J., 1982, Hummocky cross-stratification: significance of its variable bedding sequences: Geological Society of America Bulletin, v.93, p. 663-680.

Driese, S.G., Byers, C.W., and Dott, R.H. Jr., 1981, Tidal deposition in the basal Upper Cambrian Mt. Simon Formation in Wisconsin: Journal of Sedimentary Petrology, v.51, p.367-381.

Duke, W.L., 1985, Hummocky cross-stratification, tropical hurricanes and intense winter storms: Sedimentology, v.32, p.167-194.

Duke, W.L., Prave, A.R. and PennStrat, 1991, Storm- and tide-influenced prograding shoreline sequences in the Middle Devonian Mahantango Formation, Pennsylvania in Smith, D.G., Reinson, G.E., Zaitlin, B.A., and Rahmani, R.A., eds, Clastic Tidal Sedimentology: Canadian Society of Petroleum Geologists, Memoir 16, p.349-370.

Elliott, T., 1986, Shallow Siliclastic Seas in Reading, H.G., ed., Sedimentary Environments and Facies: Blackwell Scientific Publications, Oxford, p. 155-188.

Eriksson, K.A., 1977, Tidal deposition from the Archean Moodies Group, Barberton Mountainland, South Africa: Sedimentary Geology, v.18, p.257-281.

Eriksson, K.A., 1979, Marginal marine depositional processes from the Archean Moodies Group, Barberton Mountainland, South Africa: evidence and significance: Precambrian Research, v.8, p.153-182.

Eriksson, K.A., Krapez, B., and Fralick, P.W., 1994, Sedimentology of Archean greenstone belts: signatures of tectonic evolution: Earth Science Reviews, v.37, p. 1-88.

Fralick, P.W., and Miall, A.D., 1989, Sedimentology of the Lower Huronian Supergroup (Early Proterozoic), Elliot Lake area, Ontario, Canada: Sedimentary Geology, v.63, p.127-153.

Fralick, P.W., and Barrett, T.J., 1991, Precambrian depositional systems along the southwestern edge of the Superior Craton: Geological Association of Canada, Mineralogical Association of Canada, Society of Economic Geologists, Joint Annual Meeting, Toronto '91, Field Trip A3: Guidebook, 54 p.

Friedman, G.H., Sanders, J.E., and Kopaska-Merkel, D.C., 1992, Principles of Sedimentary Deposits - Stratigraphy and Sedimentology: Maxwell Macmillan Canada, Toronto, 717 p.

George, A.D., 1994, Tidal sedimentation in part of the Late Silurian Grampians Basin, southeastern Australia: Journal of Sedimentary Research, vol. B64, p.311-325.

Hamblin, A.P., and Walker, R.G., 1979, Storm-dominated shelf deposits: the Fernie-Kootenay (Jurassic) transition, southern Rocky Mountains: Canadian Journal of Earth Sciences, V.16, p.1673-1690.

Harms, J.C., Southard, J.B., Spearing, D.R., and Walker, R.G., 1975, Depositional Environments as Interpreted from Primary Sedimentary Structures and Stratification Sequences: SEPM, Short Course 2, 161 p.

Hayes, M.O., 1967, Hurricanes as geological agents: case studies of Hurricanes Carla, 1961, and Cindy, 1963: Bureau of Economic Geology, Report of Investigations, No. 61, 55p.

Hein, F.J., 1987, Tidal/littoral offshore shelf deposits - Lower Cambrian Gog Group, southern Rocky Mountains, Canada: Sedimentary Geology, v.52, p.155-182.

Klein, G. deVries, 1971, A sedimentary model for determining paleotidal range: Geological Society of America Bulletin, v.82, p.2585-2592.

Klein, G. deVries, 1975, Clastic Tidal Facies: Continuing Education Publication Company, Champaign, Illinois, 141p.

Klein, G. deVries, 1977, Tidal circulation model for deposition of clastic sediments in epeiric and mioclinal shelf seas: Sedimentary Geology, v.18, p.1-12.

Klitzsch, E., Harms, J.C., Lejal-Nicol, A., and List, F.K., 1979, Major subdivisions and depositional environments of the Nubia Strata, southwestern Egypt: American Association of Petroleum Geologists Bulletin, v.63, p.967-974.

Komar, P.D., 1976, Beach Processes and Sedimentation: Prentice-Hall Inc., New Jersey, 429p.

