SEDIMENTATION MODELS

for

GLACIAL DELTAIC SUCCESSIONS

in the

THUNDER BAY AREA

by

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ABSTRACT

The comparison of three mapped successions in northern Ontario to glacial deltas reviewed in the literature results in the definition of four end-member depositional environments for glacial deltaic sedimentation. Similar processes of sedimentation occur within two main glacial delta types, distal-fed, and ice-contact. Distal-fed deltas divide into nonglacial and ice-influenced. The other two end member types defined are subglacial and supraglacial ice-contact deltas.

Fine-grained laminated beds sedimented by interflows and overflows, as well as diamict and subaqueous outwash deposits underlie the glacial deltaic sequences. The prodelta region consists of multiple reverse-graded beds, massive units, and laminated sediments deposited from interflows and overflows, and minor rippled units indicating intermittent underflows. Within the delta front underflows deposited rippled and graded units, and occasionally planar cross-stratified units were sedimented by grainflows. The delta plain contains trough cross-stratified sands and gravels which infill multiple distributary channels. Dropstone deposition was restricted to the prodelta and delta front regions of ice-influenced distal-fed deltas, and ice-contact deltas.

Distributary mouth bars, large scale cyclic sedimentation, subaqueous outwash systems overlain by a glacial deltaic sequence, multiple processes of sedimentation within the delta front, and reworking of glaciogenic deposits have not previously been documented in glacial deltaic systems. These deposits and processes, as well as the inability to define the strandline position indicate glacial deltaic systems are complex.

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CHAPTER I

INTRODUCTION

Purpose

This thesis was undertaken to develop a model outlining processes controlling sedimentation within glacial deltas. Three different glacial deltas (KOA, Beardmore, Camp 25) were mapped in detail, and the depositional environment of each delta was determined. The processes operating within these depositional environments were compared and contrasted to glacial-deltaic sedimentation described by other authors. The model was developed from the similarities and differences of the three glacial deltas mapped and glacial-deltaic successions documented in the literature.

Method of Investigation

Vertical stratigraphic sections were mapped in detail, down to the millimetre scale where necessary. Facies changes were not only mapped in the vertical sequence, but also laterally. From the 3 successions, 80 samples were collected; 76 were analyzed for grain size, and 4 for lithological analysis of clasts. Grain size analysis involved dry sieving of the coarser (< 4 phi) material, and pipette analysis of the silt and clay size fraction (> 4 phi). Cumulative weight percent was plotted against the phi size for these samples. The mean and standard deviation were also calculated. Histograms of weight percent against phi size were plotted for 13 of the samples.

A total of 267 paleocurrent measurements were taken within the 3 successions mainly on ripple cross-laminated units. Some measurements were obtained from planar and trough cross-stratified beds, and rarely from imbricated clasts within coarse-grained units.

At the KOA succession a theodolite transit and chain were used to determine the relative elevations and lateral spacing of the stratigraphic sections logged. In both the

Beardmore and Camp 25 successions the upper boundary of the sections was at a constant topographic level. The bearing and distance between the sections was measured by compass and chain.

Location and Access

Three separate glacial-deltaic deposits formed during the meltback of the Laurentide ice sheet (see Figure 1.1) were mapped in the Thunder Bay to Longlac region. The first site is a deltaic succession located north of Beardmore on Highway 580 at a longitude of 87°59' and a latitude of 49°38'. Access is possible by two-wheel drive vehicle. Proceed east through Beardmore on Highway 11 to Highway 580. Turn left (north) and proceed for 2.6 km on Highway 580, to a dirt road on the left (south) side of the highway which leads directly to the succession.

The second delta is located north of Highway 11, on the Camp 25 road, approximately half way between Geraldton and Longlac, at a longitude of 86°46' and a latitude of 49°44'. The Camp 25 road is 15.6 km east along Highway 11 from Highway 584(access to Geraldton). Turn left (north) onto the Camp 25 road, and follow the road for 2.1 km to where it forks. Turn right (north) and the pit is directly on the left side (west) of the road.

The KOA delta was the third succession mapped, and is located approximately 2 km east of the city limits of Thunder Bay behind the KOA campgrounds. It has a longitude of 89°08' and a latitude of 48°03'. Access is possible by vehicle. Proceed east along Highway 11-17 to Highway 527 (Spruce River Road). Turn right (south) and follow the road for 0.5 km. Turn left (east) onto a dirt road. Follow the road for 1.1 km to the succession.

Topography

A brief description of the topography of the area near each delta will be outlined. The Beardmore succession is located in an east-west trending valley (see Figure 1.2). The

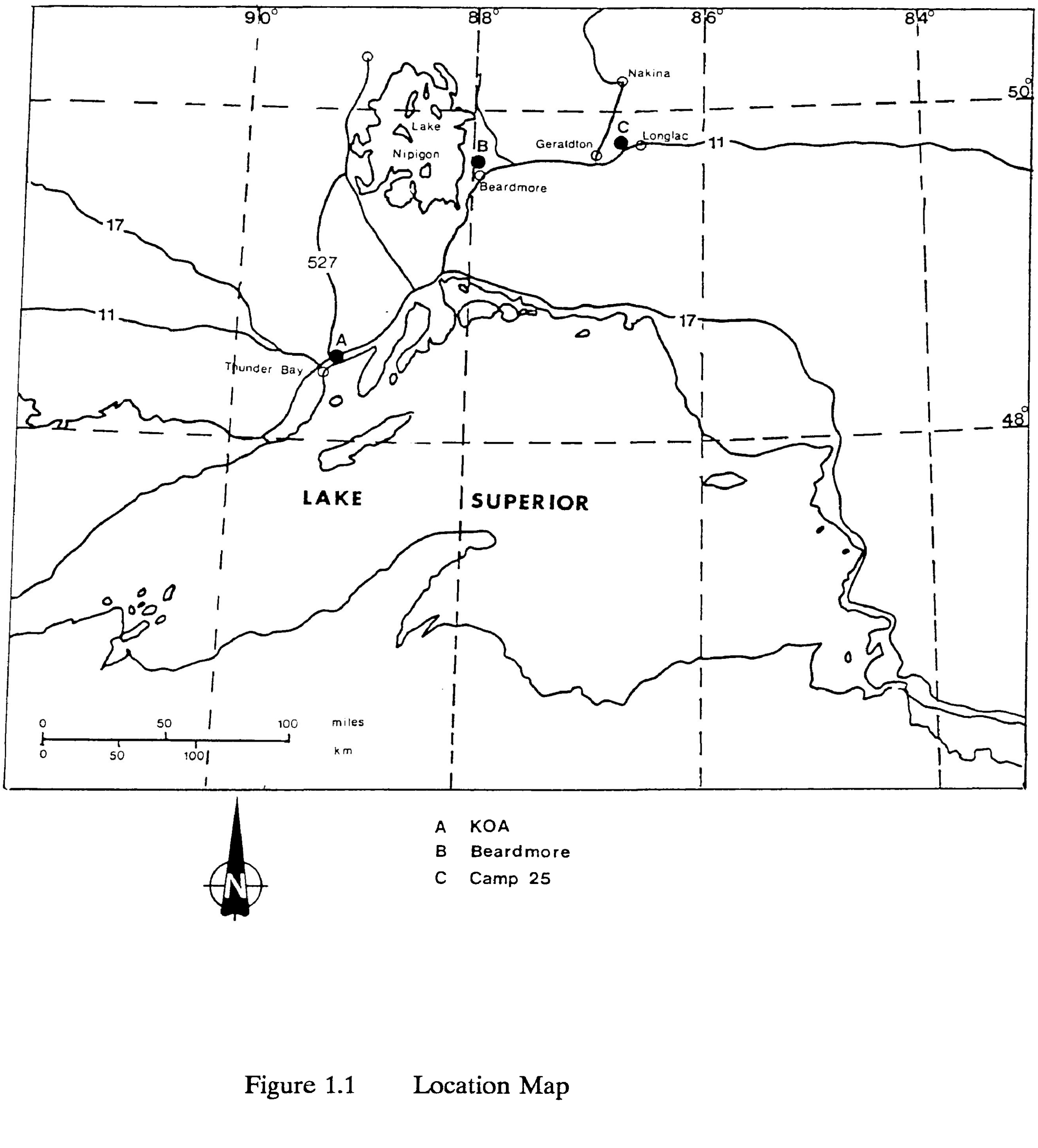


Figure 1.1 Location Map

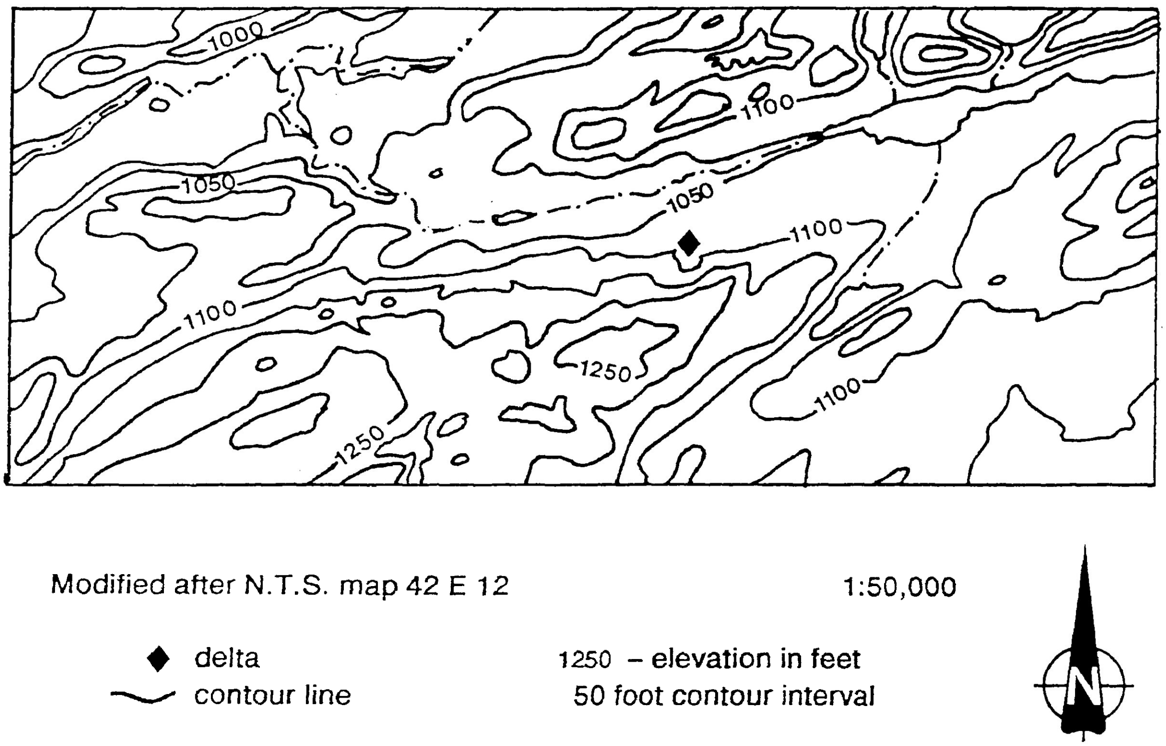


Figure 1.2 Topography near the Beardmore succession.

lowest part of this valley is occupied by a creek, fed from Standingstone Lake to the east. The top of the succession is near the 1100 foot contour line. To the southwest, the topography rises to over 1300 feet.

The Camp 25 succession is found in a pit excavated into the south side of a lobate, mound-like hill (Figure 1.3A). This lobe-shaped feature ends abruptly on the west, due to the presence of an erosional scarp cut by Lake Kenogamisis. The succession is found between 1100 and 1150 feet. Figure 1.3B (from preliminary map 3132, Kristjansson et al,1989) outlines the Quaternary geology of the area. This map indicates two esker systems directly south of the delta, which are trending to the west and disappear into Kenogamisis Lake. Directly to the north of the succession is another esker system which trends northeast to southwest, disappearing into the lobate shaped hill.

The KOA section is situated near the 950 foot contour line (Figure 1.4). To the north of the succession, hills up to 1400 feet are found. From the pit, the topography slopes down to Lake Superior.

Previous Work

Within the Beardmore to Longlac area, mapping of the engineering geology (Gartner,1980a; 1980b) and surficial geology (Zoltai,1965a; 1967) has been completed at a reconnaissance level. A detailed study of the Quaternary geology of the Wildgoose Lake Area was completed by Sado (1975). Closs and Sado (1981) studied the geochemistry of soils and glacial sediments near gold mineralization in the Beardmore-Geraldton area. From 1986 to present day, detailed mapping of the surficial geology in the area from Beardmore to Longlac has been undertaken by Kristjansson and Thorleifson. To date, preliminary maps of the Quaternary geology of the Wildgoose Lake-Treptow Area (Kristjansson et al,1988), Geraldton-Longlac Area (Kristjansson et al,1989) and gold grains in surface till (Kristjansson

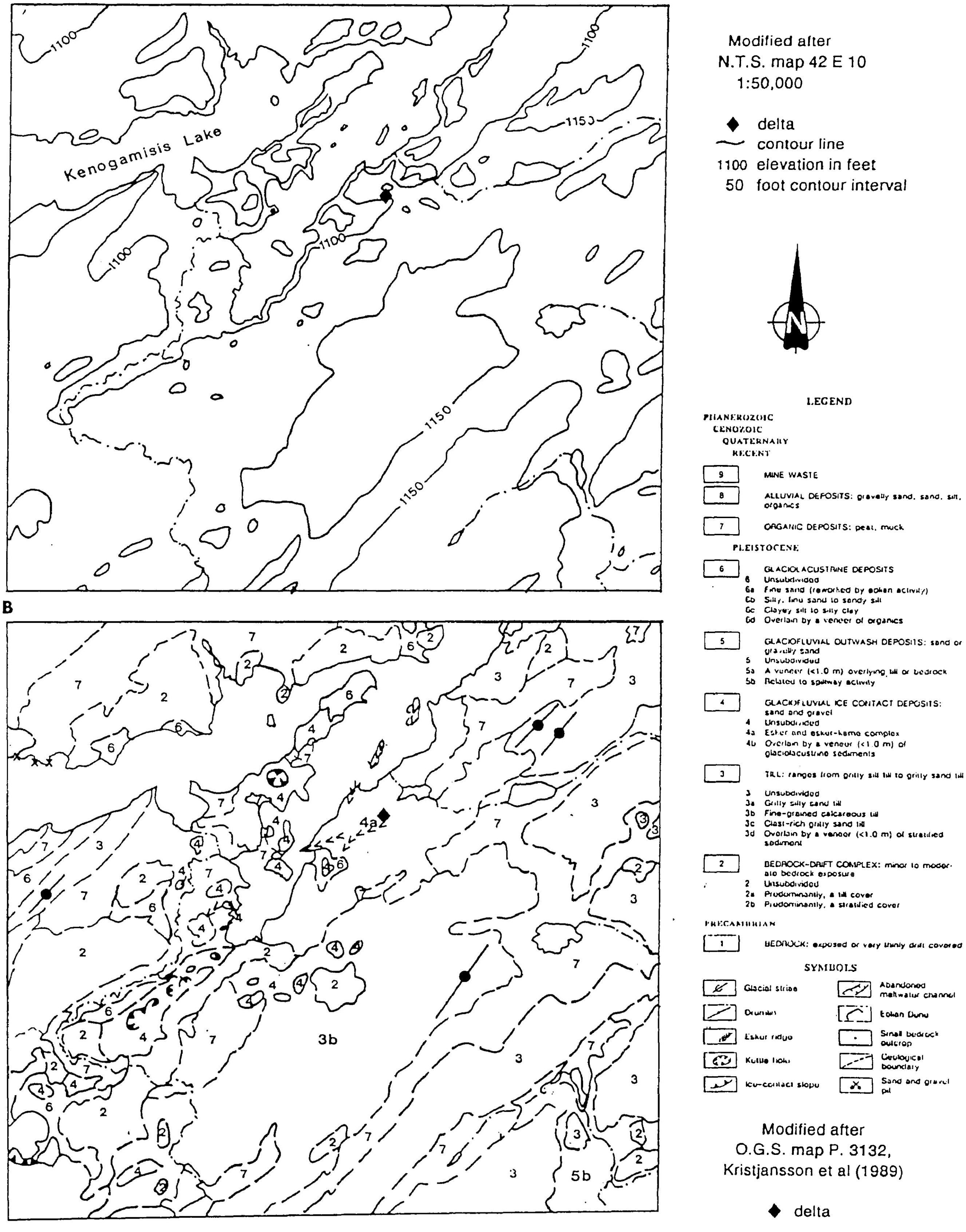


Figure 1.3 Topography (A) and Quaternary geology (B) surrounding the Camp 25 succession.

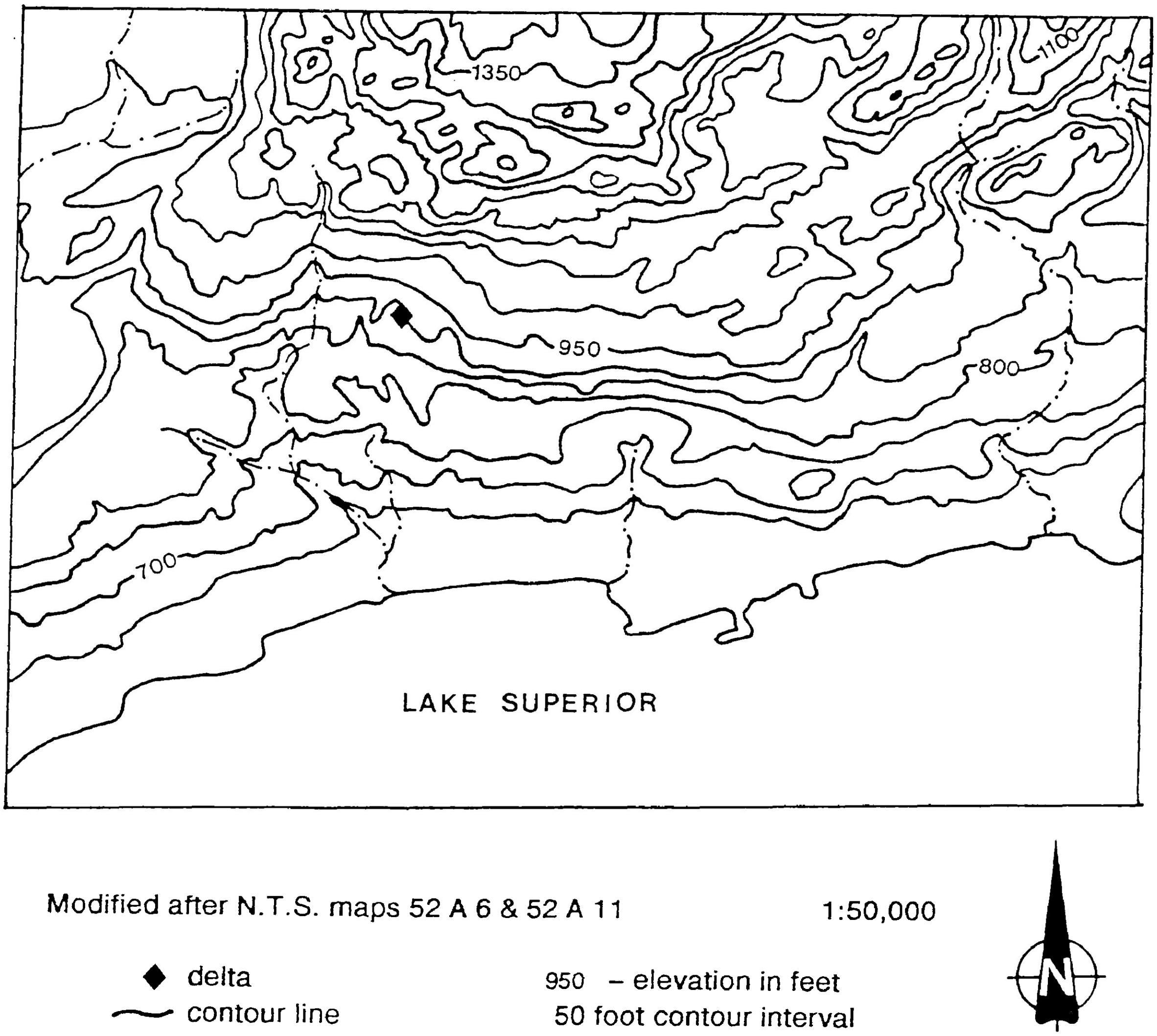


Figure 1.4 Topography near the KOA succession.

and Thorleifson,1987a), as well as a report on the visible gold content and lithology of till from overburden drill holes (Thorleifson and Kristjansson,1988a) have been published. Summaries of the initial findings of this study are found in Kristjansson (1986), Kristjansson and Thorleifson (1987b) and Thorleifson and Kristjansson (1988b). Calcareous tills within the area have been studied by Hicock (1987, 1988). A synopsis of gold exploration using tills has been presented by Hicock and Kristjansson (1989).

In 1929 Tanton produced a map of the surficial deposits of the Thunder Bay area. Since then, reconnaissance mapping of glacial features was completed by Zoltai (1963,1965a,1965b). Detailed studies within the Thunder Bay area include a report of the Quaternary geology of the City of Thunder Bay (Burwasser,1977) and a detailed study of the KOA succession by Schuster (1985). Recently, Phillips and Fralick (submitted) have studied and interpreted glacial deposits on the flanks of Mt. Baldy, northeast of Thunder Bay.

History of Glaciation

The deglaciation history of the Lake Superior basin and the north-northwestern shore of Lake Superior has been the subject of numerous papers (for example Zoltai,1963; 1965b; Farrand,1969; Dell,1974; Saarnisto, 1974; Burwasser,1977; Clayton,1983; Drexler et al,1983; Teller and Thorleifson,1983; Farrand and Drexler,1985; and Teller,1985). Not all authors agree on the position and time frame of ice fronts within the basin and surrounding areas. Table 1 summarizes the conflicting data regarding ice front positioning. The authors have determined the relative chronology of the deglaciation history of the area based upon observed morphological features such as end moraines, strandlines and other glacial deposits indicating ice marginal positions, as well as glacial lake deposits. Absolute time-scale radiocarbon dates from wood and peat were then used to assign ages to the deglaciation history.

As outlined by Schuster (1985) the KOA succession was probably deposited during the

TABLE 1.1

DEGLACIATION HISTORY of LAKE SUPERIOR BASIN

Lake Superior Basin		North-Northwestern Shore of Lake Superior
Farrand (1969), Saarnisto (1974), Phillips (1980)	Teller & Thorleifson (1983), Clayton (1983), Drexler et al (1983) Teller (1985), Farrand & Drexler (1985)	Zoltai(1963, 1965b), Burwasser (1977)
Time before present	Time before present	Time before present
		Prior 12000 - advance of Patricia ice mass
11500 - deglaciation began in SW corner of Lake Superior basin, Glacial Lake Duluth	11500 - Superior lobe covered most of the present day shoreline of Lake Superior	
11000 - rapid retreat of ice sheet - formation of eastern outlet for Glacial Lake Duluth	11000 - Superior lobe began to retreat opening up SW and S portions of basin	11000 - Patricia ice mass began retreat - Brule Creek Moraine deposited
11000 to 9500 - ice margin retreated, series of Post-Duluth lake stages	10700 - ice margin retreated almost to northern shore of Lake	11000 to 10200 - Hudson Bay lobe advance, Dog Lake Moraine deposited - Superior lobe advanced, Superior phase destroyed by overriding Marks phase readvance, Marks Moraine, Murillo Drumlin Field, Mackenzie Moraine deposited - Glacial Lake Kaministikwia formed adjacent to ice margin
	9800 - Superior lobe readvanced to cover almost all of the basin except SW section	10200 - Superior lobe begins retreat
9500 - rapid retreat of ice margin, Glacial Lake Minong (opening of entire lake)		9500 - Superior basin ice-free - Intola Moraine deposited - Kaministikwia River Spillway opened from Glacial Lake Kaministikwia
	9000 - ice margin retreated to northernmost shorelines of Lake Superior	
8000 - Houghton stage - low lake level		
5500 - Nipissing stage - higher lake level		

Minong Stage, when the ice retreated from Lake Superior, between 9000 and 9500 years before present.

Documentation of glaciation within the Beardmore Geraldton area has not received as much attention as the Lake Superior Basin. Zoltai (1967) outlined the following glaciation sequence for the area from Lake Superior to north of the Nakina moraine, bounded on the west by Lake Nipigon and extending 30 km past the town of Longlac in the east. The earliest ice movement was to the south or southwest. After this glacial phase waned, another advance took place. At this time Glacial Lake Minong occupied the Lake Superior basin. Post-Minong Lake stages inundated regions as far north as the Nakina Moraine. The northern part of this lake was separated from the Lake Superior basin due to differential uplift and became Lake Nakina. As withdrawal of ice resumed, small temporary lakes eventually coalesced and joined with Glacial Lake Barlow-Ojibway to the east. Kristjansson and Thorleifson (1987b) have recorded a glacial advance to the south and a more recent glacial readvance to the southwest in their detailed mapping from Beardmore east to Longlac.

CHAPTER II

DESCRIPTION OF LITHOFACIES ASSOCIATIONS

INTRODUCTION

This chapter outlines the lithofacies associations delineated within the three glacial deltas mapped; the Beardmore, Camp 25 and KOA successions. The lithofacies associations in each delta are described in detail. The stratigraphic framework of the lithofacies associations within each deltaic sequence are also reviewed.

BEARDMORE SUCCESSION

(a) INTRODUCTION

Detailed mapping (down to the millimetre scale) was carried out on 5 sections, totalling 21.68 metres. This involved measuring 70 paleocurrent directions, as well as collecting 10 samples. Of these ten samples, 8 were analyzed for grain size, and 2 were examined for lithological types. Figure 2.1 (see back pocket) is a detailed (1 cm = 10 cm) diagram of the sections. The contact between fine-grained units of silty-fine sand to fine sand and underlying coarser grained planar cross-stratified or deformed beds was at the same elevation from section 1 through section 5. This contact was the datum used for the sections present in Figure 2.1.

Four lithofacies associations were outlined by combining individual beds. The four lithofacies associations (L.A.) comprising the Beardmore succesion are: reverse-graded L.A.; rippled L.A.; massive L.A.; and planar cross-stratified L.A. The reverse-graded L.A. is dominated by reverse-graded beds composed of clay to fine sand. A general paleocurrent trend to the east was obtained from measurements on minor rippled beds within the L.A. The rippled L.A., composed mainly of fine sand, conformably overlies the reverse-graded L.A. Massive and graded beds are interbedded with the rippled beds. The overall paleocurrent trend for this L.A. is to the northeast. Coarser grained, medium to coarse sand, planar cross-stratified beds dominate the overlying unit, with an erosively scoured contact between the two L.A.s. This lower planar cross-stratified L.A. reveals paleocurrent trends to the north. The reverse-graded L.A. appears again in limited extent in the western sections interbedded with the planar cross-stratified units and associated with massive beds. With the exception of the extreme eastern end of the succession, the appearance of the massive L.A. divides the planar L.A. into lower and upper divisions. The massive units exhibit the largest range in grain size, and many lenses and pockets of diamicts are found within them. The upper planar cross-stratified beds trend to the north-northeast.

As can be seen in Figure 2.1, it is possible to establish a bottom contact for the reverse-graded lithofacies association, as deposits were logged beneath it. However, not enough material was recorded to delineate another lithofacies association beneath the reverse-graded beds. Deformed and contorted beds, ranging from silt to coarse-grained sand, are found in the eastern part of the succession. Planar cross-stratified pebbly gravel (trending east) and medium sands are found in the middle and to the west (section 2). Mapping to the greatest depth was carried out on the westernmost section. The lowest units here are fine-grained massive and ripple beds with paleocurrents trending southwest. Above these lie planar cross-stratified fine to coarse sands, showing paleocurrent trends of 165°, and 146°.

(b) LITHOFACIES ASSOCIATIONS

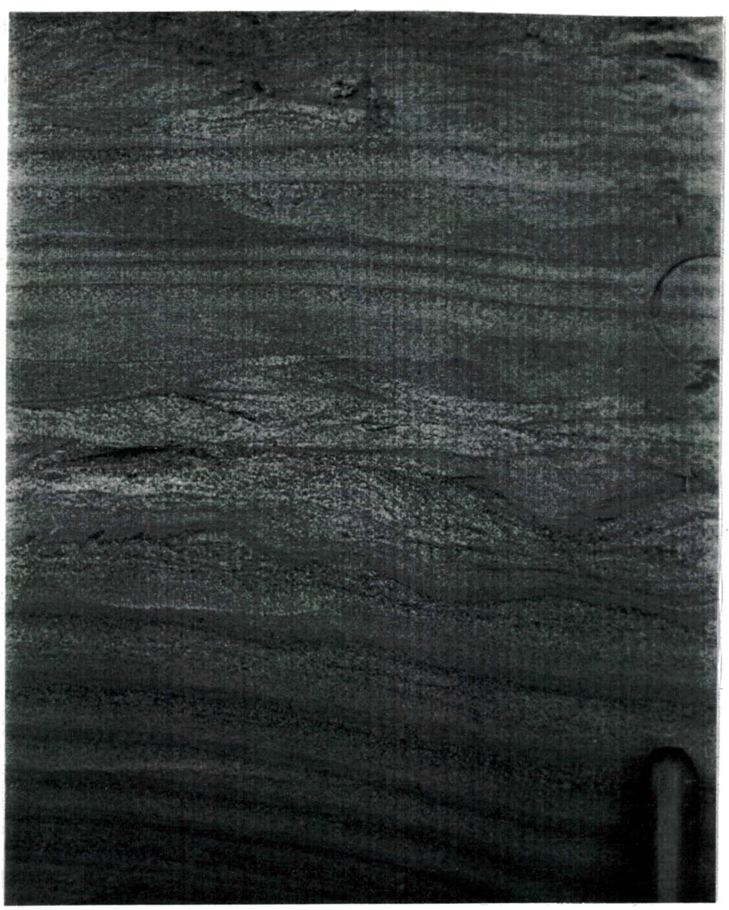
The following text describes in detail the characteristics of each of the four lithofacies associations (L.A.).

(i) Reverse-Graded Lithofacies Association

Thin, reverse-graded beds, which dominate this association, range in grain size from clay to medium sand (Figure 2.2). Overall average bed thickness is 2.3 cm. Reverse-graded beds of silt to fine sand, are the most abundant, and exhibit an average thickness of 1.9 cm.

Figure 2.2 Multiple reverse-graded beds.

Figure 2.3 Reverse-graded units interbedded with rippled and massive beds.



Reverse-graded beds of silt to medium sand, are the next most abundant, and average 2.6 cm thickness. Many of the thicker reverse-graded beds feature minor ripple development near their tops, while others appear wavy due to their draping underlying ripples. Figure 2.4A shows 3 plots of grain size analysis on samples taken from the bottom, middle and top of a representative reverse-graded bed. The average grain size coarsens from plot C to plot A (4.63 phi to 2.35 phi).

Minor massive beds (average bed thickness 2.5 cm), composed of silty-fine sand, and fine sand were found interbedded with the reverse-graded units. One thicker (9 cm) massive bed of silty clay was found at the bottom of the L.A. Only one deformed bed of clay and fine sand was found. It is located above the thicker massive bed.

Rippled as well as wavy beds that are not reverse-graded, are also found, interbedded with the reverse-graded beds (Figure 2.3). Again, the wavy beds appear to develop due to draping on underlying ripples. These wavy beds are thin, 1.5 cm average thickness, and are fine-grained clay to silty-fine sand. The rippled units average thicker beds (4 cm average) and are a bit coarser grained than the wavy beds, ranging from silty-fine sand to medium sand.

A few atypical beds are found within the L.A., at the western end of the succession. Two wedges, one composed of planar cross-stratified medium/coarse sand, and the other a diamict, occur within rippled and graded beds. Definite traction, saltation and suspension populations are evident in the grain size plot of the planar cross-bedded sand. Note the difference between the planar cross-bedded plot, and the diamict grain size plot (Figure 2.4B). The diamict is very poorly sorted, and shows no development of traction, saltation or suspension populations. Between these 2 wedges, 4 normal graded beds are found. They grade from silty-fine sand to fine sand, or clay, and average 2 cm thickness.

Most contacts within this L.A. are conformable. Both of the coarser grained wedges

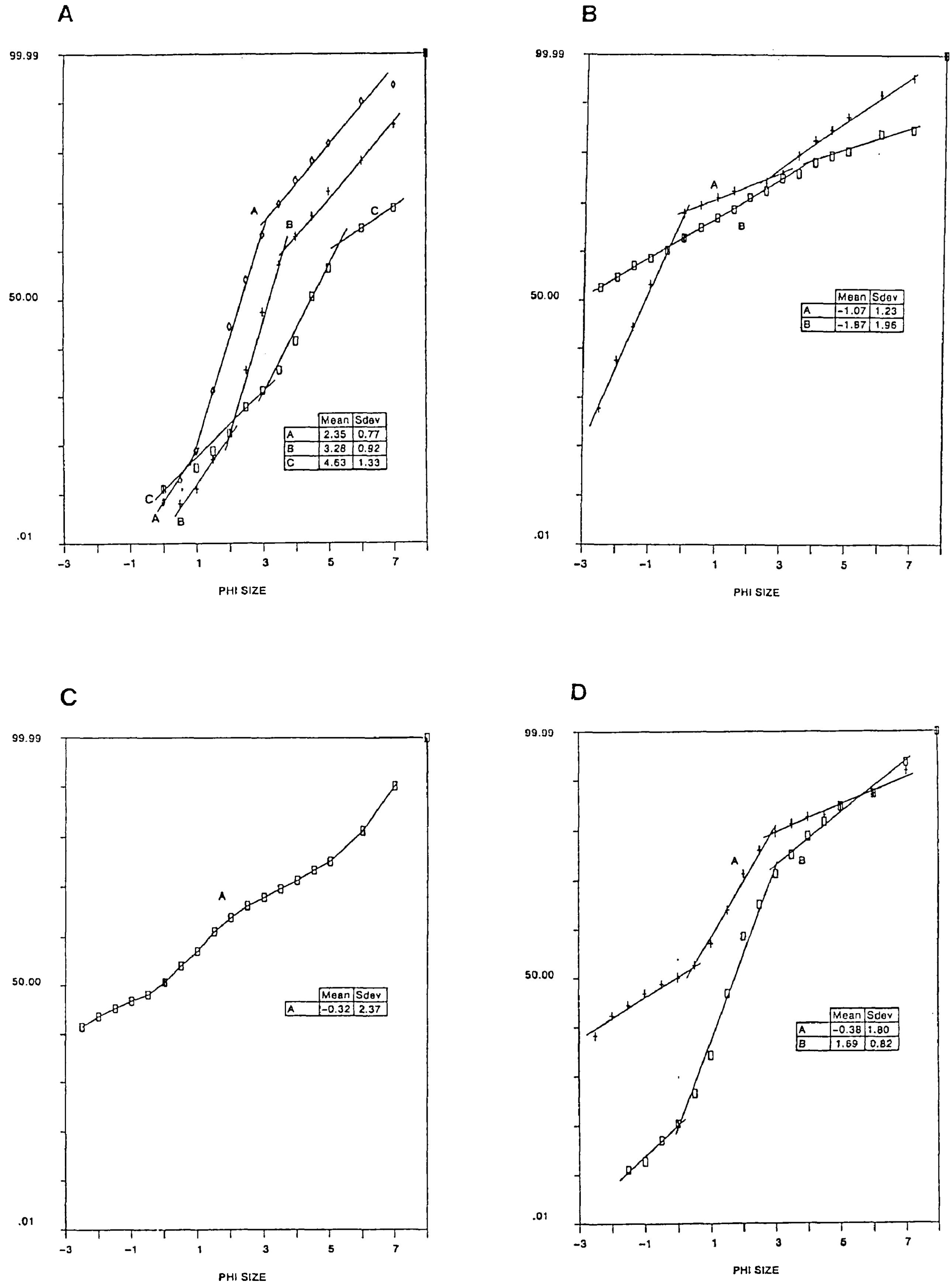
Figure 2.4 Grain size distributions.

A. Bottom (C), middle (B) and top (A) of typical reverse-graded bed.

B. Planar cross-stratified (A) and diamict (B) atypical beds within reverse graded L.A.

C. Diamict from massive L.A.

D. Planar cross-stratified beds from planar cross-stratified L.A.


A
99.99
50.00
.01
-3
-1
1
3
5
7
PHI SIZE
A
B
C
Mean Sdev
A 2.35 0.77
B 3.28 0.92
C 4.63 1.33
B
Mean Sdev
A -1.07 1.23
B -1.87 1.96
C
Mean Sdev
A -0.32 2.37
D
Mean Sdev
A -0.38 1.80
B 1.69 0.82

mentioned appear to occupy scours in the finer grained units below.

(ii) Rippled Lithofacies Association

The dominant ripple cross-stratified beds within this L.A. vary from 1.5 to 10 cm in thickness, averaging five centimetres. The thicker beds are associated with fine sand, while silty-fine sand forms the thinner beds. The cross-stratification varies from indistinct in some beds, to well defined in others. The outline of the asymmetrical ripple's upper surface tends to be slightly darker, and finer grained, than the material making up the middle of the ripple. Ripple-drift cross-lamination of both types A and B, as defined by Jopling and Walker (1968) is found in fine sand beds, averaging 10 cm and ranging from 7 to 13 cm. Frequently associated with the rippled beds are wavy finer grained beds. When composed of fine sand, or silty-fine sand, these beds average 3 cm in thickness. However, finer grained silty laminae millimeters thick repeatedly appear to be draped over the rippled sequences below. The rippled beds often show an erosive bottom contact.

Both massive and graded beds are present in this lithofacies association. The massive beds range from 1 to 11 cm thick, and vary in grain size from silt to fine/medium sand. The massive beds are interbedded with the rippled units, and often show conformable contacts, unless they are much coarser grained than the units below. In this case, the coarser units tend to load into the finer grained beds below. Isolated ripples appear in some of the massive beds. Normal graded beds average 2 cm, and show only a slight grain size decrease towards the top of the bed. Most of the graded beds range from silty-fine sand to silt at the top.

Parallel-laminated beds range from 4 to 21 cm in thickness and are dominated by either a fine/medium or medium/coarse sand component. These beds often have an erosive bottom contact, and appear at the top or bottom of the lithofacies associations. They are not commonly found interbedded with the rippled beds, as the massive and graded beds are.

Only one planar cross-stratified bed occurs in the L.A. It is found at the bottom of the lithofacies association, and is composed of pebbly sand.

(iii) Massive Lithofacies Association

The distinctive features of this lithofacies association are the wide range of grain size (silt to pebbly sand) and the lateral discontinuity of beds. Beds tend to wedge or pinch out within the face of individual sections logged (each approximately 1 m wide).

Massive beds range from 0.5 cm to 15 cm in thickness and exhibit grain sizes from silty-fine sand to medium-coarse sand. Small pebbles, as well as coarse sand stringers are often found within the massive beds. As well, pockets, lenses and wedges of diamict, composed of silty-fine sand to pebbly sand are found within the massive sands. Diamict is a non-genetic term defined by Eyles et al (1983) to refer to any poorly sorted clast-sand-mud admixture regardless of depositional environment. According to this definition the massive beds described above which contain pebbles or coarse sand stringers, could also be called diamict. The massive beds have been defined as such because generally they are well sorted and contain the pebbles or coarse sand stringers at restricted intervals or horizons within the bed. The diamict units on the other hand may show a similar range in grain size, yet they are poorly sorted throughout the unit. The massive and diamict beds have been assigned these two terms to indicate sorting differences noted when the units were mapped. Figure 2.4C is a grain size plot of a sample of diamict from this lithofacies association. It shows the relatively poor sorting of the diamict, as well as the lack of distinction of definite traction, saltation and suspension populations. Where the massive beds are coarser than the underlying beds, load structures develop. Otherwise, bottom contacts of the massive beds are conformable.

Interbedded with the massive beds are relatively thin (1 to 3 cm) beds of coarse sand or pebbly coarse sand exhibiting lamination. These beds are often erosively scoured or loaded into underlying massive beds. Some rippled beds found in this lithofacies association also exhibit erosive bottom contacts with the massive beds. Grain size of the rippled beds ranges from fine to medium sand, while beds range from 2 to 17 cm in thickness. Many of the rippled sand beds contain stringers of coarser material within them, and the occasional small pebble. Minor wavy silt laminae appear draped over the rippled beds. Two thick (7 and 9 cm) graded beds are found within this lithofacies association, yet their grain size differs considerably; one grading from coarse to medium sand, while the other grades from silty-fine sand to silt.

In section 4, the beds become better sorted towards the massive/planar L.A. contact. Near the bottom of the massive unit, massive silty-fine sand beds contain abundant lenses of diamict. It is difficult to distinguish the boundaries of the massive beds, and the diamict. As you proceed upwards through the L.A., the beds appear to become more distinctive, and definite horizons are developed. At this point, massive fine sand beds, are interbedded with pebbly sand. These massive beds contain occasional pebbles. The contacts/boundaries of the massive, and pebbly sand beds still show some intermixing. However, at the top of the succession, definite beds of rippled fine sand and pebbly sand can be seen.

(iv) Planar Cross-Stratified Lithofacies Association

The planar cross-stratified units range in grain size from fine sand to cobbly pebble gravels. The beds within the L.A. may be divided into 'sets' as defined by McKee and Weir (1953). More than one set was found in all sections except in the lower planar cross-stratified L.A. of sections 2 and 4. Set boundaries within the sections were marked by erosional surfaces or thin finer grained massive units. Within all of the upper planar cross-stratified L.A., and section 1 of the lower planar cross-stratified L.A., set boundaries dip, generally greater than 10 degrees. The dipping boundaries could be called third-order surfaces as defined by Miall (1988).

Within each set, beds are conformable, and generally exhibit small ranges in grain size. Occasionally, pebble lags exist at the bottom of a set, as in the uppermost sets which are dominated by pebble gravels and cobbly pebble gravels. The clasts in the lags are prominently imbricated, making it possible to obtain paleocurrent measurements from them ($\bar{x}$ = 341°). A lithological analysis of clasts taken from a cobbly pebble gravel shows a dominance (71%) of metasediments/metavolcanics. Felsic intrusives make up 18%, limestones 5%, iron formation 4% and diabase 2%.

In the upper planar cross-stratified L.A. the average grain size of the sets coarsens as the top of the sections are approached. Samples A and B in Figure 2.4D were taken from the uppermost set and second set, respectively, in section 2. The two plots indicate definite traction, saltation and suspension modes, and that sample A is formed of coarser material than sample B.

Minor massive beds are rare. They are very thin (1 cm) and composed of massive fine or medium sand. There is one thicker massive medium-coarse sand bed which contains the occasional pebble or cluster of smaller pebbles within it. These massive beds drape the thicker planar cross-stratified beds.

(c) GEOMETRY OF SUCCESSION

A fence diagram showing the actual field position of the succession is shown in Figure 2.5. The bottom reverse-graded L.A. is thickest in the west, and thins slightly to the east. The overall paleocurrent trend of the L.A. is generally to the east-northeast (068°). Generally, the overlying rippled L.A. shows a reverse trend, and thickens to the east. The overall paleocurrent trend is 071°. The sands in the rippled L.A., are generally coarser than the underlying reverse-graded L.A., and usually have erosive contacts. The lower planar cross-stratifed L.A. can be identified only in sections 1 through 4, as no division can be made

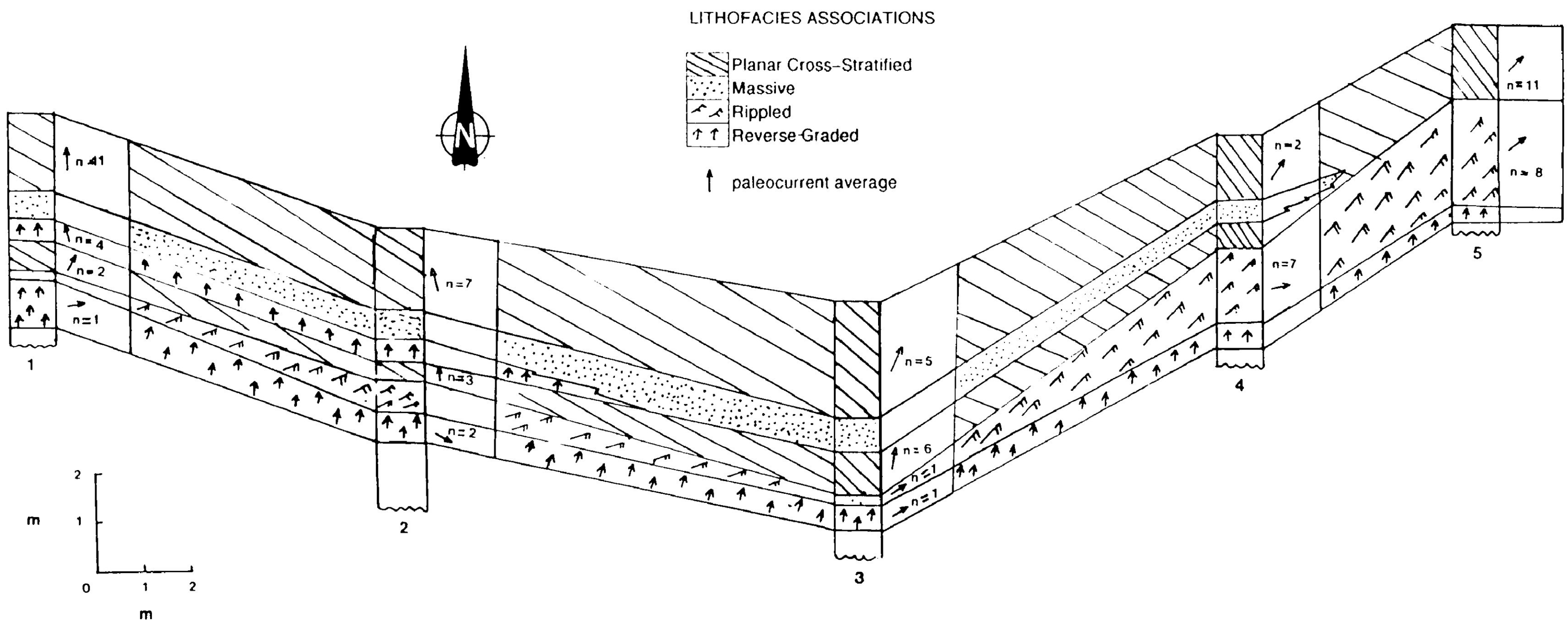


Figure 2.5 Fence diagram of lithofacies associations within the Bearmdore succession. Lithofacies associations are internally heterogeneous and are named after the dominant sedimentary structure present. See Figure 2.1 for further detail.

between the lower and upper planar L.A. in section 5. The material in this L.A. is coarser grained, and erosive, scoured contacts are common. The overall trend of the L.A. is 007°. The upper reverse-graded L.A. is found only in the 2 western most sections, and is approximately the same thickness in both sections. This L.A. wedges out between sections section 2 and 3. The overall paleocurrent trend is 346°. Like the underlying reverse-graded units, the massive L.A. does not extend entirely across the area either, as it pinches out between sections 4 and 5. It is thickest in section 3. This is overlain by the upper planar L.A. , which again has an erosive, scoured contact. There is no general trend in thickness. Overall paleocurrent trend is 015°. The individual section trends appear to indicate a lateral divergence from west to east: 355°, 345°, 024°, 040°, and 042°.

CAMP 25 SUCCESSION

a) INTRODUCTION

Eight stratigraphic sections totalling 54.85 m were logged with lithofacies a millimetre or more thick noted. Six samples were collected: five for grain size analysis, the sixth for lithological analysis. A total of 113 paleocurrent measurements were obtained. Figure 2.6 (see back pocket) is a detailed, 1 cm = 10 cm, diagram of the measured sections. The sections within the Camp 25 succession did not contain a bed or horizon which could be traced and used as an internal datum. Therefore, the elevation at the top of each section was used as the datum. The detailed sections hung from this datum may be simplified into four lithofacies associations (L.A.): massive silt, rippled sand, trough cross-stratified sand and diamict-bearing, as shown in Figure 2.6. Numerous faults located in the sections suggests beds within the lithofacies associations have been displaced relative to their site of deposition. As a result, it is not possible to determine whether paleocurrent readings taken in the field show the true current direction which existed during deposition. Therefore, general current trends for each L.A. were not calculated.

The massive silt L.A. appears lowest in the succession, and was found at the base of the three northerly sections. Minor rippled fine-grained units accompany the massive silt beds which dominate this L.A. Ripple-drift cross-lamination prevails within the overlying L.A. Overall, the rippled sand L.A. is slightly coarser grained than the massive L.A. Angular metasedimentary clasts of various sizes are imbedded within units in both the massive and rippled L.A.s. Coarser grained trough cross-stratified beds erosively scour into the underlying rippled L.A. Finer grained rippled, massive and low-angle plane-laminated beds make up the remainder of this L.A. The diamict-bearing L.A. has a restricted occurrence, being found in only 2 southerly sections. This L.A. is similar to the trough cross-stratified L.A. However, diamict units are interbedded with the trough cross-stratified, rippled and massive beds. The diamict units often form wedges, and exhibit a wide range of grain sizes within the same bed. The clasts within the diamicts are primarily Paleozoic limestone.

b) LITHOFACIES ASSOCIATIONS

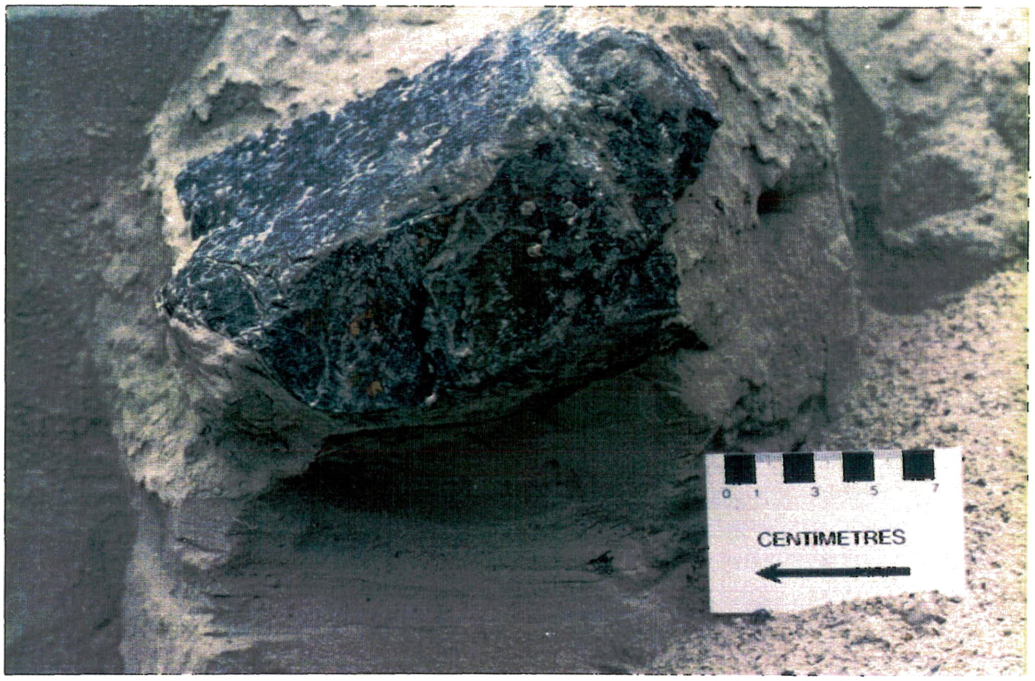
The following text describes the main characteristics of the four lithofacies associations.