Kumar, N., and Sanders, J.E., 1974, Inlet sequences: A vertical succession of sedimentary structures and textures created by lateral migration of tidal inlets: Sedimentology, v.21, p.291-323.

Kumar, N., and Sanders, J.E., 1976, Characteristics of shoreface storm deposits: modern and ancient examples: Journal of Sedimentary Petrology, v.46, p. 145-162.

Kvale, E.P., and Archer, A.W., 1991, Characteristics of two Pennsylvanian age, semidiurnal tidal deposits in the Illinois Basin, U.S.A. in Smith, D.G., Reinson, G.E., Zaitlin, B.A., and Rahmani, R.A., eds, Clastic Tidal Sedimentology: Canadian Society of Petroleum Geologists, Memoir 16, p.179-188.

Kvale, E.P., Archer, A.W., and Johnson, H.R., 1989, Daily, monthly, and yearly tidal cycles within laminated siltstones of the Mansfield Formation (Pennsylvanian) of Indiana, Geology, v.17, p.365-368.

Kvale, E.P., Cutright, J., Bilodeau, D., Archer, A., Johnson H.R., and Pickett, B., 1995, Analysis of modern tides and implications for ancient tidalites, Continental Shelf Research, v.15, p.1921-1943.

McCroy, V.L.C., and Walker, R.G., 1986, A storm- and tidally-influenced prograding shoreline - Upper Cretaceous Milk River Formation of southern Alberta, Canada: Sedimentology, v.33, p.47-60.

McKee, E.D., 1965, Experiments on ripple lamination, in G.V. Middleton, ed., Primary Sedimentary Structures and their Hydrodynamic Interpretation: SEPM Special Publication 12, p.66-83.

Nio, S-D, and Yang, C-S., Diagnostic Attributes of Clastic Tidal Deposits: a review in Smith, D.G., Reinson, G.E., Zaitlin, B.A., and Rahmani, R.A., eds, Clastic Tidal Sedimentology: Canadian Society of Petroleum Geologists, Memoir 16, p. 3-28.

Ojakangas, R.W., 1985, Review of Archean clastic sedimentation, Canadian Shield: major felsic contributions to Turbidite and Alluvial Fan-Fluvial Facies Associations: Geological Association of Canada, Special Paper 28, p.23-48.

Open University Course Team, 1989, Waves, Tides, and Shallow-water processes: Pergamon Press, Oxford, 187p.

Parker, J.R., 1980, The Structure and Environments of Deposition of the Finmark Metasediments, Thunder Bay, Ontario: unpublished HBSc. thesis, Lakehead University, Thunder Bay, Ontario, 90p.

Pye, E.G., and Fenwick, K.G., 1965, Atikokan-Lakehead sheet, Kenora, Rainy River, and Thunder Bay districts, Ontario: Ontario Department of Mines, Geological Compilation Series, Map 2065, scale 1:253 440.

Reineck, H.E., and Singh, I.B., 1972, Genesis of laminated sand and graded rhythmites in storm-sand layers of shelf mud: Sedimentology, v.18, p.123-128.

Reineck, H.E., and Singh, I.B., 1975, Depositional Sedimentary Environments: Springer-Verlag, New York, 439 p.

Reineck, H.E., and Wunderlich, F., 1968, Classification and origin of flaser and lenticular bedding: Sedimentology, v.11, p.99-104.

Rezka, R., 1987, Shallow Marine, Storm Dominated Deposits of the Shebandowan-Wawa Greenstone Belt: unpublished HBSc thesis, Lakehead University, Thunder Bay, Ontario, 79p.

Schenk, P.E., 1975, Statistical Analysis of Sedimentary Sequences; Lab Exercises and Notes: Stratigraphy.

Shegelski, R.J., 1980, Archean cratonization, emergence, and redbed development, Lake Shebandowan area, Canada: Precambrian Research, v.12, p.331-347.

Simpson, E.L., 1991, An exhumed, Lower Cambrian tidal flat: the Antietam Formation, central Virginia, U.S.A. in Smith, D.G., Reinson, G.E., Zaitlin, B.A., and Rahmani, R.A., eds, Clastic Tidal Sedimentology: Canadian Society of Petroleum Geologists, Memoir 16, p.123-133.

Simpson, E.L., and Eriksson, K.A., 1990, Early Cambrian progradational and transgressive sedimentation patterns in Virginia: an example of the early history of a passive margin: Journal of Sedimentary Petrology, v.60, p.84-100.

Soegaard, K., and Eriksson, K.A., 1985, Evidence for tide, storm, and wave interaction on a Precambrian siliciclastic shelf: Journal of Sedimentary Petrology, v.55, p.672-684.

Stott, G.M., and Schnieders, B.R., 1983, Gold mineralization in the Shebandowan belt, and its relation to regional deformation patterns, in Colvine, A.C. ed., The Geology of Gold in Ontario: Ontario Geological Survey Misc. Paper 110, p. 181-193.

Swift, D.J.P., Freeland, G.L., and Young, R.A., 1979, Time and space distribution of megaripples and associated bedforms, middle Atlantic Bight, N.A. Atlantic shelf: Sedimentology, v.26, p.389-406.

Swift, D.J.P., Hudelson, P.H., Brenner, R.L., and Thompson, P., 1987, Shelf construction in a foreland basin: storm beds, shelf slope depositional sequences in the Upper Cretaceous Mesaverde Group, Book Cliffs, Utah: Sedimentology, v.34, p.423-457.

Tanton, T.L., 1938, Quetico sheet (east half) with marginal notes: Geological Survey of Canada, Map 432A.

Terwindt, J.H.J., 1988, Paleotidal reconstructions of inshore tidal depositional environments, in deBoer, P. ed., Tide-Influenced Sedimentary Environments and Facies, p.233-263.

Tessier, B., 1993, Upper intertidal rhythmites in the Mont-Saint-Michel bay (NW France): perspectives for paleoreconstruction: Marine Geology, v. 110, p.355-367.

von Brunn, V. and Hobday, D.K., 1976, Early Precambrian tidal sedimentation in the Pongola Supergroup of South Africa: Journal of Sedimentary Petrology, v.46, p.670-679.

Walker, R.G., 1984, Shelf and Shallow Marine Sands in Walker, R.G., ed., Facies Models 2[ed]: Geological Association of Canada, p.141-170.

Walker, R.G., Duke, W.L., and Leckie, D.A., 1983, Hummocky stratification: significance of its variable bedding sequence; discussion: Bulletin of the Geological Society of America, v.94., p.1245-1249.

Williams, G.E., 1989, Late Precambrian tidal rhythmites in South Australia and the history of the earth's rotation: Journal of the Geological Society of London, v.146, p.97-111.

Williams, G.E., 1991, Upper Proterozoic tidal rhythmites, South Australia: sedimentary features, deposition, and implications for the earth's paleo-rotation in Smith, D.G., Reinson, G.E., Zaitlin, B.A., and Rahmani, R.A., eds, Clastic Tidal Sedimentology: Canadian Society of Petroleum Geologists, Memoir 16, p.161-178.

Williams, H.R., Stott, G.M., Heather, K.B., Muir, T.L., and Sage, R.P., 1991, Wawa Subprovince, in Thurston, P.C., Williams, H.R., Sutcliffe, R.H., and Stott, G.M.,eds. Geology of Ontario: Ontario Geological Survey, Special Volume 4, Part 1, p.485-539.

Wunderlich, F., 1970, Genesis and environment of the "Nellenköpfchen-schichten" (lower Emsian, Rheiniandevon) at locus typicus in comparison with modern coastal environments of the German Bay: Journal of Sedimentary Petrology, v.40, p.102-130.

APPENDIX ONE

Statistical Analyses of Vertical Sequences

Statistical analysis of vertical sequences was conducted to determine if vertical changes in bed type or lithofacies reflect transitions that are random or non-random in nature. This in turn can indicate if vertical changes in lithofacies can be attributed to cyclical and/or predictable changes in the depositional environment.

UPWARD TRANSITION MATRIX

This matrix is a record of the number of times a bed or lithofacies in a vertical sequence is succeeded by another. This is done by counting the number of times there is a bed or lithofacies change. In the matrix the values in the columns give the number of times the beds/lithofacies in the row changes upwards to the bed/lithofacies itemized in the column.

PREDICTED RANDOM TRANSITION MATRIX

The values in this matrix are based on the assumption that there is a randomness to bed or lithofacies changes. This predicts the number of transitions from one bed/lithofacies to another.