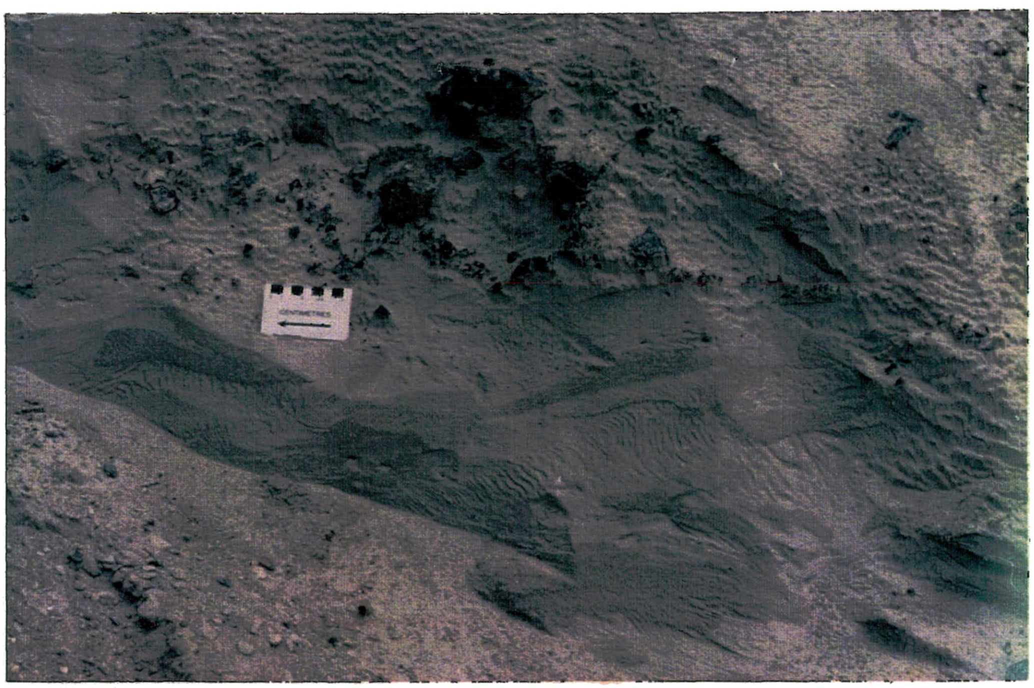
(i) Massive Silt Lithofacies Association

Thick massive beds within this L.A. are composed primarily of silt, and occasionally are formed of slightly coarser material such as silty-fine sand or fine sand. The beds range from 5 cm to 1 metre in thickness, averaging 37 cm. Angular metasedimentary clasts, from 1 cm to 20 cm in diameter, are imbedded in many of the massive units (Figure 2.7). Isolated ripples develop beneath or around the larger clasts. An atypical massive bed containing minor wedges of diamict and deformed clay laminae was found in the northernmost section. Further north, this atypical unit shows clustering and irregular layering of the dropstones (Figure 2.8).

Figure 2.7 Angular metasedimentary dropstone. Note ripple development beneath clast.

Figure 2.8 Layered and clustered dropstones of atypical unit overlying deformed rippled silts.


0 1 3 5 7
CENTIMETRES



Rippled beds ranging from silt to fine sand are associated with the massive beds. The rippled beds exhibit thicknesses from 3 to 51 cm, averaging 12 cm, and often have internal laminae highlighted by heavy mineral rich layers. They are occasionally draped by wavy silty-fine sand. Angular metasedimentary clasts are present throughout the rippled beds. In addition to the metasedimentary lonestones, a subround 40 cm diameter granitic boulder was also imbedded in the rippled fine-grained sands. Laminae below these clasts are deformed indicating the lonestones are of a dropstone origin. The rippled unit beneath the atypical bed shows deformed lamination (Figure 2.8).

Generally, sharp and conformable contacts are found between the rippled and massive beds. Gradational, conformable contacts occur between stacked massive beds.

The location of the rippled beds relative to the massive beds differs in the two northern sections (7 and 8 of Figure 2.6). In the northernmost section, the rippled and massive beds are intercalated, whereas the rippled beds in the other section are grouped together and are situated between the thicker massive beds.

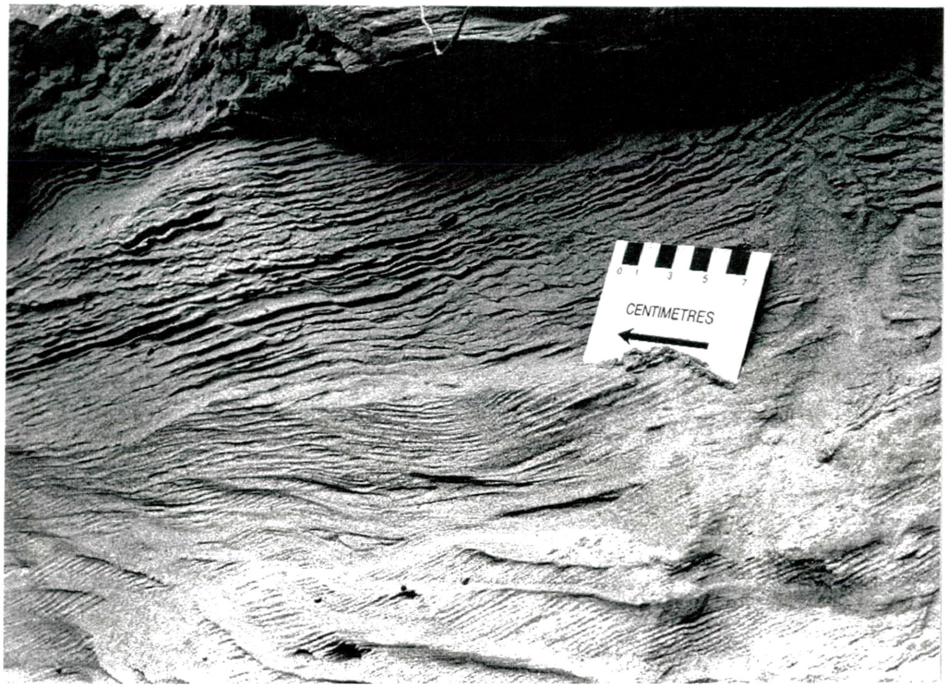
(ii) Rippled Sand Lithofacies Association

Ripple-drift cross-lamination dominated by type A, and to a lesser extent type B (as defined by Jopling & Walker 1968) is composed primarily of silt to fine sand. Laminae within silty-fine sand and fine sand beds are often delineated by heavy minerals, and are frequently deformed or distorted (Figures 2.9, 2.10, and 2.11). Angular metasedimentary clasts ranging in diameter from 1 cm to 28 cm were imbedded in the rippled units. Plot A in Figure 2.12A shows the well developed traction, saltation and suspension populations of a sample taken from a ripple-drift cross-laminated bed. The average grain size of the sample is 3.38 phi, very fine sand. The average thickness of the ripple-drift cross-laminated beds is 11 cm, with bed thicknesses from 2 cm to 78 cm being recorded. Thinner, ripple cross-laminated beds are

Figure 2.9 Succession of ripple-drift cross-laminated fine sands. Note deformation of units near top of photo.

Figure 2.10 Deformed beds near the top of the succession.

Figure 2.11 Distortion and deformation within laminae of individual beds.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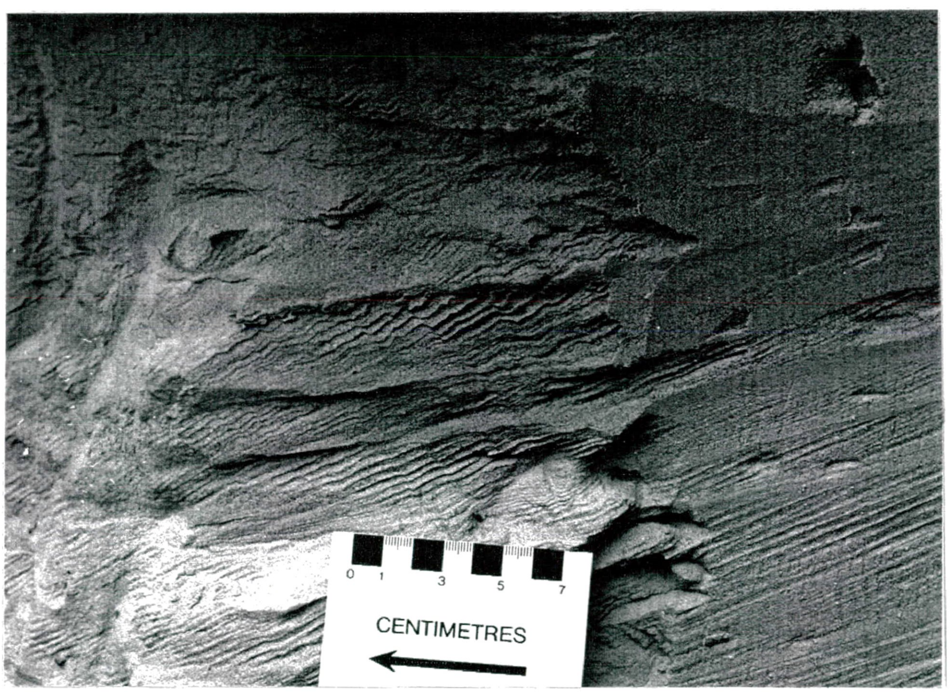
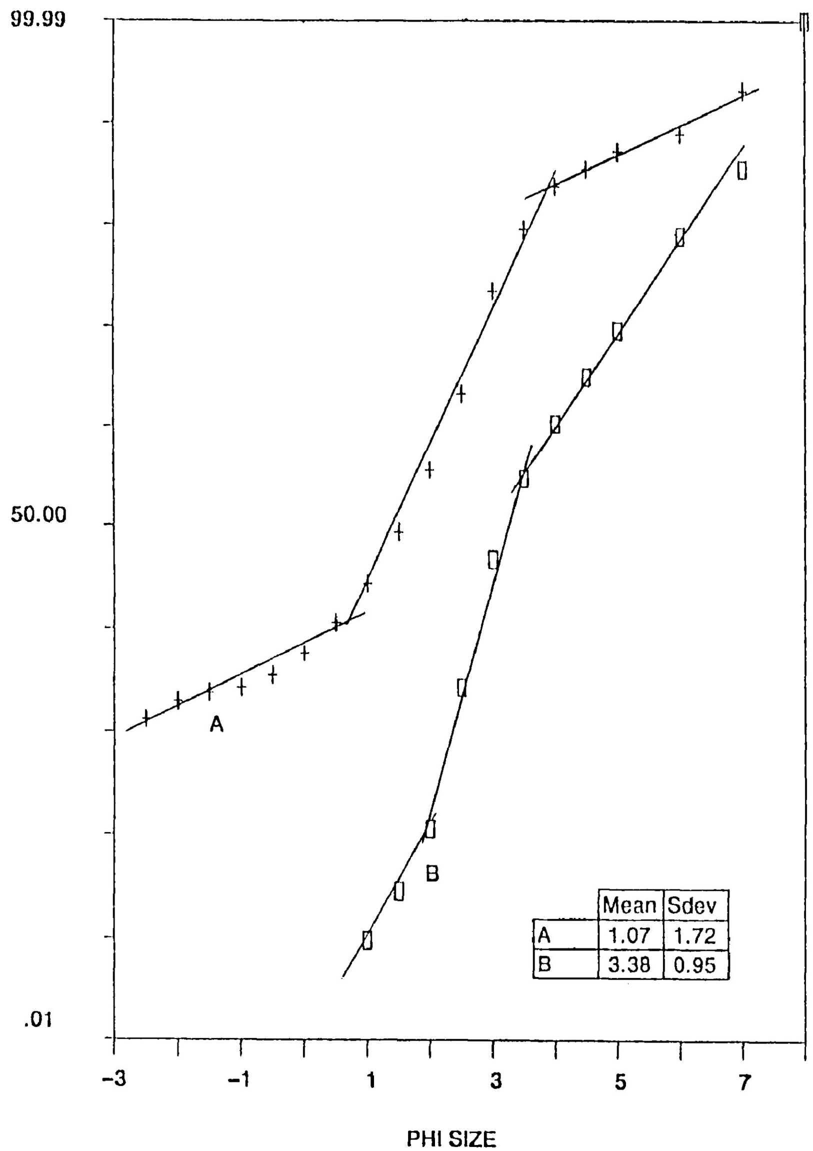

0 1 3 5 7
CENTIMETRES

Figure 2.12 Grain size distributions.

A. Ripple-drift cross-laminated unit (A). Trough cross-stratified sand unit (B).

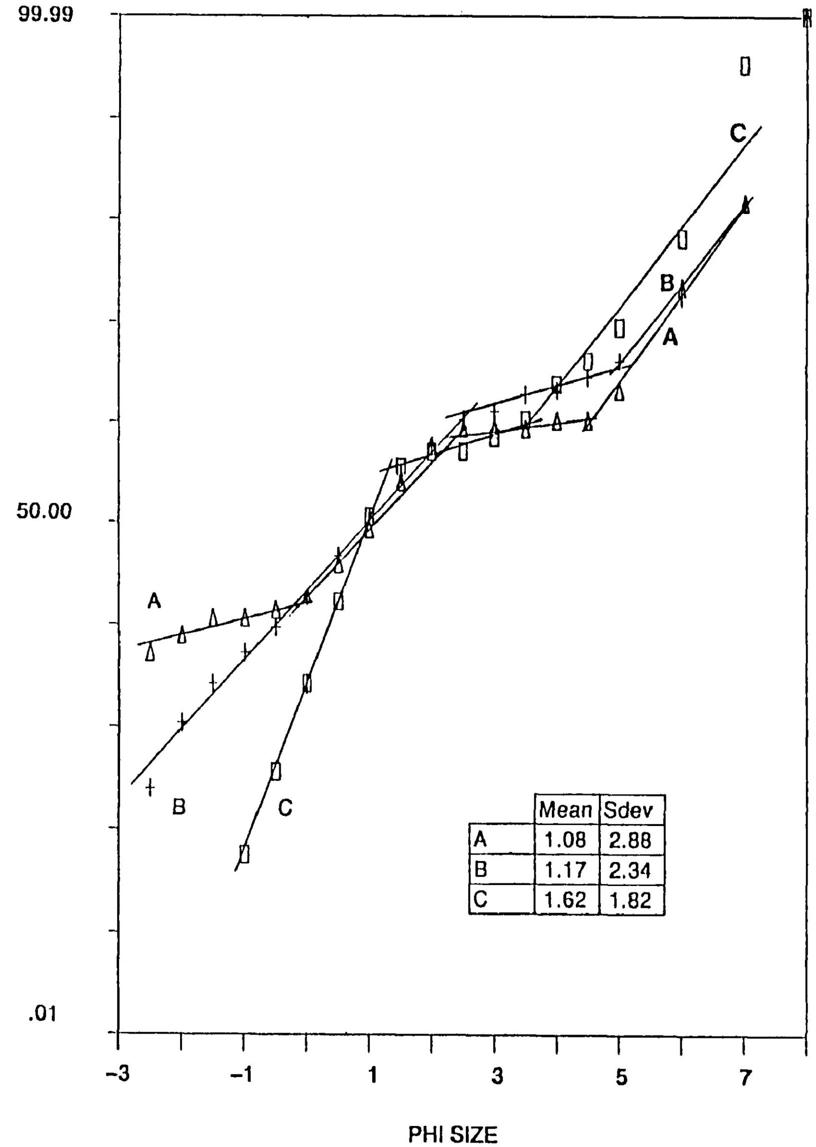
B. Diamict units.

A



	Mean	Sdev
A	1.07	1.72
B	3.38	0.95

B



	Mean	Sdev
A	1.08	2.88
B	1.17	2.34
C	1.62	1.82

associated with the ripple-drift cross-laminated beds. Contacts between the rippled beds are sharp and conformable, except occasionally a gradational, conformable contact was found.

Sharp, conformable contacts are also found between the rippled beds and minor massive and graded beds. The clay to medium sand massive beds generally overlie rippled units, and appear wavy if they are thin (1 or 2 cm). Otherwise, thick (40 cm) massive beds within this L.A. do not exhibit a wavy appearance, and contain faint or isolated ripple development. The normally graded beds are finer grained than the massive beds, grading from silt or silty-fine sand to clay or silty clay. The thicker (6 cm) graded beds show minor ripple development near their tops.

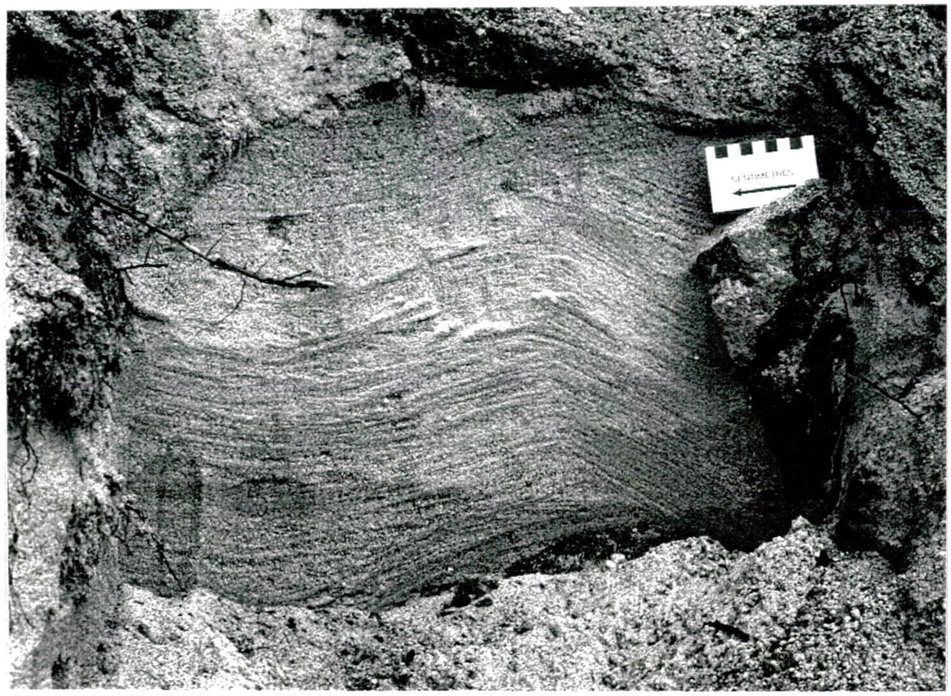
(iii) Trough Cross-Stratified Sand Lithofacies Association

Trough cross-stratified beds of fine sand to cobbly pebble gravel range in thickness from 4 to 68 cm, averaging 16 cm. Clasts within the pebbly sands to cobbly pebble gravels range from 1 to 8 cm, and occasionally appear as lags at the base of the beds. These clasts are predominantly subround to round Paleozoic limestone (61.5 %), with fewer metasediments (28.8%), granitics (9.3%) and iron formation (0.4%). The granite and iron formation fragments are subangular, yet minor angular granitic clasts also occur. Angular metasedimentary lonestones up to boulder size are present in some sections (see Figures 2.6, 2.13 and 2.14). Plot B in Figure 2.12A represents grain size analysis conducted on material from a trough cross-stratified bed. Well developed traction, saltation and suspension populations are present in the medium sand sized sample ($\bar{x}$ = 1.07 phi). Generally, contacts are sharp and erosional between stacked trough cross-stratified beds. Occasionally, thin, massive fine to medium sand beds conformably overlie the trough cross-stratified beds.

The trough cross-stratified beds erosively scour into low-angle very fine to coarse-grained parallel-laminated sands. The parallel-laminated beds range in thickness from 3 to 32

Figure 2.13 Angular metasedimentary dropstone within trough cross-stratified sands.

Figure 2.14 Close-up of dropstone. Note deformation of laminae and scour fill adjacent to the clast.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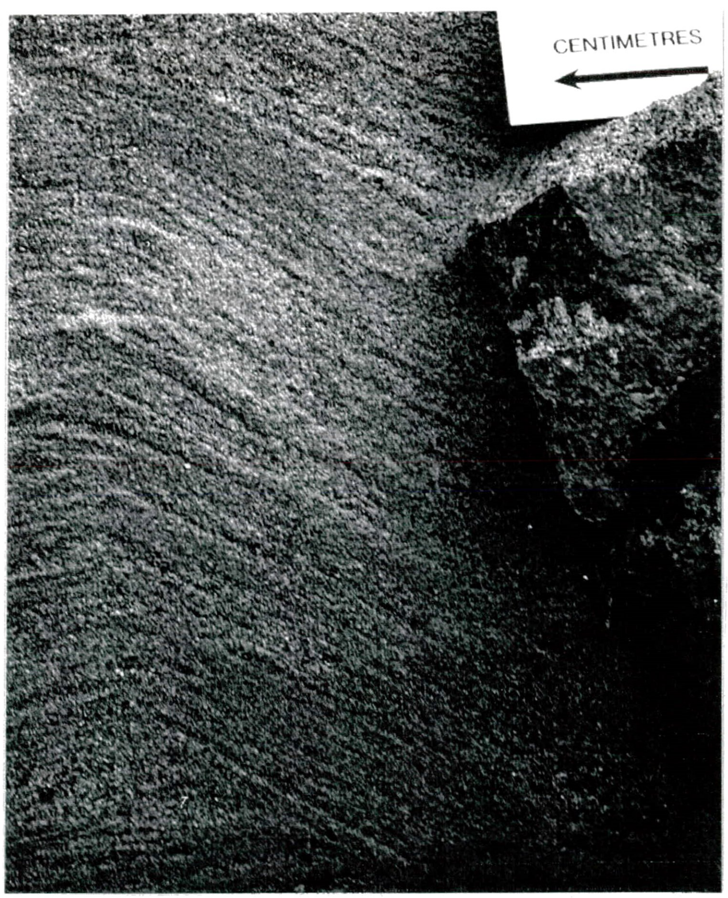
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cm, averaging 9 cm, and 20% of these sands have heavy mineral lamination within them. These units are divided into bundles by low-angle cross-cutting erosional surfaces. A transitional contact exists between the parallel-laminated beds and the underlying finer grained rippled and massive beds. The rippled beds range in thickness from 2 to 60 cm, averaging 8 cm, and are formed predominantly of fine sand. Rarely, medium sand forms isolated ripple trains whose thickness is equal to the height of the ripple. Interlayered with the rippled beds are massive silty-fine and fine sand beds, which appear wavy when situated above a rippled succession. Heavy minerals are present in both the rippled and massive beds; delineating the laminae within the ripples, or forming banded lamination in the fine massive sands. One thick (32 cm) massive bed contains several displaced bands of heavy minerals, showing horst and graben fault-like features. Two atypical beds of diamict were found in the southernmost section.

(iv) Diamict-Bearing Lithofacies Association

The diamict beds are poorly sorted, ranging in grain size from silt to pebbles (up to 5 cm) within the same bed. The pebbles are mainly subround to round Paleozoic limestones and metasediments, suggesting an exotic source. The diamict units range in thickness from 0.5 to 16 cm, averaging 6 cm, and generally appear massive except for slight development of lamination in the thicker beds. Irregular in shape, the diamict units tend to wedge out, pinch and swell, or appear as stringers within other beds (Figure 2.15). Occasionally, cleaner silt or sand lenses and horizons develop within the diamict units. Figure 2.12B indicates that diamict beds contain populations of well sorted sediments, as indicated by the steeply dipping straight line segments of the grain size plots. The histograms (Figure 2.16) of these three diamict samples also indicate well sorted and dominant populations. Note the distinct peaks in the histograms. Figure 2.16A shows a broad peak from 0.5 phi to 1.5 phi, medium to coarse sand,

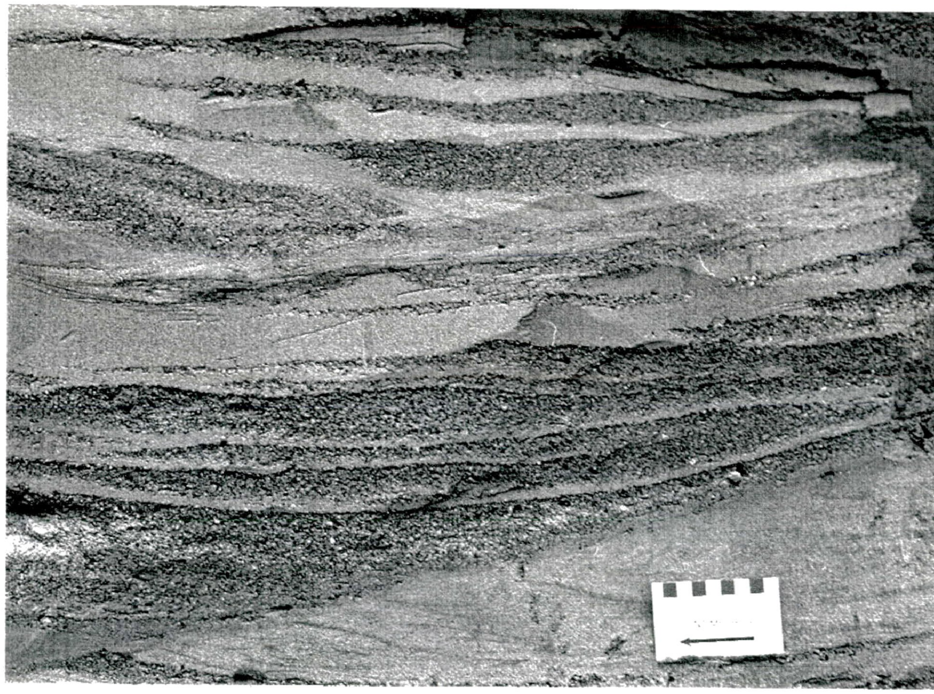
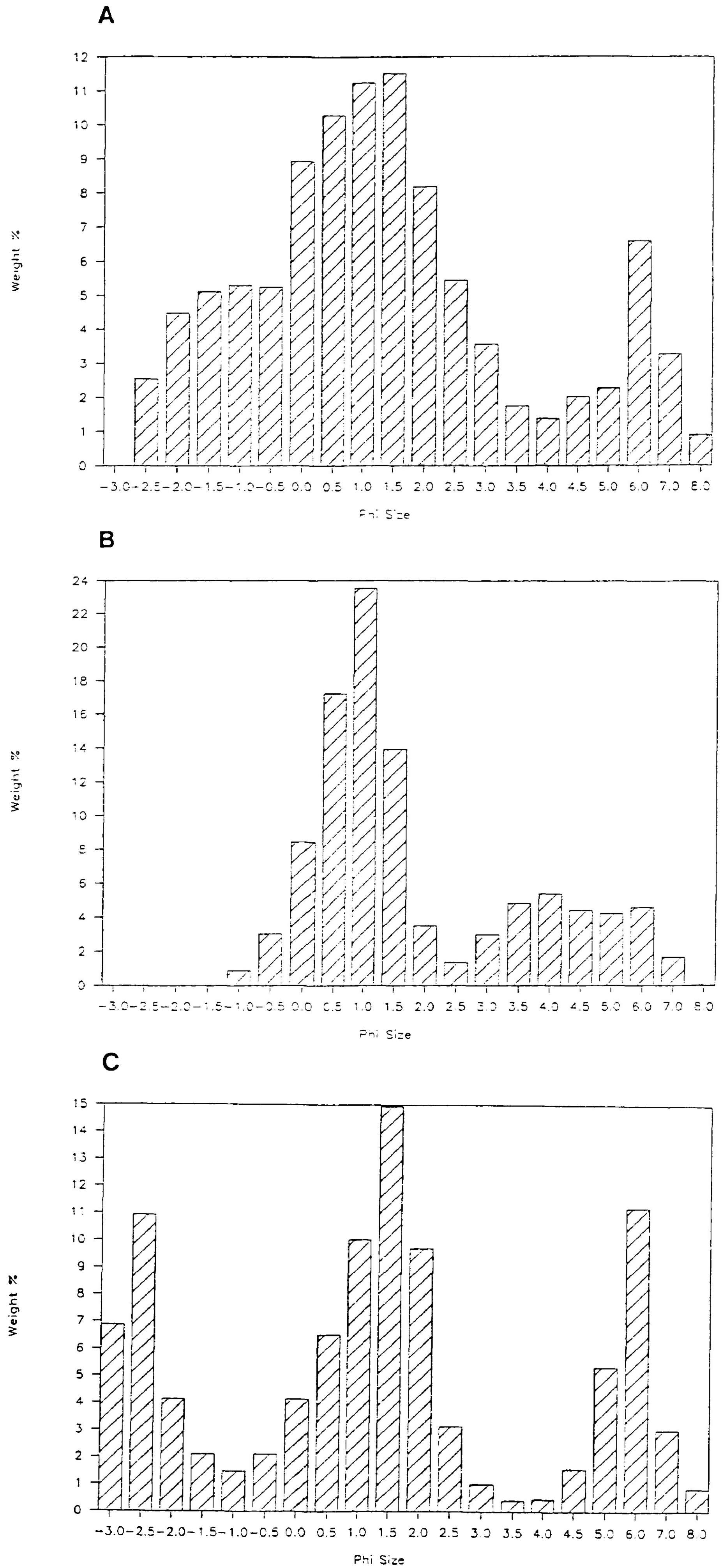


Figure 2.15 Diamict units interbedded with fine sands tend to wedge out, pinch and swell or appear as stringers within other beds.