$\mathbf{E = n_3 \times n_2 \;/\; n}$ where:

$\mathbf{E}$ = expected number of transitions
$\mathbf{n_2}$ = number of times 2 passes up into all other beds (**row total**)
$\mathbf{n_3}$ = number of times 3 passes down into all other beds (**column total**)
$\mathbf{n}$ = total number of transitions

MATRIX SHOWING RANDOM AND NON-RANDOM TRANSITIONS

Values in this matrix are determined by subtracting the values in the upwards transition matrix from the predicted random transition matrix. Positive values show that the transitions occur more frequently and are probably non-random. Values near zero indicate that the transition occur with less frequency and are representative of random events.

In the following matrices, the labels **1a** to **7** represent:

1a - massive sandstone beds
1b - parallel laminated sandstone beds
2 - flaser bedding
3 - wavy bedding
4 - lenticular bedding
5 - coarsely interlayered bedding
6a - massive siltstone beds
6b - parallel laminated siltstone beds
7 - mudstone

TIDAL FLAT ONE

Upward Transition Matrix

	1a	1b	2	3	4	5	6a	6b	7	Σ
1a	5	0	2	2	3	1	2	0	0	15
1b	1	0	0	0	0	0	0	0	0	1
2	4	0	1	0	4	0	0	0	0	9
3	0	0	2	0	1	1	0	0	0	4
4	2	0	4	2	0	1	0	0	0	9
5	3	0	0	0	1	0	0	0	0	4
6a	0	1	0	0	0	1	1	0	0	3
6b	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0
Σ	15	1	9	4	9	4	3	0	0	45

Predicted Random Transition Matrix

	1a	1b	2	3	4	5	6a	6b	7	Σ
1a	5.0	0.33	3.0	1.33	3.0	1.33	1.0	0	0	15
1b	0.33	0.02	0.2	0.09	0.2	0.09	0.07	0	0	1
2	3.0	0.2	1.8	0.8	1.8	0.8	0.6	0	0	9
3	1.33	0.09	0.8	0.36	0.8	0.36	0.27	0	0	4
4	3.0	0.2	1.8	0.8	1.8	0.8	0.6	0	0	9
5	1.33	0.09	0.8	0.36	0.8	0.36	0.27	0	0	4
6a	1.0	0.07	0.6	0.27	0.6	0.27	0.2	0	0	3
6b	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0
Σ	15	1	9	4	9	4	3	0	0	45

Matrix showing Random and Non-Random Transitions

	1a	1b	2	3	4	5	6a	6b	7	
1a	0	-0.33	-1.0	0.67	0	-0.33	1	0	0	
1b	0.67	-0.02	-0.2	-0.09	-0.2	-0.09	-0.07	0	0	
2	1	-0.2	-0.8	-0.8	2.2	-0.8	-0.6	0	0	
3	-1.33	-0.09	1.2	-0.36	0.2	0.64	-0.27	0	0	
4	-1.0	-0.2	2.2	1.2	-1.8	0.2	-0.6	0	0	
5	1.67	-0.09	-0.8	-0.36	0.2	-0.36	-0.27	0	0	
6a	-1.0	0.93	-0.6	-0.27	-0.6	0.73	0.8	0	0	
6b	0	0	0	0	0	0	0	0	0	
7	0	0	0	0	0	0	0	0	0	

TIDAL FLAT TWO

Upward Transition Matrix

	1a	1b	2	3	4	5	6a	6b	7	Σ
1a	8	4	5	0	0	2	3	0	0	22
1b	3	3	4	2	1	1	2	0	0	16
2	5	2	1	5	11	0	1	0	0	25
3	0	1	2	8	3	0	1	0	0	15
4	1	0	12	0	0	1	3	1	0	18
5	2	2	0	0	0	0	0	0	0	4
6a	3	2	1	0	3	0	0	1	0	10
6b	0	2	2	0	0	0	0	0	0	2
7	0	0	0	0	0	0	0	0	0	0
Σ	22	16	25	15	18	4	10	2	0	112

Predicted Random Transition Matrix

	1a	1b	2	3	4	5	6a	6b	7	Σ
1a	4.32	3.14	4.91	2.95	3.54	0.79	1.96	0.39	0	22
1b	3.14	2.29	3.57	2.14	2.57	0.57	1.43	0.29	0	16
2	4.91	3.57	5.58	3.35	4.01	0.89	2.23	0.45	0	25
3	2.95	2.14	3.35	2.01	2.41	0.54	1.34	0.27	0	15
4	3.54	2.57	4.01	2.41	2.89	0.64	1.61	0.32	0	18
5	0.79	0.57	0.89	0.54	0.64	0.14	0.36	0.07	0	4
6a	1.96	1.43	2.23	1.34	1.61	0.36	0.89	0.18	0	10
6b	0.39	0.29	0.45	0.27	0.32	0.07	0.18	0.04	0	2
7	0	0	0	0	0	0	0	0	0	0
Σ	22	16	25	15	18	4	10	2	0	112