Figure 2.16 Histograms of diamict samples A,B, and C plotted in Figure 2.12B.


A
Weight %
0 1 2 3 4 5 6 7 8 9 10 11 12
-3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 6.0 7.0 8.0
Phi Size
B
Weight %
0 2 4 6 8 10 12 14 16 18 20 22 24
-3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 6.0 7.0 8.0
Phi Size
C
Weight %
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
-3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 6.0 7.0 8.0
Phi Size

and another at 5.0 phi to 6.0 phi, medium silt. The sample in Figure 2.16B has a distinct peak at 1.0 phi, just into the coarse sand range, and a broader peak in the 3.0 phi to 6.0 phi, or very fine sand to medium silt range. The sample in Figure 2.16C shows three distinct peaks; one in the pebble range, one in the medium sand and one in the medium silt. It is evident from the plots and histograms that sections of the diamict bed are better sorted, and that certain grain sizes such as medium/coarse sand and medium silt are prevalent over the other sediment sizes.

The diamict units are interbedded with all other bed types found within the L.A.; trough cross-stratified and low-angle plane-laminated sands, as well as finer grained rippled and massive sands. When diamict units are found overlying coarse-grained beds, the contacts are generally sharp and conformable. However, there are a few instances where the contacts are sharp and erosional. Coarse beds of pebbly sand and pebbly gravel which overlie the diamicts show a range of contacts from erosional and sharp, through loaded to gradational. Conformable, gradational contacts are also found where one diamict unit overlies another. Generally, the coarse-grained units the diamict beds are interbedded with are trough cross-stratified, or low-angle parallel-laminated sands. The trough cross-stratified beds composed of medium to pebbly sand range in thickness from 5 to 27 cm, averaging 15 cm. Similar to the diamict units, the scattered clasts within the trough cross-stratified beds have an exotic origin. Generally, trough cross-stratified beds overlie each other, and are found associated with not only diamict units, but also fine-grained rippled beds and low-angle plane-laminated units. The low- angle plane-laminated sands composed of silt through pebbly sand, range in thickness from 2 to 30 cm, averaging 7 cm. A few of the plane-laminated sands have heavy mineral banding associated with them. Where the low-angle parallel-laminated beds are associated with each other, contacts are sharp and conformable, or occasionally gradational and conformable.

Otherwise, the parallel-laminated beds show an erosive and sharp contact with underlying finer beds.

The rippled beds are composed of silt to medium sand, yet are dominated by fine sand. The beds range from 1 to 10 cm in thickness, averaging 4 cm, and laminae within a few of the beds are marked by heavy minerals. Also, diamict stringers rarely appear within the rippled beds. Where diamict units overlie rippled or massive beds, loaded or sharp erosional contacts exist (Figure 2.17). Generally, the diamict is conformably overlain by a fine-grained unit (Figure 2.18). The massive beds within this L.A. show a large range in grain size (silt to pebbly sand), and bed thickness (0.25 cm to 21 cm, averaging 4 cm). Diamict stringers are associated with some of the massive beds. Pockets of pebbles are also found interbedded in the massive units.

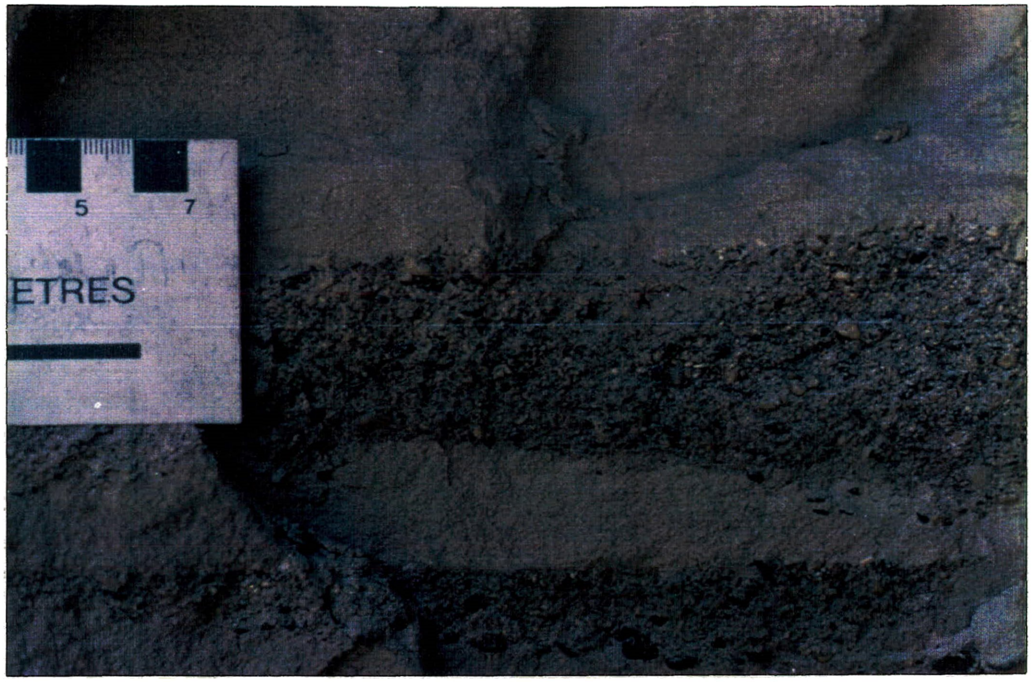
Another important feature to note within the L.A. are the numerous horst and graben fault-like features similar to those described within the trough cross-stratified L.A. These faults, along with beds or units which dip back into the face of the section, suggest that many of the beds within this L.A. have been displaced from their original site of deposition. It appears unlikely that the faults were syndepositional as they cross-cut several different bed types. If faulting had taken place at the time of deposition, sedimentation of an overlying unit would drape the fault within the underlying unit. This was not documented in either lithofacies association.

c) GEOMETRY OF SUCCESSION

A fence diagram showing the actual field position of the succession is shown in Figure 2.19. The fine-grained massive L.A. was found at the base of the three northern sections. Since the northernmost section was excavated to a greater depth, the massive L.A. appears to thicken to the north. It is not possible to determine the true thickness trend of the massive

Figure 2.17 Sharp contact of diamict unit is gradational to a loaded contact on the right hand side of the photo.

Figure 2.18 Diamict units interbedded with massive silts.


5 7
ETRES

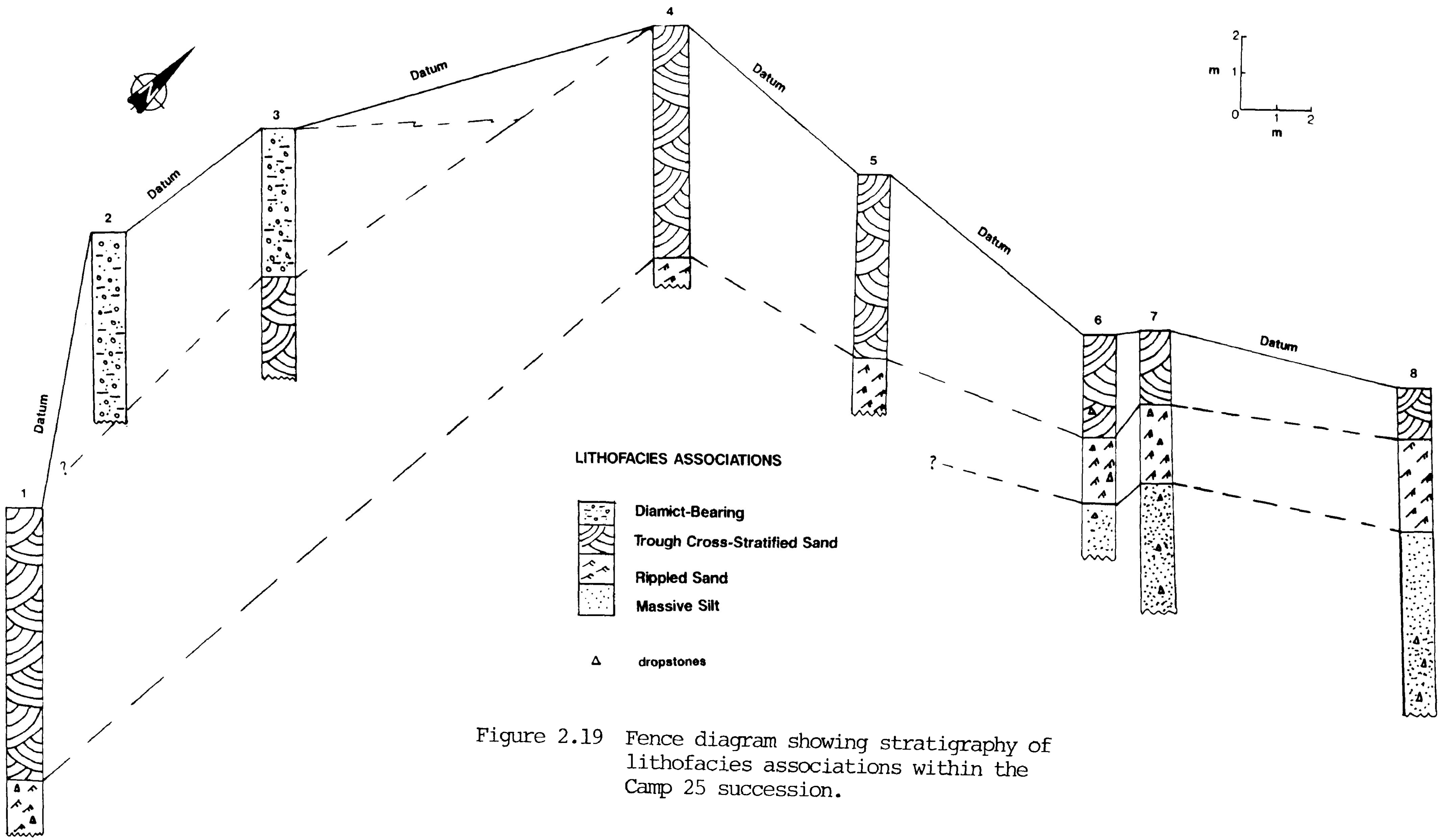


Figure 2.19 Fence diagram showing stratigraphy of lithofacies associations within the Camp 25 succession.

silt L.A., as the bottom contact of the unit was not found. Overlying the massive silt beds is the fine-grained rippled L.A. Based on the appearance of this L.A. in the northern, and southernmost section, it is possible to suggest that the rippled sand L.A. may exist beneath the other southern sections. The fine sand beds of the rippled L.A. are erosively scoured by the overlying trough cross-stratified sand L.A. This L.A. occurs throughout the succession. The diamict-bearing L.A. has a very limited occurrence in the southern portion of the succession. This L.A. is found overlying the trough cross-stratified sands.

As noted by the L.A. descriptions in the preceding text dropstones were found in the massive, rippled and trough cross-stratified lithofacies associations. A quick summary of the dropstone locations while looking at Figure 2.19 is warranted. Dropstones were found only within the lower half of the massive L.A. in Section 8. They were found within both the massive and rippled L.A.. in sections 7 and 6, as well as the trough cross-stratified L.A. in section 6. Other than these three sections, clasts were also found in the rippled L.A.. in section 1 at the opposite end of the succession.

KOA SUCCCESSION

(a) INTRODUCTION

Detailed mapping (to the millimetre scale) of 11 sections totalling 61.6 m was conducted on this sand and gravel assemblage. A 1 cm = 10 cm diagram of the sections (Figure 2.20) is present in the back pocket. At the KOA succession a theodolite transit and chain were used to determine the relative elevations and lateral spacing of the stratigraphic sections logged. A total of 59 samples were collected for grain size analysis and eighty-four paleocurrent measurements were taken. Schuster (1985) mapped six sections in the same succession. The sections he documented were utilized to assist in interpreting the overall depositional environment of the succession. Therefore, pertinent material from his study will be included in relevant parts of the description and discussion.

Six lithofacies associations (L.A.) are outlined on figure 2.20; rippled sand L.A., trough cross-stratified sand L.A., trough cross-stratified gravel L.A., massive-stratified sand and gravel L.A., massive gravel L.A. and diamict L.A. Although the sections in figure 2.20 are hung at their relative elevations, they are not relatively spaced laterally. Therefore, the lithofacies associations delineated within Figure 2.20 exhibit a substantial vertical exaggeration.

The stratigraphically lowest L.A., silty sandy diamict, though usually massive occasionally exhibits minor ripple cross-stratification or parallel to low-angle cross-bedding. Pebble to boulder size angular clasts imbedded in the diamict load into the lamination when it is present. The massive-stratified sand and gravel L.A., composed of fine to coarse sand, pebbly sand and gravel abruptly overlies the diamict. Internally, beds may be massive, parallel-laminated, planar cross-stratified or trough cross-stratified. It, in turn, is abruptly overlain by the fine-grained deposits of the rippled sand L.A. Sediments in this L.A. are dominantly fine and very fine-grained rippled and ripple-drift cross-laminated sands. Graded and massive beds are associated with the rippled units. In addition, coarser grained massive, parallel-laminated, trough and planar cross-stratified units are found. Massive and parallel-laminated clays were also present. Wedges of the massive gravel L.A. are interbedded with the rippled sand L.A. These massive gravel deposits are often laterally transitional into massive, graded and nongraded coarse-grained sand beds. The upper contact of the rippled sands is erosively scoured and channeled, the depressions being filled by the trough cross-stratified sand L.A. These sands are transitional into the uppermost L.A. within the gravel pit, which consists of trough or large-scale planar cross-stratified gravel. Bioturbation has destroyed the internal structures in the surface-proximal gravels of this L.A.

(b) LITHOFACIES ASSOCIATIONS

The following text describes the characteristics of each L.A. in detail.

(i) Diamict Lithofacies Association

The generally massive, poorly sorted diamict beds range from 3 to 122 cm in thickness and are matrix supported (Dmm of Eyles et al,1983). The matrix composition varies from clay to medium sand. Angular to subangular clasts found within the diamict beds range from 1 cm to 60 cm in diameter. Layers of clasts within the diamict occasionally show a preferred orientation. In section S5, vertical orientation of the clasts emphasizes vertical bedding within the diamict (Figure 2.21). Occasionally the clasts load into cleaner lenses and pockets of clay, fine sand, medium sands and pebbly sands (Figure 2.22). As seen in Figure 2.23, some of these pockets and lenses exhibit parallel-lamination, low angle lamination or minor ripple development (Dms of Eyles et al,1983).

As well as containing cleaner horizons, the diamict units are interbedded with rare trough cross-stratified medium sands, clean fine sand units, laminated pebbly gravels and pebble/cobble horizons. Grain size plots in Figures 2.24, 2.25 and 2.26A indicate the poor sorting of massive diamict units, and development of separate populations indicating different modes of transportation such as traction, saltation and suspension are not seen. In contrast, grain size plots in Figure 2.26B, C, D are show minor development of separate populations, and in case D development of three distinct populations.

As the contact with the overlying massive-stratified sand and gravel L.A. is approached, the diamict beds become clay rich, and exhibit remnant parallel-laminated clay horizons (Figure 2.27). The clay coats sand and pebbles within the matrix, resulting in a "crumbly" appearance to the diamict.

Contacts between the diamict units and the stratified sorted beds are generally sharp

Figure 2.21 Diamict units showing clasts oriented parallel to very steep layering.

Figure 2.22 Diamict bed showing stratified horizons.

Figure 2.23 Clast loading into laminated horizons within diamict beds.

Figure 2.24 Grain size distributions.

A. Massive diamict beds section S6.
B. Massive diamict beds section S4.
C. Massive diamict beds section S7.
D. Massive diamict beds section S5.

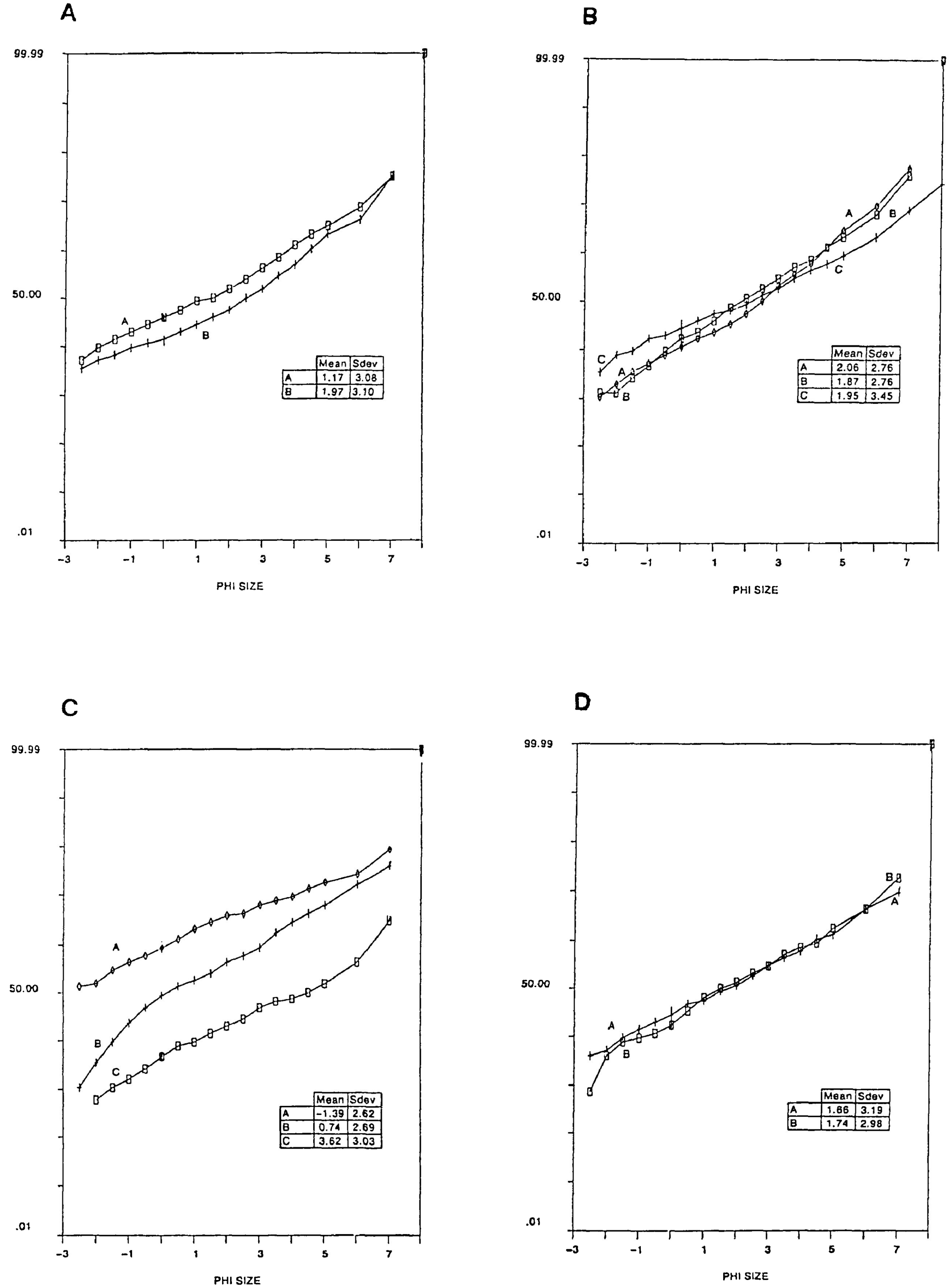

A
99.99
50.00
.01
-3 -1 1 3 5 7
PHI SIZE
Mean Sdev
A 1.17 3.08
B 1.97 3.10
B
99.99
50.00
.01
-3 -1 1 3 5 7
PHI SIZE
Mean Sdev
A 2.06 2.76
B 1.87 2.76
C 1.95 3.45
C
99.99
50.00
.01
-3 -1 1 3 5 7
PHI SIZE
Mean Sdev
A -1.39 2.62
B 0.74 2.69
C 3.62 3.03
D
99.99
50.00
.01
-3 -1 1 3 5 7
PHI SIZE
Mean Sdev
A 1.86 3.19
B 1.74 2.98

Figure 2.25 Grain size distributions.

A. Massive diamict beds section S5.
B. Massive diamct beds section S5.
C. Massive diamict bed section S6 (A).
Dirty pebbly sand section S5 (B).
D. Massive diamict beds section S1.