Matrix showing Random and Non-Random Transitions

	1a	1b	2	3	4	5	6a	6b	7	
1a	368	0.86	0.09	-2.95	-3.54	1.21	1.04	-0.39	0	
1b	-0.14	0.71	0.43	-0.14	-1.57	0.43	0.57	-0.29	0	
2	0.09	-1.57	-4.58	1.65	6.99	-0.89	-1.23	-0.45	0	
3	-2.95	-1.14	-1.35	5.99	0.59	-0.54	-0.34	-0.27	0	
4	-2.54	-2.57	7.99	-2.41	-2.89	0.36	1.39	0.68	0	
5	1.21	1.43	-0.89	-0.54	-0.64	-0.14	-0.36	-0.07	0	
6a	1.04	0.57	-1.23	-1.34	1.39	-0.36	-0.11	0.82	0	
6b	-0.39	1.71	1.55	-0.27	-0.32	-0.07	-0.18	-0.04	0	
7	0	0	0	0	0	0	0	0	0	

TIDAL FLAT THREE

Upward Transition Matrix

	1a	1b	2	3	4	5	6a	6b	7	Σ
1a	11	2	0	1	0	1	0	0	0	15
1b	2	8	0	0	1	0	0	0	2	13
2	0	0	0	0	3	0	0	0	0	3
3	1	0	2	0	0	0	0	0	0	3
4	0	0	1	2	0	0	1	0	0	4
5	1	0	0	0	0	0	0	0	0	1
6a	0	1	0	0	0	0	0	0	0	1
6b	0	0	0	0	0	0	0	0	0	0
7	0	2	0	0	0	0	0	0	0	2
Σ	15	13	3	3	4	1	1	0	2	42

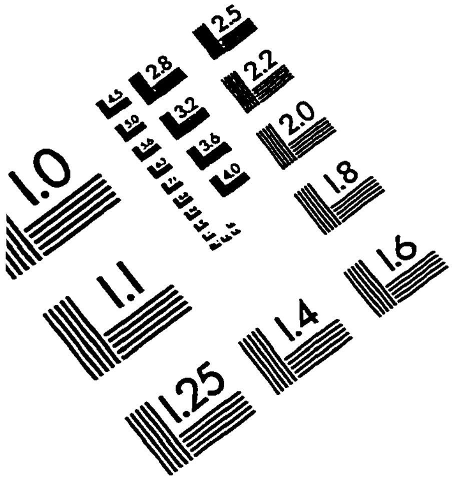
Predicted Random Transition Matrix

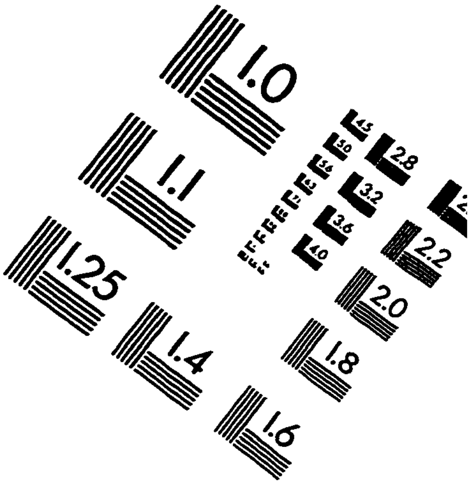
	1a	1b	2	3	4	5	6a	6b	7	Σ
1a	5.36	4.64	1.07	1.07	1.43	0.36	0.36	0	0.71	15
1b	4.64	4.02	0.93	0.93	1.24	0.31	0.31	0	0.62	13
2	1.07	0.93	0.21	0.21	0.29	0.07	0.07	0	0.14	3
3	1.07	0.93	0.21	0.21	0.29	0.07	0.07	0	0.14	3
4	1.88	1.24	0.29	0.29	0.38	0.1	0.1	0	0.19	4
5	0.36	0.31	0.07	0.07	0.1	0.02	0.02	0	0.05	1
6a	0.36	0.31	0.07	0.07	0.1	0.02	0.02	0	0.05	1
6b	0	0	0	0	0	0	0	0	0	0
7	0.71	0.62	0.14	0.14	0.19	0.05	0.05	0	0.1	2
Σ	15	13	3	3	4	1	1	0	2	42