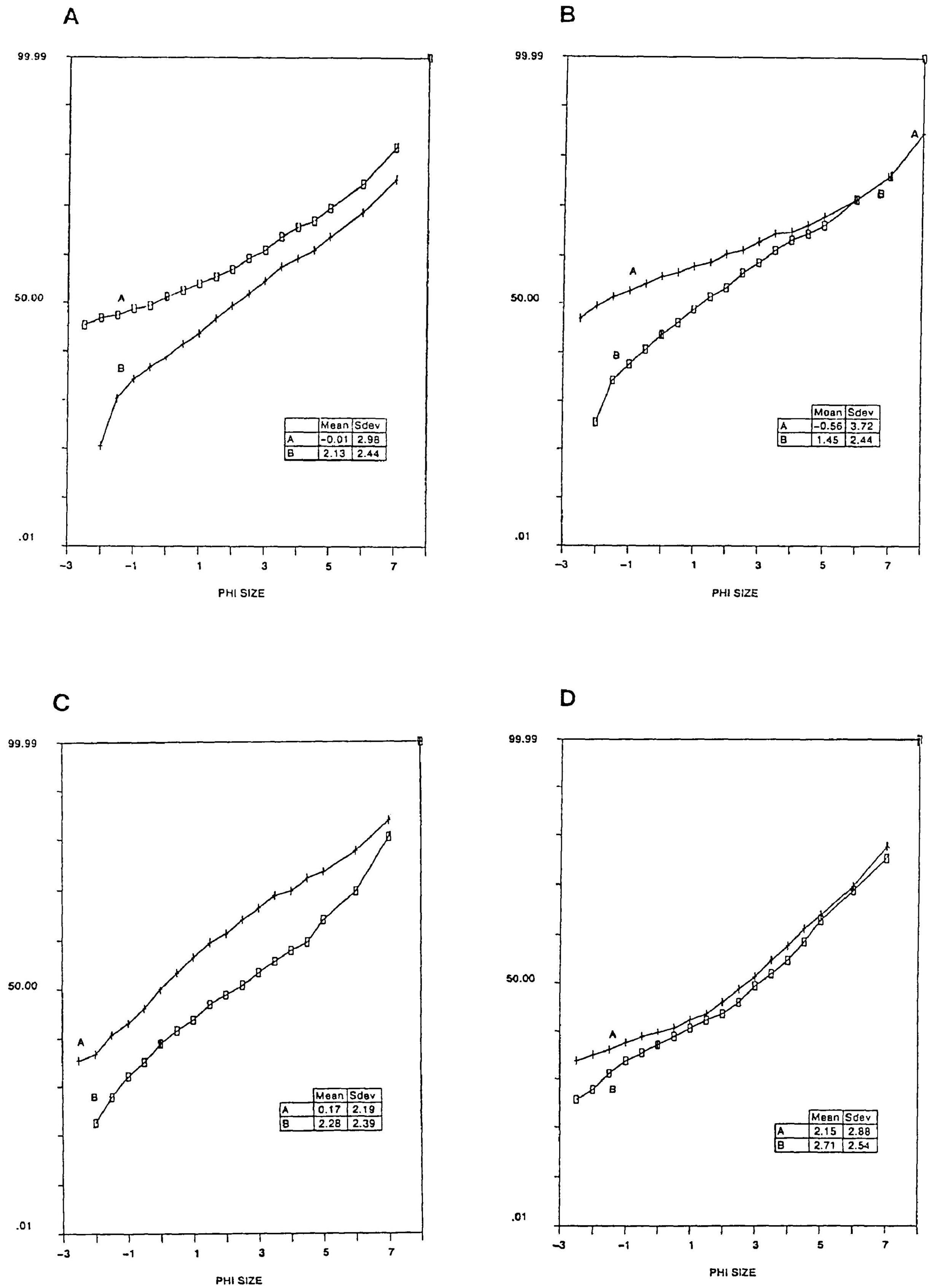

A
B
C
D
99.99
50.00
.01
-3
-1
1
3
5
7
PHI SIZE
Mean Sdev
A -0.01 2.98
B 2.13 2.44
A -0.56 3.72
B 1.45 2.44
A 0.17 2.19
B 2.28 2.39
A 2.15 2.88
B 2.71 2.54

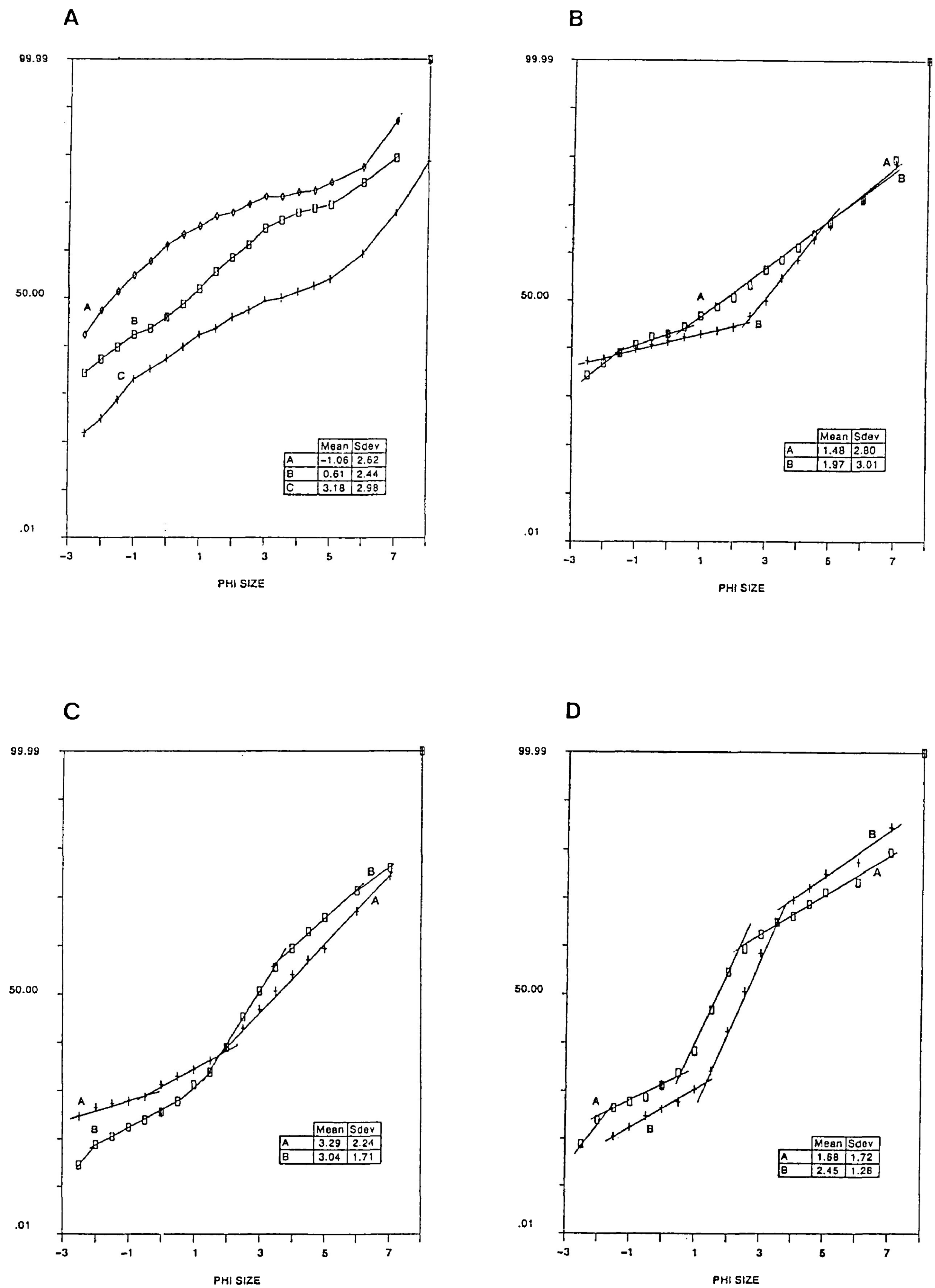
Figure 2.26 Grain size distributions.

A. Massive diamict bed section S7 (A). Massive diamict beds section S6 (B,C).

B. Sandy horizon within diamict section S5 (A). B was a sandy horizon taken from beneath a large dropstone.

C. Parallel-laminated horizons within diamict from section S6.

D. Clean sand lenses within diamict beds from section S4 (A) and S5 (B).



A
99.99
50.00
.01
A
B
C
	Mean	Sdev
A	-1.06	2.62
B	0.61	2.44
C	3.18	2.98
-3 -1 1 3 5 7
PHI SIZE
B
99.99
50.00
.01
A
B
	Mean	Sdev
A	1.48	2.80
B	1.97	3.01
-3 -1 1 3 5 7
PHI SIZE
C
99.99
50.00
.01
A
B
	Mean	Sdev
A	3.29	2.24
B	3.04	1.71
-3 -1 1 3 5 7
PHI SIZE
D
99.99
50.00
.01
A
B
	Mean	Sdev
A	1.88	1.72
B	2.45	1.28
-3 -1 1 3 5 7
PHI SIZE

Figure 2.27 Clay rich diamict bed showing laterally truncated remnant parallel-laminated clay horizons.

and conformable. Contacts between stacked diamict beds are generally gradational. The diamict beds are distinguished by differences in grain size and abundance of clasts.

(ii) Massive-Stratified Sand and Gravel Lithofacies Association

The sediments within this L.A. may be divided into two groups based on their location within the pit, and their position in the stratigraphic column.

(a) Group 1

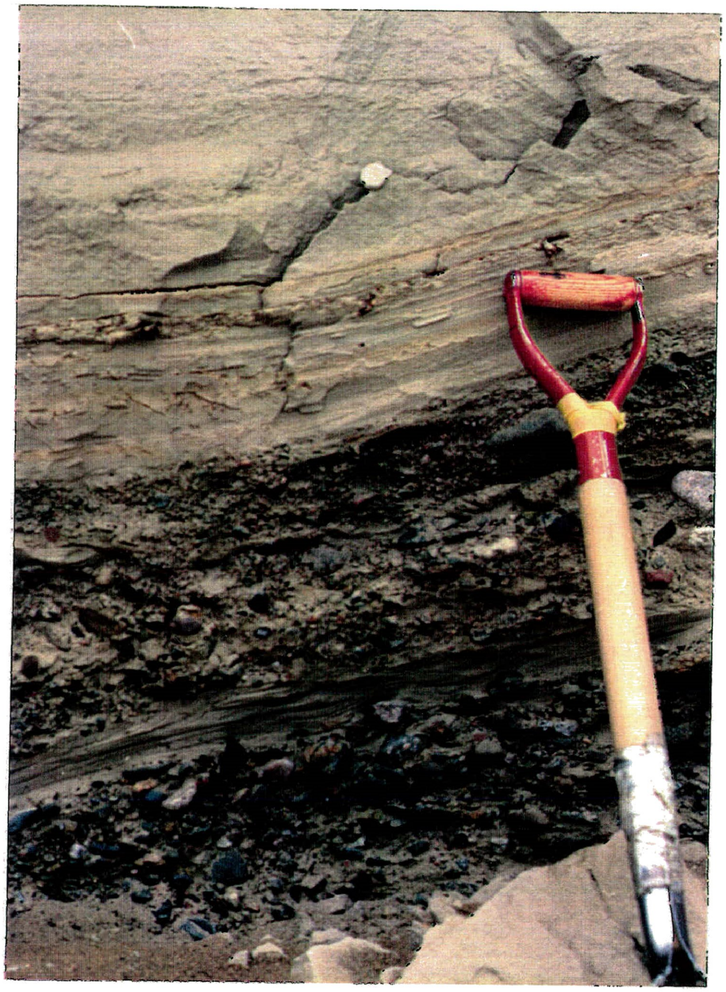
The beds within this group directly overlie the diamict L.A. Massive silty-fine sand to coarse sand beds range from 6 to 25 cm in thickness, averaging 15 cm. Gradational contacts were present between stacked massive beds. Contacts between interlayered coarser stratified beds are sharp and erosional. Pebbly sand to pebble-cobble gravels which make up associated cross-stratified beds contain subangular to subround clasts up to 12 cm in diameter, and have an average bed thickness of 14 cm.

(b) Group 2

The units in group 2 are interbedded with the rippled sand L.A., and generally occur at a lower elevation in the pit in sections S1, S2 and S3. One exception is section S7A, located at a higher elevation than both group 1 and 2. Four different bed types were found in group 2. The first type of bed is massive and stratified pebbly sands and gravels which contain subround to angular clasts up to 10 cm in diameter. These beds are matrix or clast supported (Figure 2.28), average 14 cm in bed thickness and were found at the base of section S2. Between sections S1 and S2 these beds form a lensoid feature (Figure 2.29). Thin (0.5 cm) well sorted granule and small pebble horizons as well as thin (2 cm) units of granules and small pebbles in a silt matrix are the second and third bed types (Figure 2.30). These thin beds were found throughout all three sections. The last bed type is thick (20 cm) diamict units with a silt matrix which contains subangular to subround clasts up to 10 cm in diameter. Clast rich layers

Figure 2.28 Stratified pebbly gravels (S) and massive pebbly gravel (M) found at the base of section S2.

Figure 2.29 Lenticular pebbly gravel found between section S1 and section S2.


M
S

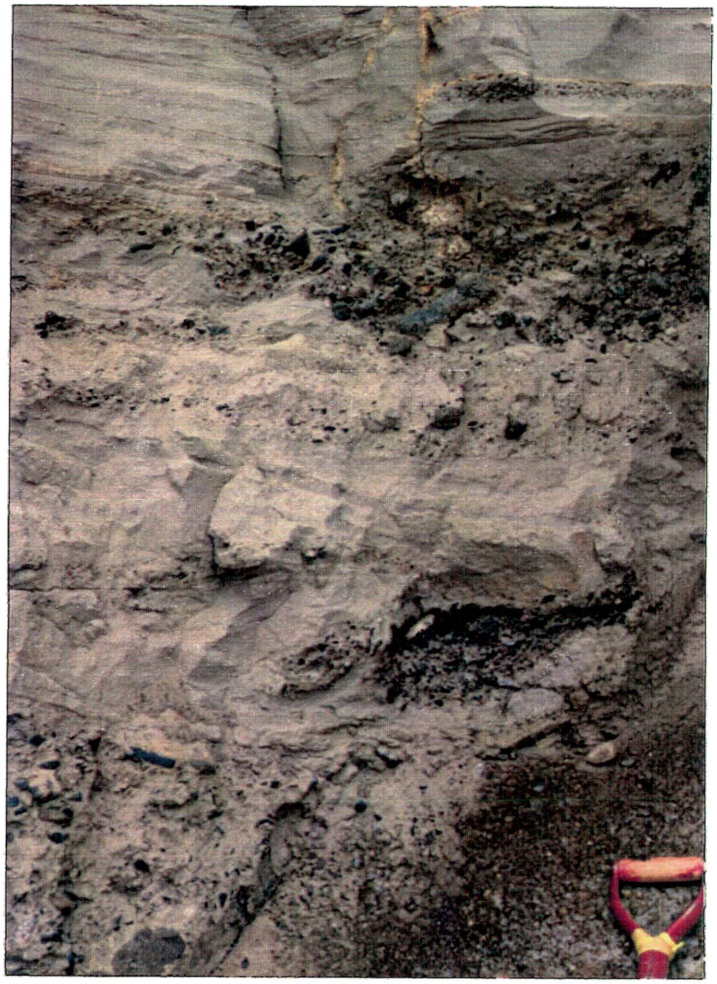


Figure 2.30 Matrix (M) and clast (C) supported diamict units as well as pebbly silt (P) are interbedded with the silt beds of the rippled L.A.

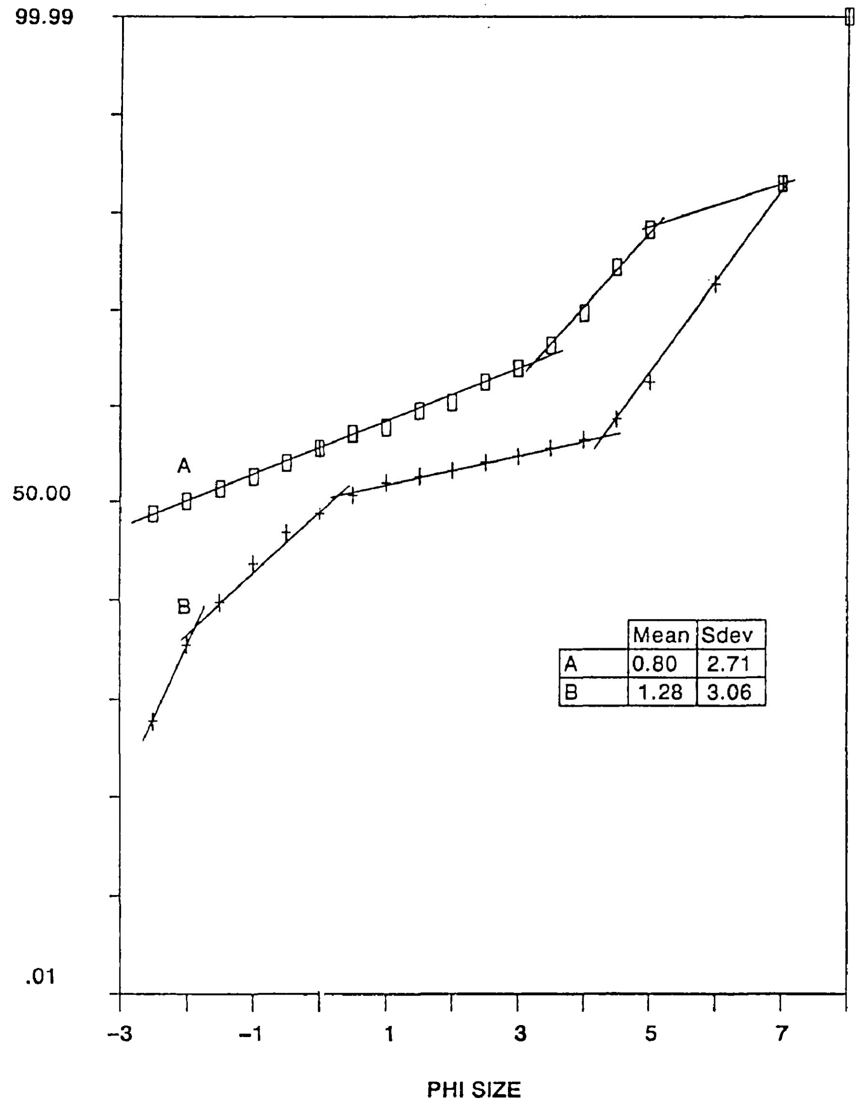
as well as laminated cleaner horizons were found within the diamict units (Figure 2.30). Samples A and B in Figure 2.31 indicate it is possible to distinguish the development of minor subpopulations within some of the diamict beds. The diamict beds were found at the base of section S2, at the top of section S3, in the middle of section S7A, and throughout section S1. All of these bed types were interlayered with clean silt beds of the rippled sand L.A. One deformed bed found at the top of section S2 contains coarse pebbly sand which has loaded into the finer-grained silts (Figure 2.32).

(iii) Rippled Sand Lithofacies Association

In a similar manner to the massive-stratified sand and gravel lithofacies association, the sediments within this L.A. may be divided into two groups based on their location within the pit, and their position in the stratigraphic column.

(a) Group 1

The sediments within this group directly overlie group 1 of the massive-stratified sand and gravel L.A. or the diamict L.A. if the massive-stratified sand and gravel L.A. is not present. Ripple-laminated fine-grained sand beds dominate this L.A. and this group, yet ripple cross-lamination was found in beds ranging from silt to medium sand. The ripple cross-laminated units range from 0.5 cm to 26 cm in thickness, with the average thickness increasing with coarser grain size. For example, the average bed thickness in very fine sand was 2.5 cm, but was 5 cm in medium sand. Ripple-drift cross-lamination formed in silty-fine sand to fine-medium sand and is less prevalent than the ripple cross-lamination. The ripple-drift cross-laminated beds range from 1 to 24 cm, and show an average thickness (7 cm) greater than the ripple cross-laminated beds. Ripple-drift cross-lamination of type A, B and sinusoidal (as defined by Jopling and Walker 1968) were noted. In thicker units, transitions from type A to B, or type B to sinusoidal were found. Rarely, the complete sequence from type A through



	Mean	Sdev
A	0.80	2.71
B	1.28	3.06

Figure 2.31 Grain size distributions. Diamict samples from section S1.

Figure 2.32 Load features at top of section S2.

type B through sinusoidal was noted. The grain size plots of Figure 2.33A indicate the rippled beds developed traction, saltation and suspension populations.

Massive and graded beds are interbedded with the rippled units (Figure 2.34). Contacts are generally sharp and conformable between the rippled, massive and graded beds. The massive beds ranged from 0.5 to 13 cm and average approximately 4 cm thickness. These massive beds are composed of silt to medium sand. Normal graded and to a lesser extent reverse-graded beds were documented. The reverse-graded beds show a large range in grain size (clay to medium-coarse sand), and thickness (0.5 cm to 5 cm). Some individual reverse-graded beds have a large range in grain size (for example clay to medium sand), while others showed very slight change in grain size (silt to silty-fine sand). The normally graded units show a similar wide variability in grain size (clay to medium sand) and thickness (1 cm to 18.5 cm). Similar to the reverse- graded beds, some individual units show a wide range in grain size (medium sand to clay) while other beds show a slight change in grain size (silt to silty-clay). Fine sand grading to silt and silty-fine sand were the most abundant normally graded beds. Two sets of samples taken from normally graded beds are plotted in Figure 2.33B and 2.33C. Both diagrams indicate a decrease in average grain size from fine to very fine sand. Note the very small to nonexistent traction portion of the curves compared to ripples.

Clay units mapped were usually thin, averaging 1.3 cm, and ranged from 0.25 cm to 7 cm. The pink, red, brown and purple clay units are massive or parallel-laminated with laminae a few millimeters thick.

Minor associations of parallel-laminated, trough and planar cross-stratified beds are present within this L.A. The parallel-laminated beds are composed of very fine sand to medium-coarse sand and average 5 cm in thickness, ranging from 1.5 to 10 cm. The trough and planar cross-stratified beds are composed of medium-coarse to pebbly sands with unit thickness

Figure 2.33 Grain size distributions.

A. Ripple cross-laminated units.

B. Four samples taken from bottom to top (D,B,C,A) in a normally graded bed within rippled L.a.

C. Bottom (C), middle (B) and top (A) of graded bed within rippled L.A.

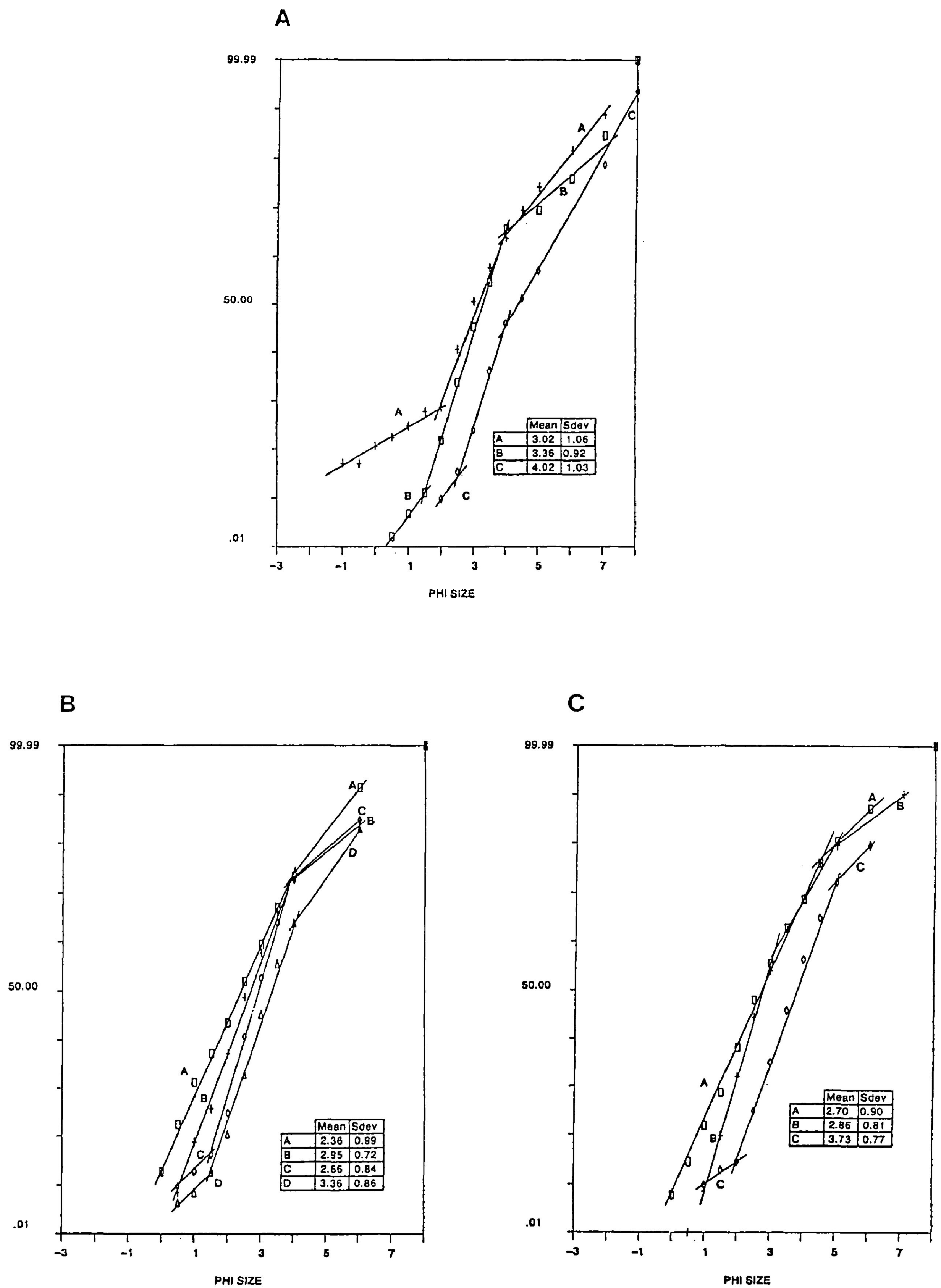
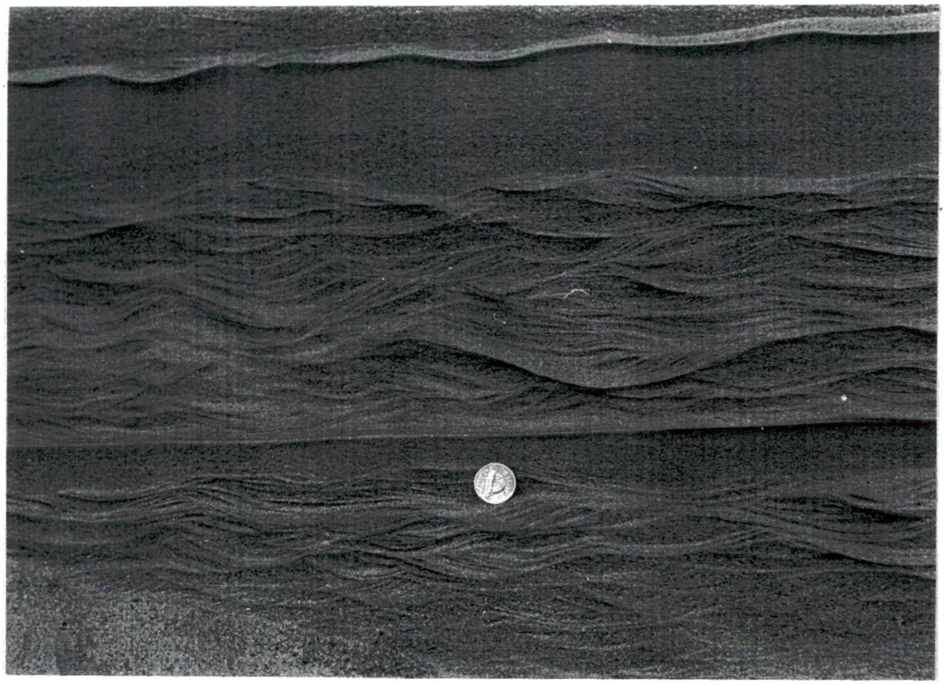
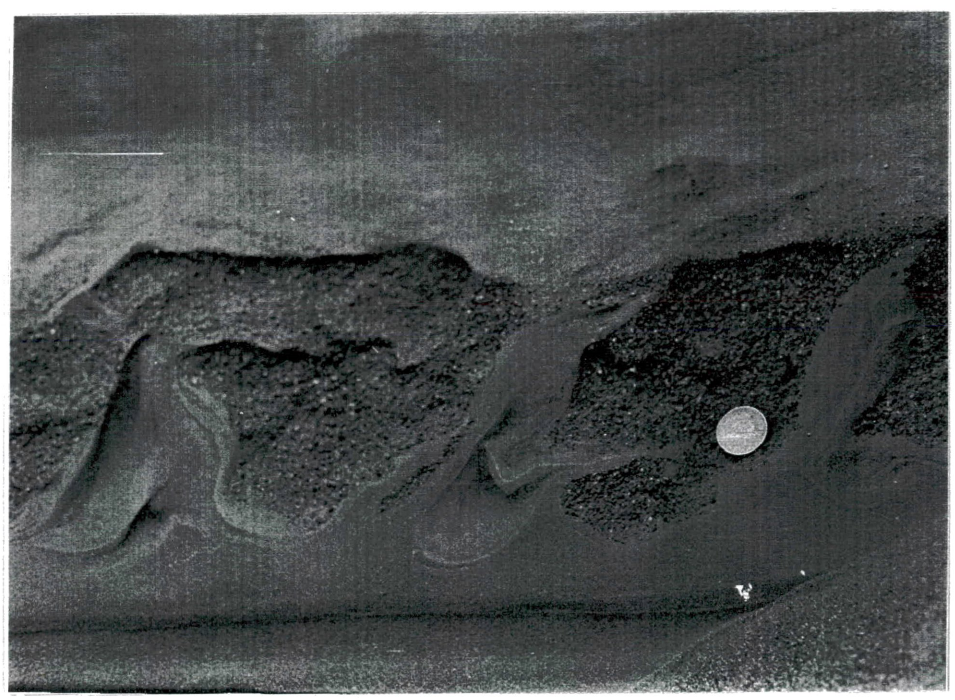

A
99.99
50.00
.01
-3
-1
1
3
5
7
PHI SIZE
A
B
C
Mean Sdev
A 3.02 1.06
B 3.36 0.92
C 4.02 1.03
B
99.99
50.00
.01
-3
-1
1
3
5
7
PHI SIZE
A
B
C
D
Mean Sdev
A 2.36 0.99
B 2.95 0.72
C 2.66 0.84
D 3.36 0.86
C
99.99
50.00
.01
-3
-1
1
3
5
7
PHI SIZE
A
B
C
Mean Sdev
A 2.70 0.90
B 2.86 0.81
C 3.73 0.77

Figure 2.34 Rippled sands interbedded with massive units.

Figure 2.35 Load and flame features in rippled sand L.A.





averaging 7 to 8 cm. Minor thick (35 cm) coarse grained massive beds were also noted. These coarser-grained units appear at the top of repeated coarsening upward cycles within the succession (see following text) and are transitional from the underlying finer grained rippled sands. The cross-stratified non-channelized sands capping these cycles exhibit erosive basal contacts.

Loaded contacts appear in every section. Coarser grained units load into finer grained units creating ball and pillow features or load and flame structures (Figure 2.35). Other deformation features found were water escape structures and minor listric faults. Deformation is more prevalent in section S7 than the other sections.

Within this L.A. the clay units, rippled successions and coarser massive and stratified beds appear in repeated stratigraphic positioning. The clays are stratigraphically the lowest and show a transitional contact to the silts and rippled, graded, and massive fine sands. These rippled and associated beds coarsen to fine-medium sand and are transitional to coarser grained parallel-laminated, planar, trough and massive units. This cycle from clay, through rippled sands and stratified or massive coarser sands is repeated in every section within this L.A. Occasionally the clays are absent and the cycle begins with the very fine-grained rippled units. An angular unconformity (Figure 2.36) was found within section S6.

(b) Group 2

This group was found interbedded with the massive-stratified sand and gravel L.A. at a lower elevation in the succession in sections S1, S2 and S3. Th e group was also found in section S7A, located at a higher elevation than both group 1 and 2. The beds within this group are generally finer grained than group 1 and are composed mainly of silt and minor silty-fine sand. Four main bed types are found: rippled, massive, rhythmite, and lenticular. The rippled beds are generally composed of the silty-fine sand, range in thickness from 0.5 to 8 cm and

Figure 2.36 Angular unconformity within the rippled sand L.A. found in section S6.

average 2 cm. The massive beds average 7.2 cm thickness, ranging from 1 to 15 cm and are composed mainly of silt. Samples from these massive beds indicate the development of saltation and suspension populations (Figure 2.37A). The rhythmites average 5.7 cm and are composed of silt and silty-clay laminae averaging 0.5 cm. These rippled, massive, and rhythmite units are interbedded with group 2 coarser grained beds of the massive-stratified sand and gravel L.A., and may be seen in Figures 2.28 through 2.30 and Figure 2.32. Lenticular silts and clays with rare dropstones average 17.6 cm for bed thickness (Figure 2.38). Contacts are generally sharp and conformable between these 4 kinds of beds. One silt bed 30 cm thick was deformed due to loading of the bed above it, as described previously in the group 2 section of the massive-stratified sand and gravel L.A.

Two thick, fine-grained deformed units were found in section S7A. The deformed beds are composed of fine silt, yet have pockets and lenses of fine sand and clay. A large angular boulder was present within one deformed bed. The deformed units are underlain by red and purple clays and a diamict unit (described previously in group 2 of the massive-stratified sand and gravel L.A.). Laminated silts, silty-fine sand and fine sand beds averaging 3 cm thickness overlie the deformed beds. Figure 2.37B indicates samples taken from silt horizons are missing the traction population segment.

(iv) Massive Gravel Lithofacies Associations

This lithofacies association contains gravels, and wedges of reworked gravel which are interbedded with group 1 of the rippled sand L.A.

Gravels

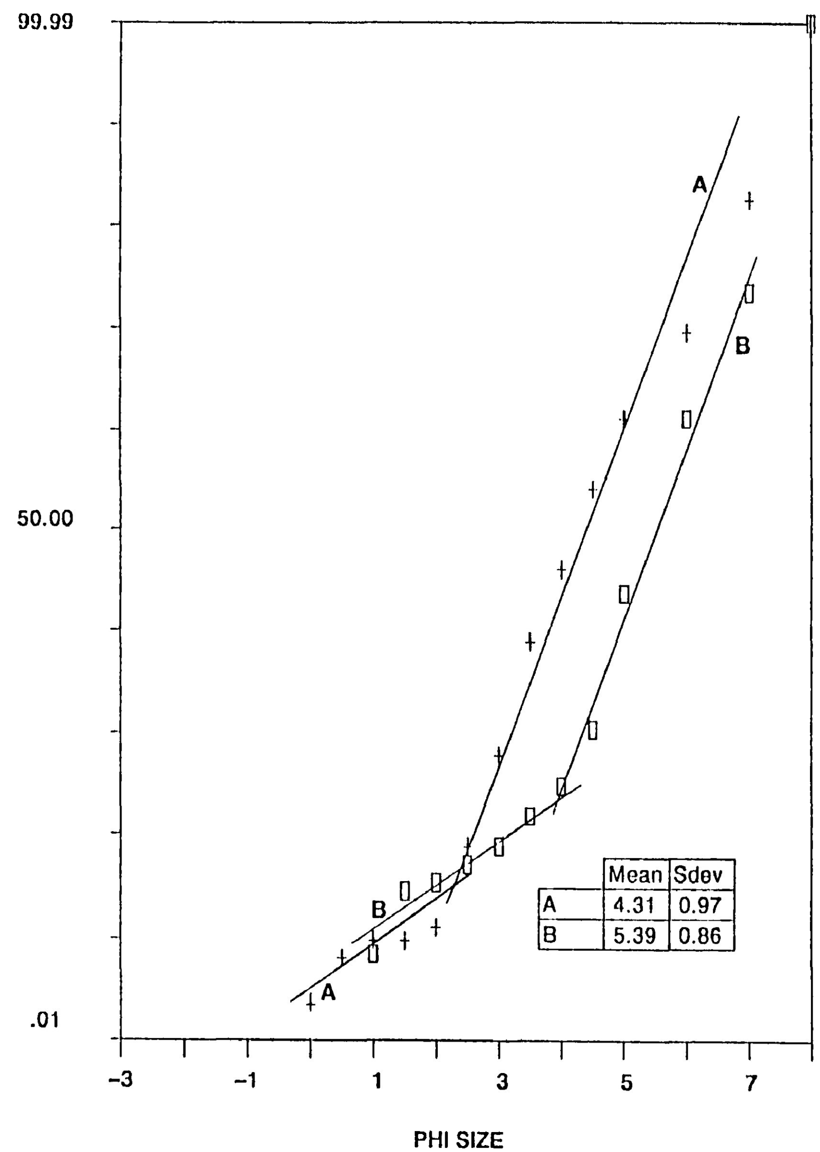
The gravel beds are thick, averaging 61 cm, and range from 7 to 230 cm. Subangular to subround clasts up to 40 cm diameter were found in the pebble to boulder gravel beds. The gravels are generally open framework with a matrix of pebbles or small cobbles. Quite often

Figure 2.37 Grain size distributions.

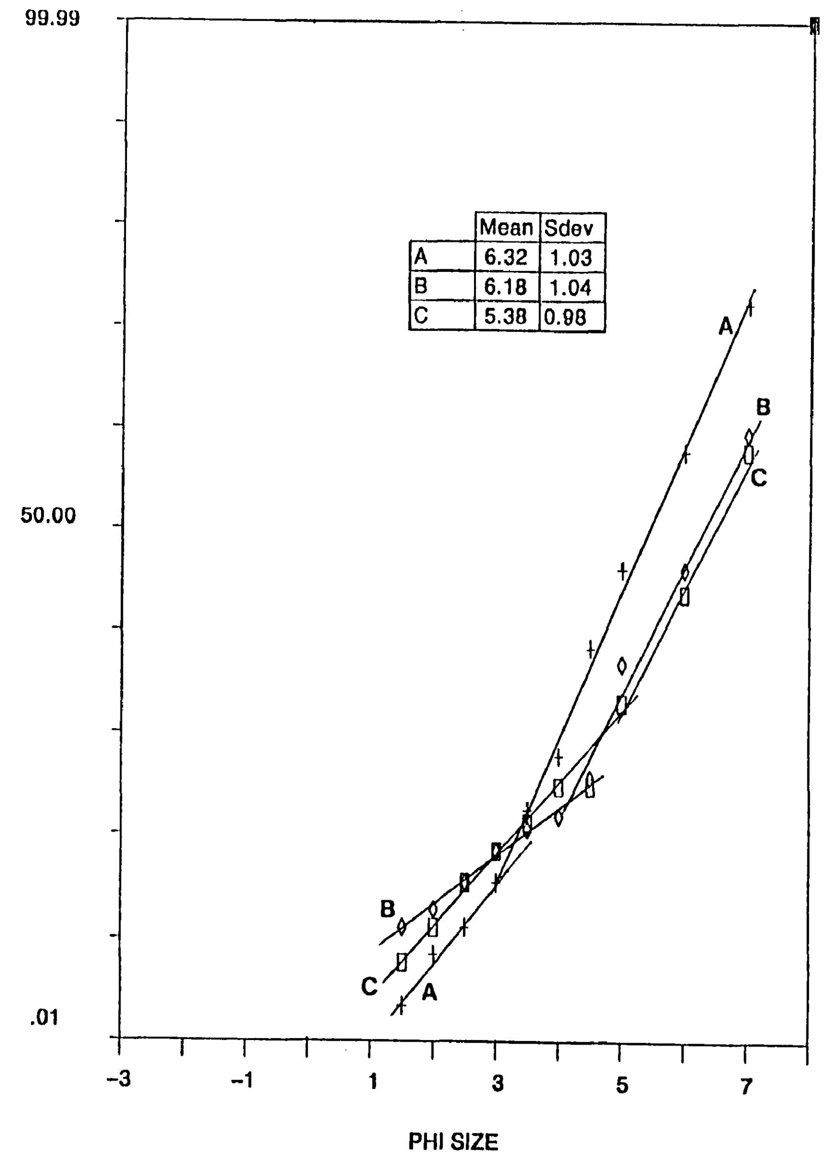
A. Massive silts sections S2, S3.

B. Silts from section S7A.

A


99.99
50.00
.01
-3
-1
1
3
5
7
PHI SIZE
A
B
Mean Sdev
A 4.31 0.97
B 5.39 0.86

B


99.99
50.00
.01
-3
-1
1
3
5
7
PHI SIZE
A
B
C
Mean Sdev
A 6.32 1.03
B 6.18 1.04
C 5.38 0.98

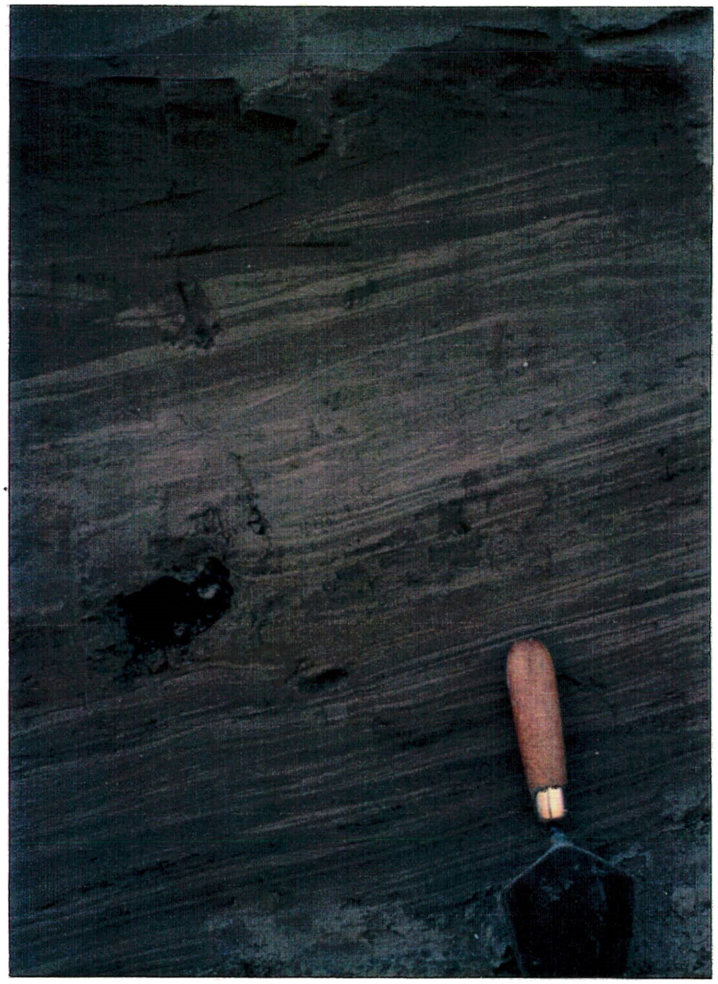


Figure 2.38 Lenticular silts and clays with dropstone.

finer material appears to have filtered in between the clasts. The gravel units are occasionally reverse graded, and have an apparent dip of 48 to 55 degrees (Figure 2.39). Figure 2.41A shows the development of separate populations in grain size plots for samples taken from the gravel beds. The histograms in figure 2.41B for the same samples indicate the dominance of a coarse grained fraction (-2.5 phi to -3.5 phi) within the samples.

Wedges

Beds within the wedges range from 3 to 24 cm in thickness, averaging 9 cm. The wedges are finer grained than the gravels describe above, and are composed of pebble and pebble-cobble gravels at the widest part of the wedge. These proximal beds show both clast and matrix support. Open framework horizons often have finer-grained material filtering into the top of the layer and voids beneath the clasts. In rare cases, the clasts in the wedges appear imbricated. The material in the wedges often loads into the finer grained units of the rippled L.A (Figure 2.40). These wedges pinch out and/or gradually change laterally into massive or graded sand units.

Figure 2.42 shows grain size analysis and location of samples taken within a gravel wedge. Increasing number for the samples indicates increasing distance from the main gravel beds. For example, sample 1 is from the widest part of the wedge, and was in closest proximity to the gravel beds. Sample 6 was taken at the tip of the wedge, and is furthest away from the gravel beds. At location 5, samples were taken from the top, middle and bottom of the wedge. Grain size decreases along the wedge away from the gravel beds. All samples indicate development of separate tansportation populations. Sample 6 lacks a traction population. The histograms for these samples are shown in Figure 2.43. In samples 1 through 4, representing increasing distance along the wedge from the coarser gravel beds, the importance of the 2.5 phi population decreases along strike from the coarsest to finer such that by sample 4 it is a

Figure 2.39	Steeply dipping boulder gravel beds mapped in section S9 and bouldery cobble gravels mapped in section S10.

Figure 2.40	Wedges of pebble and cobbly pebble gravel load into finer grained sand beds. Gravels are matrix and clast supported with rare imbrication.

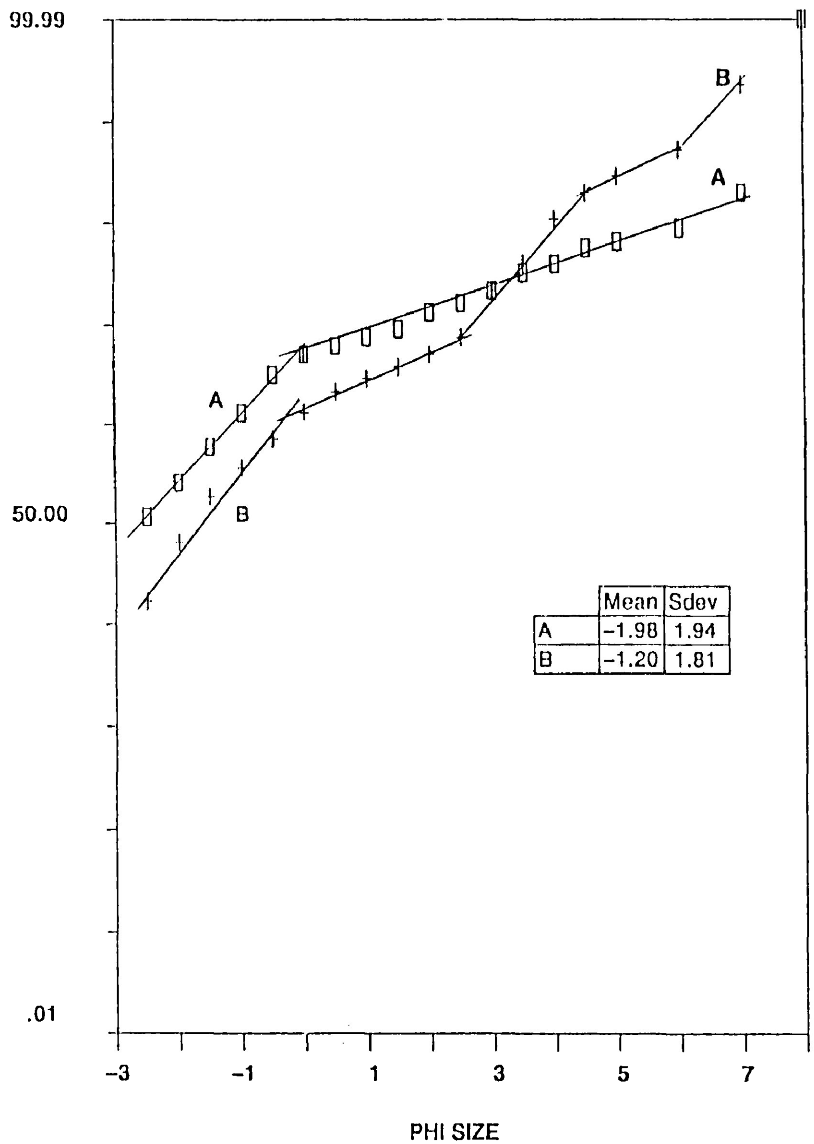
S9 S10

Figure 2.41

A. Grain size distributions of samples from gravel beds.

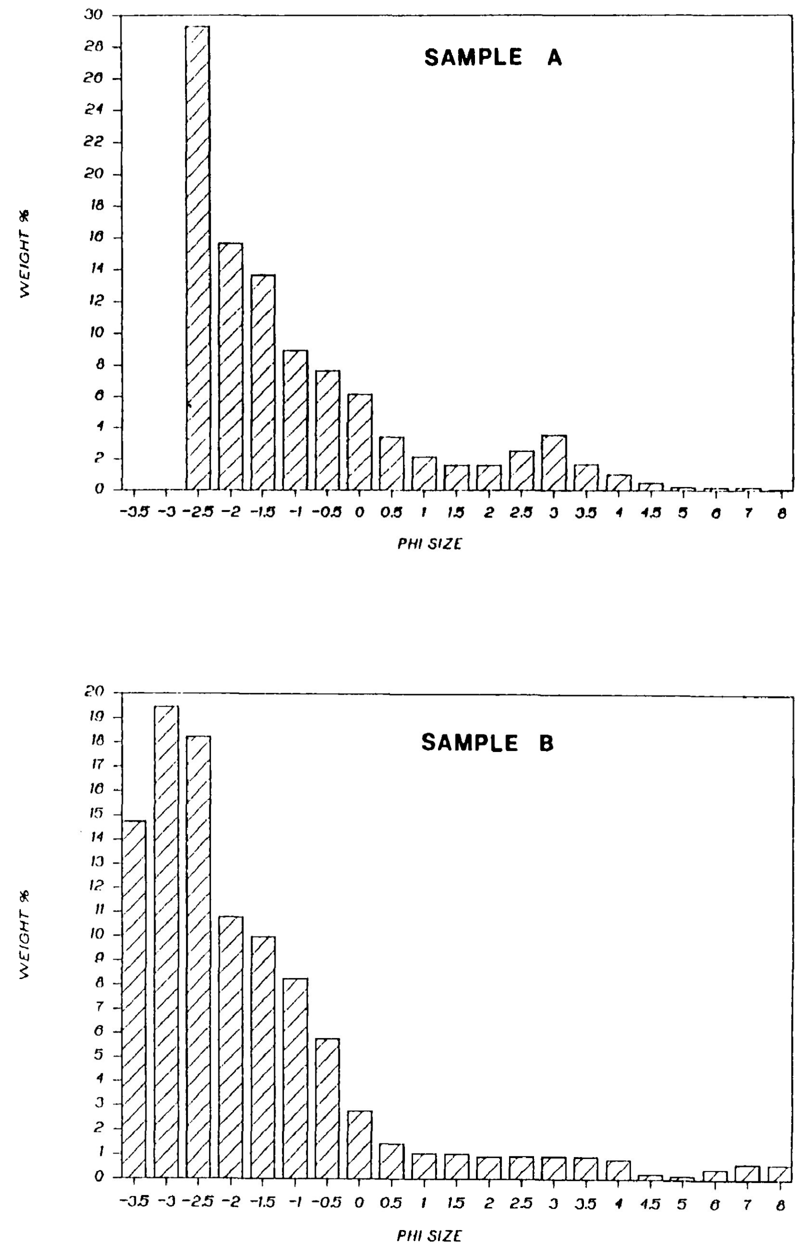
B. Histograms for samples A and B shown in figure A.

A



99.99
50.00
.01
-3
-1
1
3
5
7
PHI SIZE
A
B
Mean Sdev
A -1.98 1.94
B -1.20 1.81

B



SAMPLE A
WEIGHT %
PHI SIZE
-3.5 -3 -2.5 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 6 7 8
SAMPLE B
WEIGHT %
PHI SIZE

Figure 2.42 Grain size distributions.
A, B, C, and D are plots of samples from a gravel wedge. Location and position of samples is indicated in E.

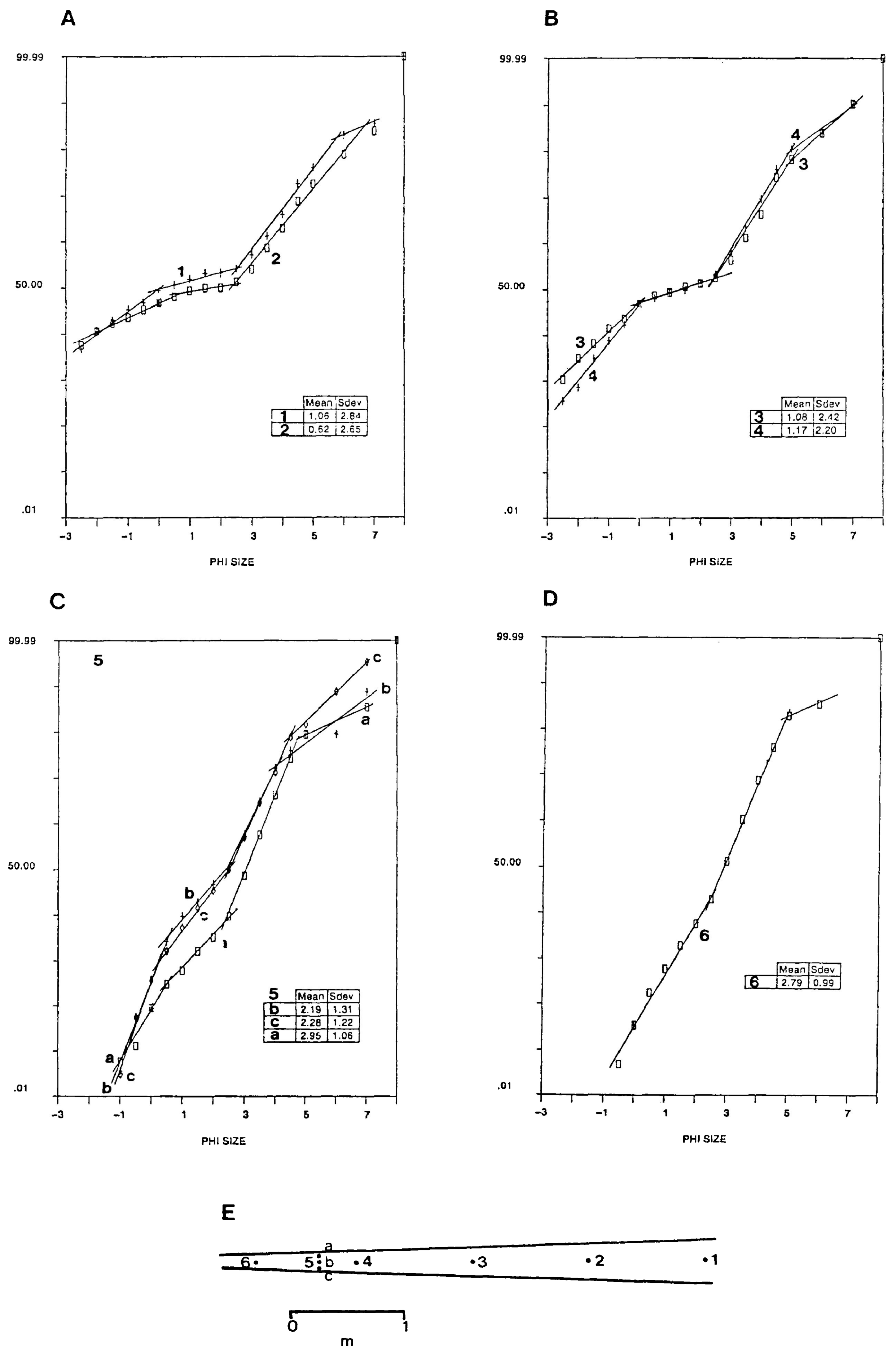
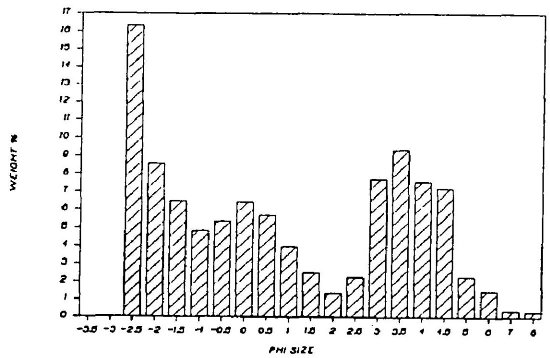
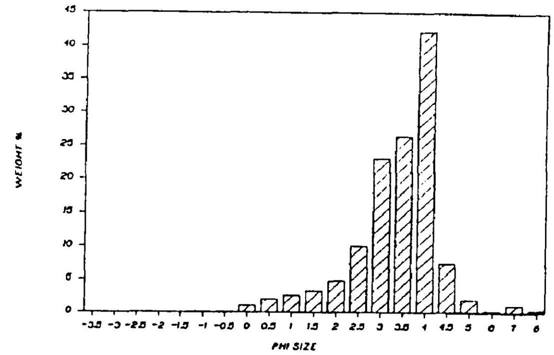

A
99.99
50.00
.01
-3
-1
1
3
5
7
PHI SIZE
1
2
Mean Sdev
1 1.06 2.84
2 0.62 2.65
B
99.99
50.00
.01
PHI SIZE
3
4
Mean Sdev
3 1.08 2.42
4 1.17 2.20
C
99.99
50.00
.01
PHI SIZE
5
a
b
c
5 Mean Sdev
b 2.19 1.31
c 2.28 1.22
a 2.95 1.06
D
99.99
50.00
.01
PHI SIZE
6
Mean Sdev
6 2.79 0.99
E
6
5
a
b
c
4
3
2
1
0
1
m

Figure 2.43 Histograms of samples within wedge. Numbers correspond to sample numbers shown in figure 2.42E.