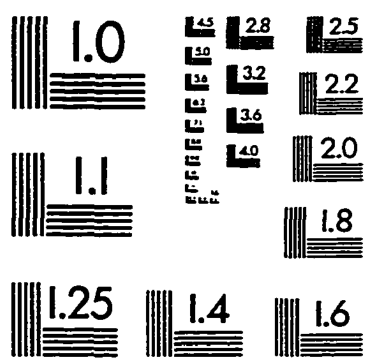
Matrix showing Random and Non-Random Transitions

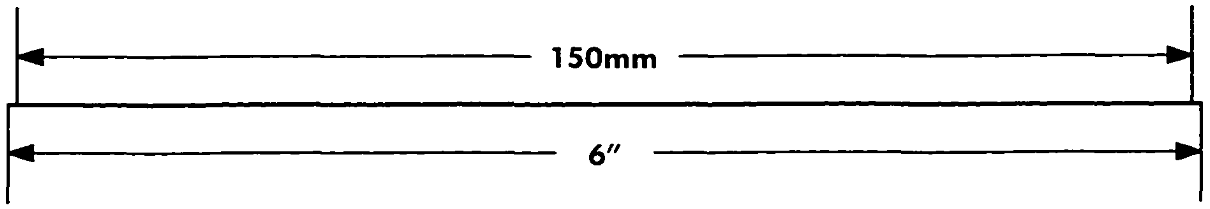
	1a	1b	2	3	4	5	6a	6b	7	
1a	5.64	-2.64	-1.07	-.07	-1.43	0.64	-0.36	0	-0.71	
1b	-2.64	3.98	-0.93	-0.93	-0.24	-0.31	-0.31	0	1.38	
2	-1.07	-0.93	-0.21	-0.21	2.71	-0.07	-0.07	0	-0.14	
3	-.07	-0.93	1.79	-0.21	-0.29	-0.07	-.07	0	-0.14	
4	-1.88	-1.24	0.71	1.71	-0.38	-0.1	0.9	0	-0.19	
5	0.64	-0.31	-0.07	-0.07	-0.1	-0.02	-0.02	0	-0.05	
6a	-0.36	0.69	-0.07	-0.07	-0.1	-0.02	-0.02	0	-0.05	
6b	0	0	0	0	0	0	0	0	0	
7	-0.71	1.38	-0.14	-0.14	-0.19	-0.05	-0.05	0	-0.1	

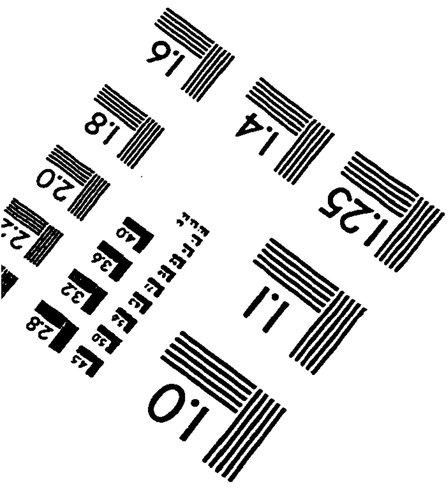
IMAGE EVALUATION TEST TARGET (QA-3)

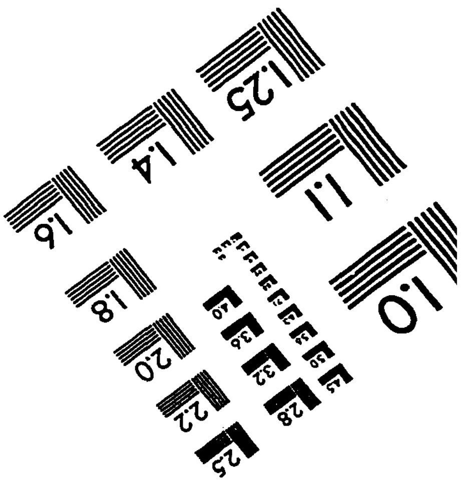












APPLIED IMAGE, Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989