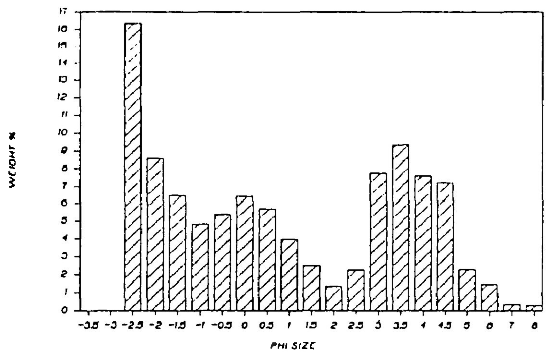
1



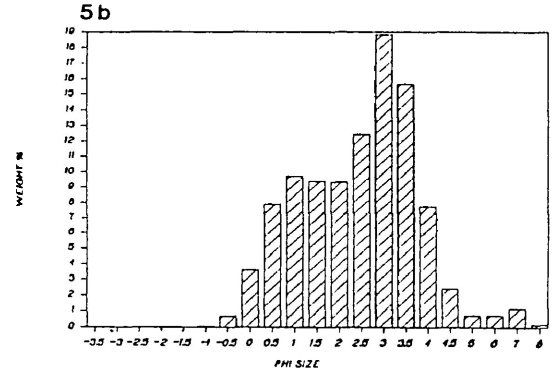
5a



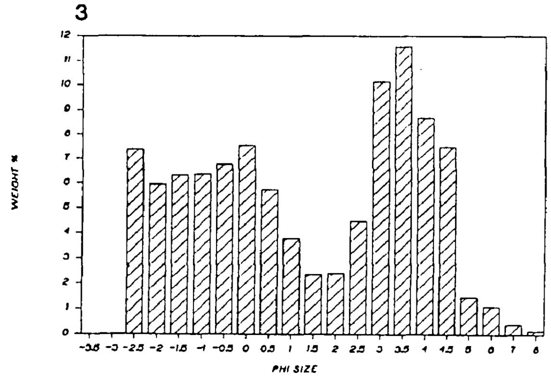
2



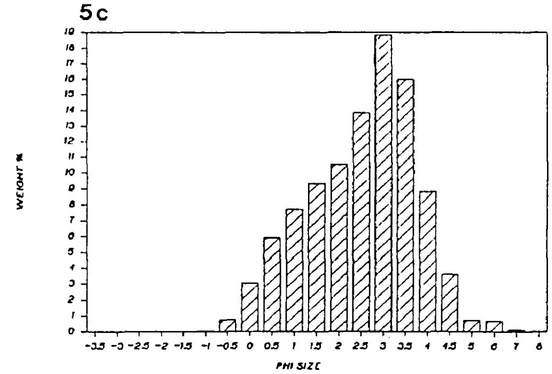
5b



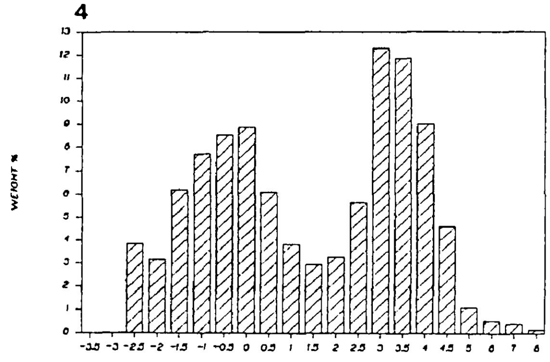
3



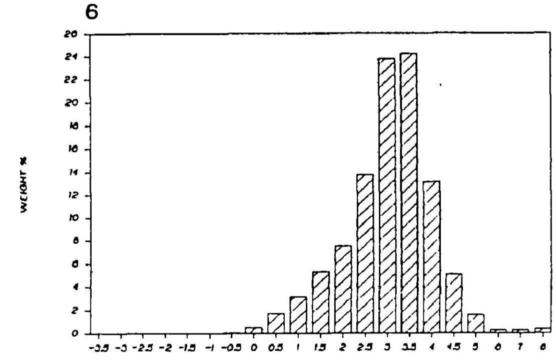
5c



4



6



minor peak. The other peaks in these samples are at 0.0 phi and 3.5 phi. Samples 5A, B, and C taken from the top, middle and bottom of the same position further down the wedge show peaks at 4.0 phi in 5A, and 3.0 phi in B and C. In sample 6, furthest down the wedge, there is a large peak from 3.0 phi to 3.5 phi.

(v) Trough Cross-Stratified Sand Lithofacies Association

Trough cross-stratified beds composed of fine sand to pebbly sand range in thickness from 4 to 56 cm, averaging 18 cm (A in Figure 2.44). Contacts are sharp and erosive between both the individual lense shaped trough cross-stratified beds, and the large scale units which contain stacked sets of the trough cross-stratified beds. The base of these larger scale bedforms erosively scours into the underlying rippled sand L.A. and appears to be channel shaped. Rare pebble lags were found. Figure 2.45A shows the development of separate traction, saltation and suspension populations within samples taken from this L.A.

(vi) Trough Cross-Stratified Gravel Lithofacies Association

The beds of this L.A. are composed of pebble, pebble cobble, and rare cobble gravels, ranging from 7 cm to 146 cm in thickness, and averaging 28 cm. The matrix coarsens from medium/coarse sand to very coarse sand within the pebble and pebble-cobble gravels respectively. The largest clasts within the gravels were 13 cm in diameter.

The gravels are trough and occasionally planar cross-stratified, showing sharp, erosional contacts between beds (B in Figure 2.44). Grain size plots of samples taken from the L.A. show traction and saltation populations (Figure 2.45B).

In sections 5 and 6 the upper metre to a metre and a half are root bioturbated, obliterating original bed structure.

c) GEOMETRY OF SUCCESSION

A fence diagram of the succession is shown in Figure 2.46. As mentioned earlier a

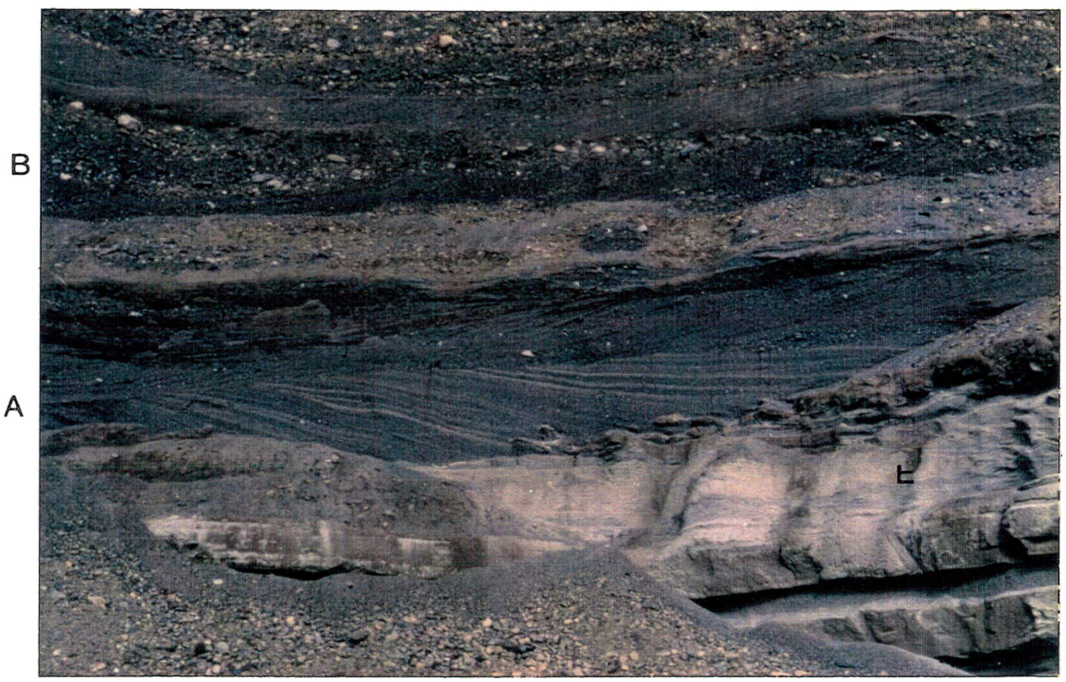


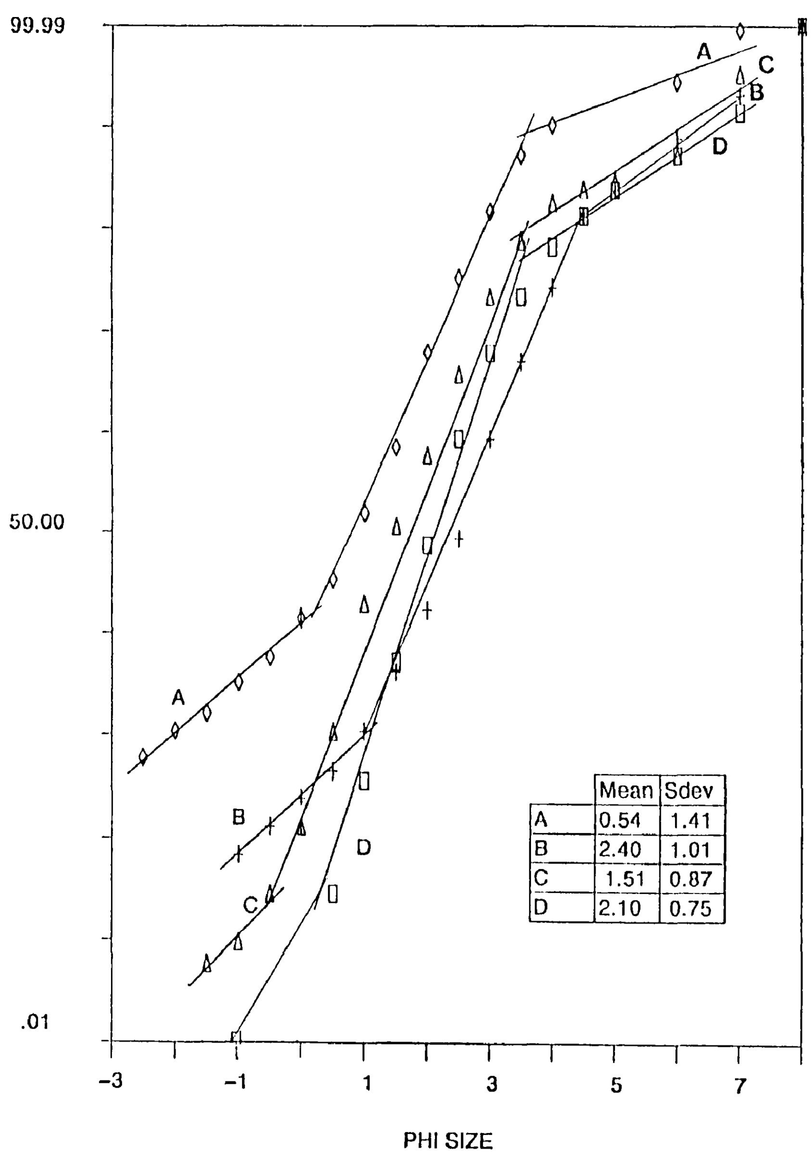
Figure 2.44 Trough cross-stratified sands (A) transitional to trough cross-stratified gravels (B).

Figure 2.45 Grain size distributions.

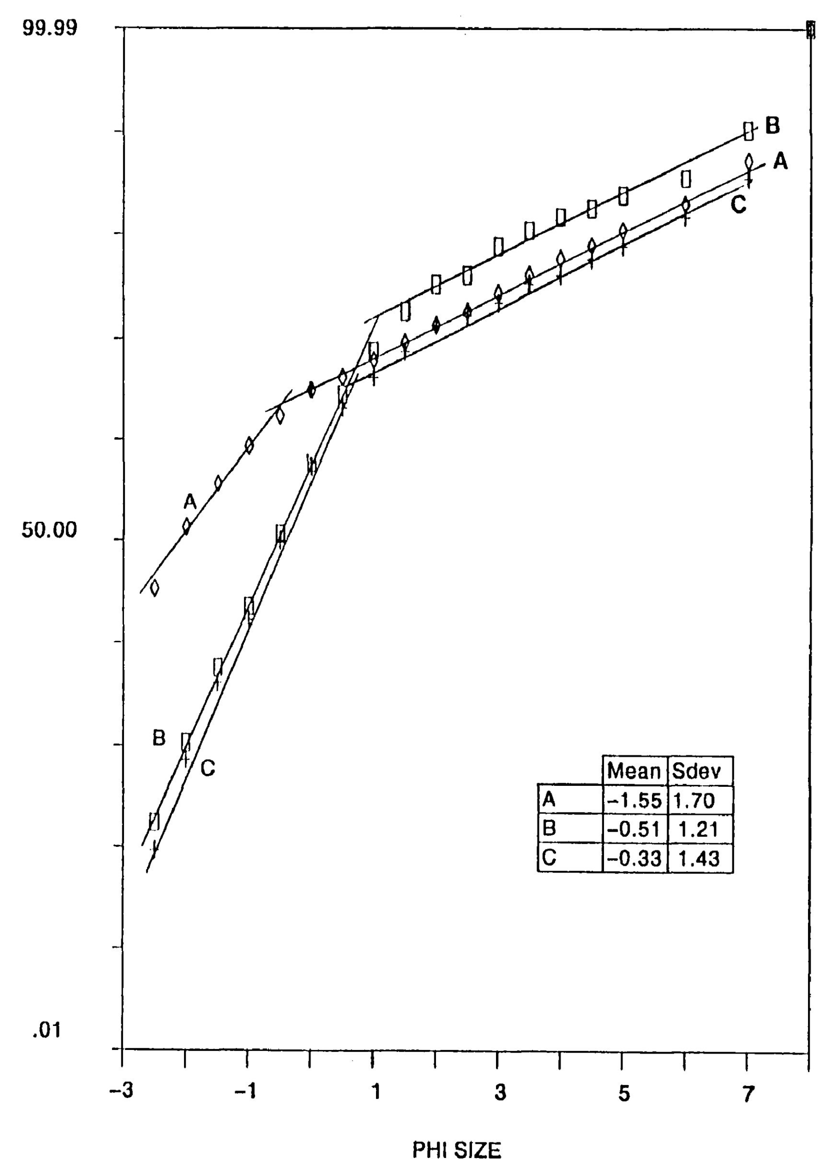
A. Trough cross-stratified sands.

B. Trough cross-stratified gravels.

A


99.99
50.00
.01
-3
-1
1
3
5
7
PHI SIZE
A
B
C
D
Mean Sdev
A 0.54 1.41
B 2.40 1.01
C 1.51 0.87
D 2.10 0.75

B


99.99
50.00
.01
-3
-1
1
3
5
7
PHI SIZE
A
B
C
Mean Sdev
A -1.55 1.70
B -0.51 1.21
C -0.33 1.43

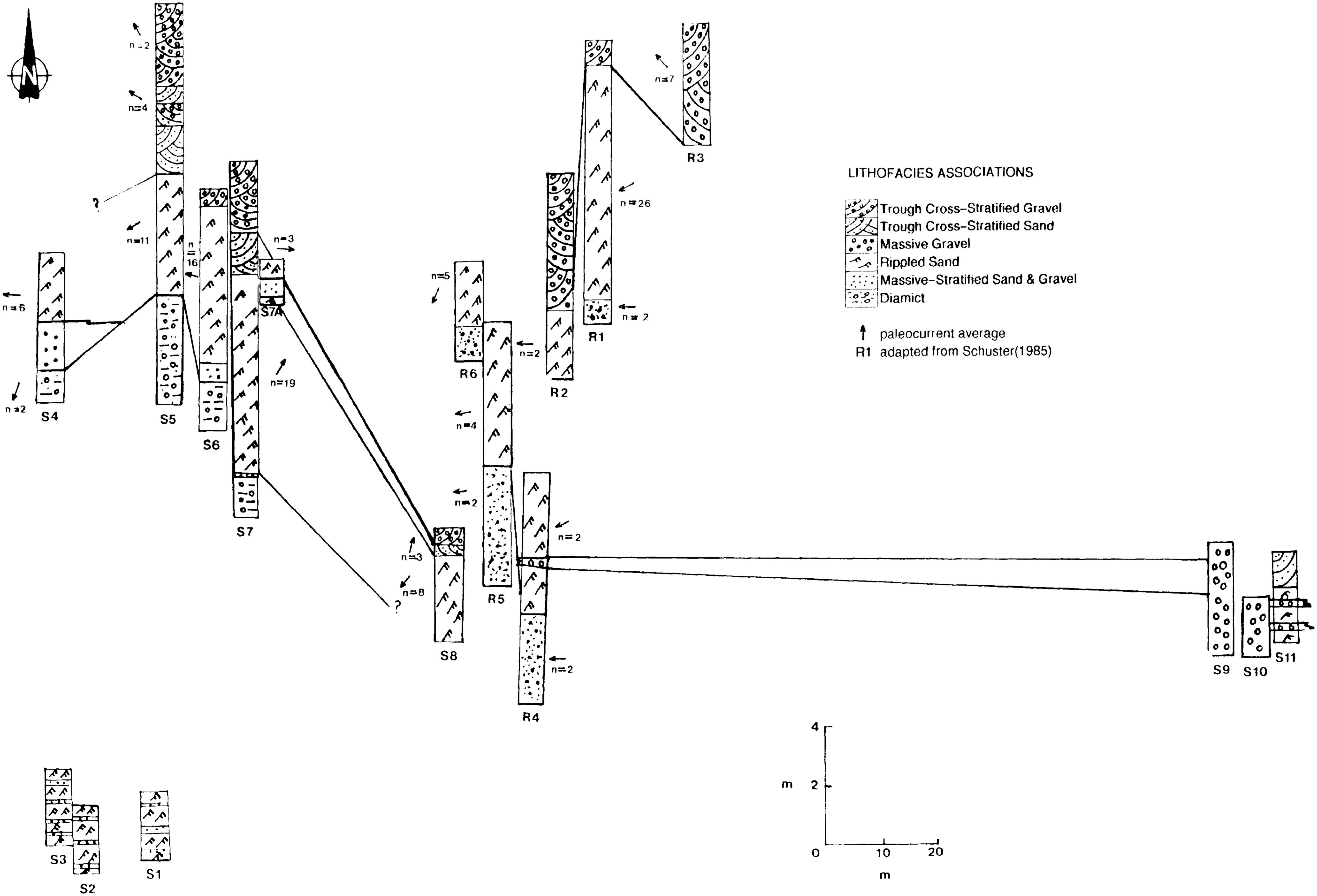


Figure 2.46 Fence diagram showing stratigraphy of lithofacies associations within the KOA succession. Sections are positioned on true relative elevations.

theodolite transit and chain were used to determine the relative elevations and lateral spacing of the stratigraphic sections logged. Please note the vertical scale of Figure 2.46 is exaggerated 5-fold. The diamict L.A. is the lowest stratigraphically, and is restricted to the western sections. Two paleocurrent measurements obtained from stratified units within the diamict in section S4 average 203°. The massive-stratified sand and gravel L.A. abruptly overlies the diamict L.A. It was found in all sections except for S5. It may be present beneath section S8, and R2, as the bottom contact of the rippled sand L.A. was not found in these successions. Beds within the massive-stratified sand and gravel L.A. which were mapped by Schuster (1985) show an overall paleocurrent trend to the west (268°). The rippled sand L.A. is the thickest L.A., and overlies the massive-stratified sand and gravel L.A. Paleocurrents within the rippled sand L.A. generally show a southwest to westerly trend. One exception is noted in section S7, with a paleocurrent trend to the north-northeast (034°). The rippled sand L.A. within Schuster's (1985) sections also show a general southwest to westerly trend. When the overall trend of the rippled sand L.A. of Schuster's (1985) sections (252°) and sections mapped here (284°) is combined, the overall trend for the rippled sand L.A. in the pit is almost due west (262°). Group 2 of the rippled sand L.A. and group 2 of the massive-stratified sand and gravel L.A. are interbedded in sections S1, S2, S3 which are at the lowest elevation in the succession. These lithofacies are also found interbedded in section S7A, at a higher elevation near the top of the rippled L.A. Section S7A is contained within a wedge shaped package of sediments dipping at approximately 20 to the horizontally bedded rippled sand L.A. (Figure 2.47). In the eastern section of the pit (sections S9 and S10), stratified pebble to boulder gravels were mapped and assigned to the massive gravel L.A. Wedges of gravel from these deposits were interbedded with the rippled sand L.A. (section S11) directly beside the stratified gravels of section S10 and further to the west in sections R4 and R5. The trough cross-stratified sand

Figure 2.47 Wedge shaped slice of sediments overlying the horizontally bedded rippled L.A. with marked disconformity.

L.A. erosively scours into the rippled sand L.A. This L.A. has a restricted occurrence, appearing in only 4 sections, and exhibits a wide range in paleocurrent trends. These sands are transitional to trough and planar cross-stratified gravels, present at the top of the columns. The overall paleocurrent trend for these gravels is to the northwest (323°).

CHAPTER III

DEPOSITIONAL ENVIRONMENT

INTRODUCTION

This chapter outlines the depositional environment for the three deltaic successions mapped. The same procedure is followed for each delta. The processes involved during deposition, as well as site of deposition are interpreted for each lithofacies association. The stratigraphic framework of the lithofacies associations, as well as the processes of deposition for each lithofacies association are outlined to determine the overall depositional environment of each delta.

BEARDMORE SUCCESSION

(a) INTRODUCTION

Four lithofacies associations (L.A.) were delineated in the Beardmore succession. Reverse-graded, rippled, massive and planar cross-stratified lithofacies associations were deposited within a low lying east-west trending valley, as outlined previously in Figure 1.2.

The overall coarsening upward succession and lithofacies present in the Beardmore assemblage strongly suggests a deltaic system prograding into a glacial lake which probably formed during the retreat of the Nipigon phase of the Hudson Bay ice mass (as defined by Zoltai,1965b), approximately 10,000 years B.P. Each of the L.A.s represent deposition within a distinct region of the delta. A delta may be divided into three areas; the delta plain (topsets), the delta front (foresets) and the prodelta (bottomsets). Definitions of delta plain, delta front and prodelta areas and their boundaries tend to vary and overlap in the literature. For the purpose of this discussion, the following definitions will be used. The delta plain is the region containing level or nearly level sediments which are continuous with a landward alluvial plain. The delta front is the sloping region between the delta plain and prodelta, and represents the area of most active deposition. The prodelta is the region which lies beyond the delta front, and contains horizontal or gently inclined layers of sediment. Before suggesting in what area of the delta each L.A. was deposited, the problem of distinguishing between the delta plain and delta front environment must be discussed. In glacial deltas discussed by Smith and Eriksson (1979), Clemmenson and Houmark-Nielsen (1981), Leckie and McCann (1982), Kelly and Martini (1986), and McPherson et al (1987) the delta plain is composed of coarse-grained sands and gravels of a braided river system. If the delta front of a delta is dominated by fine sands such as the successions mapped by Leckie and McCann (1982) and Kelly and Martini (1986) it is easy to delineate the coarser grained delta plain beds from the delta front succession. The problem arises when sediments in the delta plain and delta front are relatively the same grain size. Outwash plains of fans studied by Boothroyd and Ashley (1975), and Boothroyd and Nummedal (1978) indicate delta plain material decreases in grain size downfan to fine-grained sand at the distal margin. The fan or delta front fed by these outwash plains would be fine-grained also and the distinction between the delta plain and delta front would have to be based on information other than grain size. This problem may also exist if the delta plain and delta front environment are both coarse-grained. However, if the delta front deposits are coarse-grained high angle planar cross-stratified beds (i.e. the foresets of a typical Gilbert delta), the transition between the delta front and delta plain environment should be marked by an erosional contact caused by the rapidly switching channels of the coarse-grained fluvial system within the delta plain. Many glacio-deltaic sequences have been documented which show this erosional contact between the delta plain and delta front environments (Gustavson et al,1975; Smith and Eriksson,1979; and Clemmensen and Houmark-Nielsen,1981). Within the Beardmore succession, an erosional contact between delta plain and delta front environment was not seen. However, the dipping set boundaries within the planar cross-stratified L.A. may be interpreted to represent foreset surfaces of the delta (see (iv) planar cross-stratified L.A. in following text). Therefore, for the following discussion, the four L.A.s will be assigned to the prodelta and delta front environment.

The reverse-graded L.A. found at the base of the succession represents prodelta deposits. The rippled and massive L.A.s which overlie the reverse-graded L.A. were deposited in the lower delta front area. Both of these L.A.s are overlain by planar cross-stratified gravels which represent the mid to upper delta front deposits.

In the Beardmore pit, there are two coarsening upward successions. The lower one was deposited by flows mainly to the east and northeast, and consists of the rippled L.A. juxtaposed between the reverse-graded L.A., and the lower planar cross-stratified L.A. The upper succession trends mainly to the north, and is composed from bottom to top of the reverse-graded L.A., massive L.A., and the upper planar cross-stratified L.A. The depositional environment of each of these L.A.s will be expanded on in the following text.

(b) LITHOFACIES ASSOCIATIONS

(i) Reverse-Graded Lithofacies Association

The reverse-graded L.A. is found at the base of both coarsening upward sequences within the Beardmore succession. The following discussion of the deposition of the L.A. suggests the reverse-graded units are part of the prodelta region of the delta.

Documentation of reverse-graded beds within a glacial deltaic setting are sparse in the literature. Both Aario (1972) and Jorgensen (1982) record minor reverse-graded beds. Jorgensen (1982) suggests the reverse grading is a result of dispersive pressure, as outlined by Bagnold in 1954. It should be noted that the concept of dispersive pressure causing inverse grading has only been documented in coarser sized material. Aario (1972) states the reverse-graded beds in his study area record suspension deposition. The inverse grading "suggests deposition by currents of increasing velocity, the fine-sediment supply ceasing during the deceleration phase." The reverse-graded beds of the Beardmore delta were likewise probably deposited by interflows and overflows (dominated by suspension deposition) within a glacial lake, rather than by underflows. Generally, reverse grading is rare because in systems where fluid pressure (P) and boundary shear stress (τ_o) are the principal forces acting to move grains, the upward increase in grain size denotes an increase in flow velocity (u) with time. Obviously if the accelerating current is in contact with a noncohesive bed erosion not deposition will be occurring. Thus, to get reverse grading either the primary force inducing motion must not be fluid pressure (this is the case when dispersive pressure causes reverse grading), or the flow can not be in contact with the bed. Therefore, it is possible to suggest that deposition of the reverse-graded beds was carried out by interflows and overflows, rather than underflows. Any deposition from constantly operating underflows would result in formation of traction current deposits.

The grain size plots of the bottom, middle and top of a typical reverse-graded bed show increases in average grain size from bottom to top. While the water is fairly quiet, clay in suspension within the lake will settle out depositing background fine-grained material. As the flow initially extends out into the lake, very fine sand grains will be sedimented. As the flow reaches its peak, the velocity is at a maximum, and larger grain sizes will be deposited over the finer material. The repetitive stacking of the thin reverse-graded beds in this L.A. suggest that the inter/over flows were short, discrete pulses entering the lake.

These pulses probably represent fluctuating flow conditions within the river system entering the lake. According to Middleton and Southard (1984) the relative porportion of material which moves as bed load and suspended load is a function of the material itself (especially its size) and the flow conditions. Middleton and Southard (1984) state very coarse bed material (gravel) in rivers would travel as bed load, whereas fine to medium sand would be carried as suspended load. Due to fluctuating hydraulic conditions, Middleton and Southard (1984) define the intermittent suspension load, which is formed of material coarser than fine sand, which is not in continuous suspension. As described earlier, the coarsest portion of the reverse-graded units is generally fine and in rare cases medium sand.

The grain size plot of the reverse-graded units (Figure 2.4A) indicates traction, saltation and suspension populations. The process outlined above suggests the reverse-graded units represent suspension deposition from interflows and overflows entering the lake from the mouth of a river. The material carried into the lake will already have been sorted to some degree by river processes into traction, saltation and suspension populations. The presorted nature of the sediment (due to the river processes) would probably not be destroyed through suspension deposition from the interflows and overflows. Therefore, it is possible to expect that grain size analysis completed on samples taken from the reverse-graded units may indicate 'relict' grain size populations, as seems to be the case shown in Figure 2.4A.

It would be expected that as the flow wanes after peaking, finer material would settle out producing a normal-graded succession overlying the reverse-graded unit. The reverse-graded beds documented in Beardmore and by Aario (1972) and Jorgensen (1982) do not show this trend. Aario's (1972) explanation of the cessation of fine-sediment supply would explain the lack of graded fine material at the top of the bed, yet it does not seem feasible that the supply of fine grained sediment would end abruptly. The lack of a normally graded interval overlying the reverse-graded unit is perplexing.

Minor massive units found interbedded with the reverse-graded beds were deposited by interflows or overflows entering the lake. Generally, massive beds may form by rapid deposition of sediment (primary) or by dewatering of a bed after it has been deposited (secondary) (Reineck and Singh, 1980). Deposition of these massive beds could be considered of a primary nature. The deformed bed of fine sand and clay, found overlying a thick massive bed was formed by the loading of sand into the clay. When the sand was deposited on the clay, unequal loading caused vertical movements of the sand layer. The sand either sunk a lobes, or the clay layer pushed upward in the form of tongues.

Rippled beds interlayered with the reverse-graded beds suggest occasional flows were denser than the lake water, resulting in development of an underflow. The deposition of ripples is discussed in more detail in the section on the depositional environment of the rippled L.A.

One possible explanation for the atypical beds found in the western end of the succession may be that at the time of deposition of reverse- graded beds within the lake basin, a subaqueous distributary channel developed down the delta front. Clemmensen and Houmark-Nielsen (1981), Vos (1981), Kostachuk and McCann (1987) and Prior and Bornhold (1988) all document development of subaqueous distributary channels or 'chutes' within the delta front. Within the distributary channel planar cross-stratified sand beds were deposited. Due to the slope induced instability of the material in the channel, it slumped, forming the diamict bed. Also as a result of this slump, finer material ejected as the sediment flowed would have been resedimented forming thin graded beds.

(ii) Rippled Lithofacies Association

Rippled cross-stratified beds, along with type A and B climbing ripple lamination (as defined by Jopling and Walker 1968) were found interbedded with minor massive and graded beds. These units overlie the finer grained reverse-graded L.A., and are erosively scoured by the overlying planar cross-stratified L.A. The association of the rippled units with the massive and graded beds, as well as the juxtaposition between the reverse-graded and planar cross-stratified L.A. suggest the rippled L.A. represents deposition of lower delta front sediments in a glacial deltaic setting. Numerous authors (for example Jopling and Walker,1968; Aario,1972; Gustavson et al,1975; Shaw,1977; Smith and Eriksson,1979; Clemmensen and Houmark-Nielsen,1981; and Leckie and McCann,1982) have documented similar associations, and have interpreted deposition as part of a glacial deltaic system. Therefore, the rippled beds may be interpreted as being deposited by density underflows entering a glacial lake, specifically flow which comes in contact with the delta toesets and lake bottom. Jopling and Walker (1968) suggested that the ripple lamination resulted from density underflows of sediment-laden meltwater flowing into a glacial lake. The different types (A,B, sinusoidal) are a result of small fluctuations in the current velocity, as well as variations in the composition and concentration of suspended sediment. Type A represents deposition dominantly from bed load, while sinusoidal lamination would represent dominant fallout from suspension. The change from type A to B to sinusoidal records an increase in the ratio between suspended load and bed load.

The graded beds found interlayered with the rippled beds may be deposited by two processes. Many authors (Ashley,1975; Gustavson,1975; Gustavson et al,1975; Harrison,1975; Sturm and Matter,1978; and Cohen,1979) suggest graded beds in their studies originated from seasonally-operating density underflow/turbidity currents. Sturm and Matter (1978) also document graded bed deposition from underflows which are actually low-density slump generated turbidity currents. Smith and Ashley (1985) state seasonally-operating density underflows distribute the bulk of sediment in lakes dominated by underflows. However, they also note that it is difficult to distinguish whether the underflow was generated seasonally or by deformation and failure of unstable deltaic deposits.

The massive units found interbedded with the reverse-graded beds may have also been deposited by interflow or overflows, by the manner suggested previously in the reverse-graded L.A. The interbedding of the rippled as well as the graded and massive beds is to be expected, as interflow and overflows will occur intermittently with underflows.

The parallel-laminated beds within this L.A. are restricted to two sections. In the western section, a series of parallel-laminated beds overlie the one planar cross-stratified unit in this L.A. The position and association of the planar and parallel–laminated beds has been interpreted as representing deposition within a subaqueous distributary channel which developed down the delta front, similar to those inferred in the reverse-graded L.A. Vos (1981) documents subaqueous distributary channels on a delta front of a fan delta which show a fining upward sequence from trough cross-bedding up into plane bedding, followed by a complex combination of plane and ripple bedding. In the rippled L.A. only part of this fining upward sequence appears. It is possible to suggest the overlying planar cross-stratified L.A. may have eroded away the uppermost sequence of the channel.

The other parallel-laminated units are located in the easternmost section. These units are interbedded and associated with massive, graded and rippled beds. In this sequence, these beds may be part of a low density turbidity current as described by Lowe (1982). The possibility that these beds represent additional subaqueous distributary channels can not be ruled out though.

(iii) Massive Lithofacies Association

The lateral discontinuity of the massive and diamict beds as well as their composition and position in the succession suggest the majority of the units in the massive L.A. were deposited by sediment gravity flows. Sediment gravity flows occurring on delta fronts have been documented by numerous authors (for example de Vries Klein et al,1972; McPherson et al,1987; Postma,1984). Deposition from sediment gravity flows in a glacial environment has also been discussed by various authors (for example Eyles and Eyles,1983; Miall,1983; Mustard and Donaldson,1987). Jorgensen (1982) and Leckie and McCann (1982) have interpreted units within glacial deltaic successions mapped as representing deposition from sediment gravity flows within the delta front. Leckie and McCann (1982) interpreted structureless sand within a glacial delta to represent grain flows on the delta front. Jorgensen (1982) interpreted similar sands to indicate deposition from flows transitional between liquefied and turbulent flow (as described by Lowe 1976). Matrix supported diamictite documented by Jorgensen (1981) has been interpreted as originating from debris flows as defined by Hampton in 1972. In other glacially influenced environments Miall (1983) and Mustard and Donaldson (1987) interpret massive and slightly graded sandstone units to represent deposition from grain flows/fluidized flows/liquefied flows as described by Lowe (1976,1979). Similary, these authors interpret matrix supported diamictites as a product of debris flows. Likewise, it is possible to suggest the massive and diamict beds are products of sediment gravity flows within the delta front.

In the westernmost section of the succession the massive L.A. is interbedded with primarily rippled units, interpreted to have been deposited by underflows/turbidity currents in a similar manner to that described in the rippled L.A. The central sections which exhibit the massive L.A. are a mixture of interbedded massive beds, massive beds with coarser stringers, graded beds, diamict beds and rippled units. These beds represent an influx of intermittent sediment gravity flows reworking and resedimenting the material of the delta front. The initiation of the sediment gravity flows can not be determined, but may have been caused by slumping on the delta front.

The possibility of the diamict representing a pre-deltaic ice-marginal phase is unlikely since the diamict shows no sign of being associated with grounded ice (i.e. erosional contacts, incorporation of underlying beds, shaped, striated oriented clasts, shear surfaces and vertical joint sets a outlined by Eyles and Miall,1986), as should be the case due to the shallow nature of the lake.

(iv) Planar Cross-Stratified Lithofacies Association

As described earlier, the planar cross-stratified L.A. is formed of one or more large-scale planar cross-stratified sets. These planar cross-stratified sets represent deposition in the upper delta front and are interpreted as "foresets" of a typical Gilbertian delta. Gilbert (1885) first documented avalanching in Pleistocene deltas by noting that the slope of the delta face is equal to the angle of repose of the coarser material which slides down the face of the delta under its own weight. As the delta progrades, the steeply inclined layers of the delta face are superimposed over the underlying gently sloping strata. Examples of glacial "Gilbert" delta foresets deposited by avalanching are numerous (for example Gilbert,1972; Orombelli and Gnaccolini,1978; Cohen,1979; Smith and Eriksson,1979; and Clemmensen and Houmark-Nielsen,1981). The beds of the planar cross-stratified L.A. were deposited by avalanching, and represent classic Gilbertian delta foresets.

As described previously the sets within this L.A. are differentiated by erosional surfaces, which may or may not be draped by massive units. Clemmensen and Houmark-Nielsen (1981) suggest angular unconformities between their foreset beds, combined with fining upward sequences within the foresets represent delta progradation in several episodes. In a similar manner, the sets within the L.A. may represent separate stages of delta progradation. The set boundaries in the Beardmore succession are also dipping. These set boundaries can be called a third-order surface (as defined by Miall 1988). According to Miall, third order surfaces indicate stage changes or changes in bedform orientation.

Rare massive finer grained beds represent deposition on reactivation surfaces between the planar cross-stratified beds. Miall (1988) suggests his 3rd order surfaces "indicate a large-scale 'reactivation.'" The reactivation surfaces develop due to fluctuating water stages, similar to the process operating on linguoid bars as described by Collinson (1970). The planar cross-stratified and minor massive beds may be considered a larger scale of Collinson's bar model. During highwater stage, bed load sediment avalanches down the delta front, depositing large scale planar cross-stratified units. During less energetic flow stages, suspension deposition of fine-grained material occurs on the surface of the planar cross-stratified beds. Avalanching begins again, in the following high water stage, burying and preserving the falling water stage deposits.

Within the foresets themselves, fining upward sequences within a set were rarely observed. Often, grain size increased within an individual set. This coarsening upwards trend in grain size within individual foresets has not been previously documented. As already stated, planar cross-stratified beds are formed by avalanching of bed load down the delta face. Coarser material should roll to the base of the slope, whereas, finer material is caught in irregularities and deposited further up the slope, producing a fining upward unit as the system progrades. As the avalanching continues fining upward beds would be stacked upon each other, as documented by Clemmensen and Houmark-Nielsen (1981). There are two possible explanations for the unusual coarsening upward trends documented at Beardmore. The first is that larger material does not avalanche to the toeset area. A second possibility requires an increase through time in the velocity of the current delivering sediment to the break in slope. Neither of these explanations can completely explain the coarsening upward trend. It is evident that more work is needed to determine why grain size increases upward within individual sets.

The predominance of subangular metasediments and metavolcanics in the pebble samples taken from the planar cross-stratified beds indicates a local source for the sediments.

(c) OVERALL BEARDMORE SEQUENCE

The environment represented by the beds in the Beardmore succession appear to be that of a deltaic system prograding into a glacial lake. The close association of the trend of the paleocurrents between the reverse-graded L.A. and the overlying rippled L.A. suggests the bottom reverse-graded L.A. represents prodelta deposition. At this time the glacial lake was dominated by numerous pulsating, discrete interflows and overflows, which deposited the thin, stacked reverse-graded beds (Figure 3.1A). Occasionally these interflows and overflows would deposit nongraded beds. The presence of a few rippled beds interlayered with the reverse-graded units, suggest occasionally the plume water was denser (probably due to sediment concentration) than the lake water, and underflows developed. Rarely, coarser grained material would load into underlying finer-grained sediment, causing minor deformation of a bed. The beds in the reverse-graded L.A. indicate deposition from flows trending generally in an easterly (091°) direction.

As the delta began to prograde, underflows in the area of the section studied became more common, and dominantly rippled beds, as well as minor graded beds, were deposited in the distal section of the delta front (Figure 3.1B). The rippled beds show the area where the underflow was in contact with the bottom. Occasional interflows and overflows deposited some of the massive beds. The underflows show a general easterly trend (083°), similar to the reverse-graded beds. The presence of restricted coarser grained parallel-laminated and planar cross-stratified units in the reverse-graded and rippled L.A.s suggests the development of subaqueous distributary channels down the delta front.

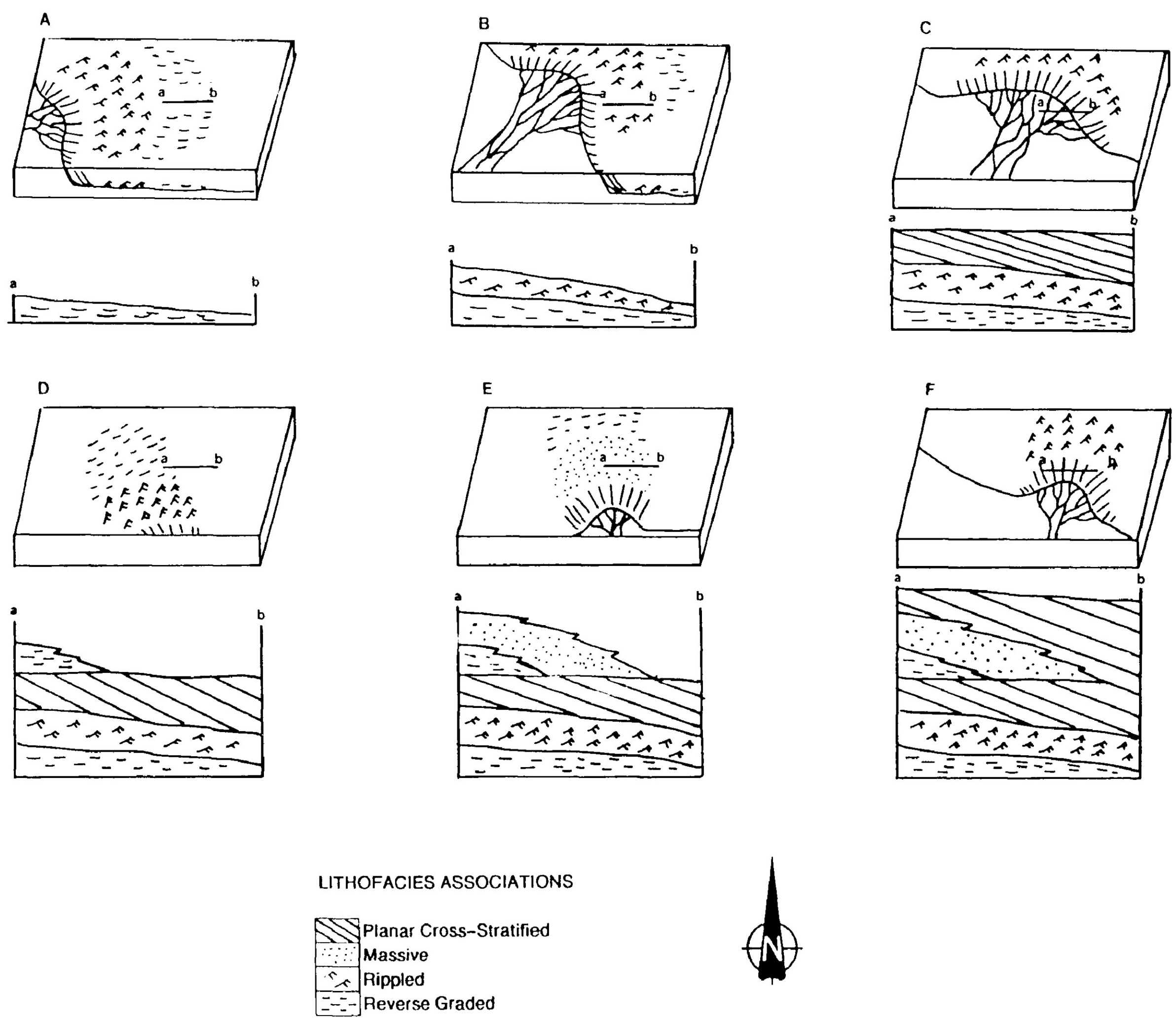


Figure 3.1 Sequence of deposition of lithofacies associations within the Bearmdore succession. Line a - b represents the face of the sand and gravel pit. Direction of progradation is defined by paleocurrent trends in the pit.

The lower planar beds represent a small scale "Gilbertian" delta prograding into the lake. The foresets were deposited mainly by avalanching of the traction load, as explained earlier. Since these sediments are coarser than the underlying rippled sands, the planar beds often loaded into the rippled beds. The flow appears to have taken on a more northerly course, as the overall trend for this L.A. is 007°, as shown in Figure 3.1C.

At this time, the locus of deposition switched, and another deltaic sequence began building into the lake. Interflow and overflow pulses deposited limited reverse-graded beds distally from the actual delta. These beds, present only in sections 1 and 2 indicate the delta was building initially to the north-northwest (343°) (Figure 3.1D). As the delta continued to prograde, underflows began to dominate deposition and rippled beds were deposited on the lake bottom. At this time, it appears that the delta front may have been relatively unstable, as numerous discrete pulsing sediment gravity flows deposited the discrete, discontinuous beds of the massive L.A. (Figure 3.1E). The upper planar L.A. represents the "Gilbertian" foresets prograding over the bottomset beds (Figure 3.1F). The individual section trends from west to east mentioned earlier, suggest the foresets were building out in a general arcuate or lobe shape manner. The general trend for the upper planar L.A. is 015°.

CAMP 25 SUCCESSION

(a) INTRODUCTION

Four lithofacies associations (L.A.) were outlined from the deposits examined at the Camp 25 succession. The sequence was excavated in the side of a lobate hill. The sediments coarsen upward from fine-grained massive silt and rippled sand L.A.s to trough cross-stratified sand and diamict-bearing L.A.s. Angular outsized dropstones within the massive silt and rippled L.A.s suggest deposition within a lake, influenced by floating ice. The lobate shaped hill is part of a larger region interpreted as glaciofluvial ice contact deposits by Kristjansson et al (1989). Esker systems directly north and south of the succession suggest close proximity of the ice margin during deposition. The overall coarsening upward sequence combined with geographic and topographic positioning suggest the succession represents a delta prograding into a proglacial lake.

For the discussion of the depositional environment of the Camp 25 deposits, the L.A.s will be assigned to the prodelta and delta front, as it is not possible to determine whether the sediments represent delta plain deposition. The massive silt L.A. represents deposition within the prodelta region. The rippled sand, trough cross-stratified sand and diamict-bearing L.A.s were all deposited on the delta front. The rippled sand L.A. represents deposition within the "distal" portion of the delta front, while the trough cross-stratified sand L.A. is indicative of the "proximal" delta front. The diamict-bearing L.A. records flood events within the braided river system, with the effects being recorded in the sediments in the delta front. The depositional environment for each of the L.A.s is described in detail in the following text.

(b) LITHOFACIES ASSOCIATIONS

(i) Massive Silt Lithofacies Association

As described previously, the massive silt L.A. is the basal unit in the Camp 25 delta. It is restricted to the three northern sections and is overlain by the rippled sand L.A. and the coarse-grained trough cross-stratified and diamict-bearing L.A.s. Minor rippled beds are associated with the massive silts. Silt and clay units overlain by coarsening upward sequences of sand have been documented by numerous authors, who interpret deposition as part of a glacial deltaic system (for example Theakstone,1976; Shaw,1977; Smith and Eriksson,1979; Jorgensen, 1982; Leckie and McCann, 1982; and Kelly and Martini,1986). The stratigraphic position and grain size suggest the massive silt L.A. represents the prodelta region of the

Camp 25 sequence. Outsized metasedimentary clasts found throughout the massive and minor rippled beds of the L.A. support this interpretation. Deformation of laminae beneath these clasts combined with their lack of hydraulic equilibrium with surrounding sediments suggests they are dropstones. The dropstones have two possible origins: rafting from icebergs or deposition through melting of a basal portion of the ice front of a glacier. According to Shaw (1985) "clasts dropped from an ice shelf or floating ice sheet are not distinguishable from those rafted by icebergs or lake ice." However, the following text will demonstrate that in some glacial sequences one origin of the dropstones is more probable than the other. A general review of debris zones within a glacier indicates the existence of three zones: basal, englacial and supraglacial. The basal zone is debris-rich due to basal erosion, frontal incorporation and supraglacial entrainment around the glacier margins. Within the englacial zone debris is generally dispersed. However, high concentrations may occur where debris is carried up from the bed along shear planes. Within the supraglacial zone, debris is derived from adjacent slopes or represents englacial or basal debris transported to the ice surfaces along shear planes or flow lines within the glacier (Shaw,1985). Studies of the lithologies of debris within the englacial zone of a glacier indicate the basal material was mostly locally derived while the topmost material was farthest travelled. The upward sequence of debris reflected in reverse order the lithologies over which the glacier had travelled (Boulton,1970).

A floating ice margin or shelf would contain debris representative of all three zones. Release of debris from a floating ice shelf or margin would be mainly from the melting of the basal zone of the glacier floating in the water. The debris released from this zone would be representative of the local lithology, as suggested by Boulton (1970).

Icebergs calving from the ice margin also carry debris from all three zones. If icebergs released sediment through basal melting only, the debris would be similar to that described above. However, Ovenshine (1970) notes that most debris released from icebergs involves tilting, fragmentation or overturning of the icebergs. The debris released through these processes would include englacial and supraglacial debris, as well as basal debris which had been transported to the englacial and supraglacial zone. As suggested by Boulton (1970), this debris should represent a larger range of lithologies, indicative of the different types of outcrop the glacier had advanced over.

The dropstones within the Camp 25 succession are predominantly angular, metasedimentary clasts. The Camp 25 delta is located within the east-trending Beardmore-Geraldton metasedimentary sub-belt (Mason and White, 1986) whereas an igneous terrain exists to the north. This indicates a local source for the dropstones and suggests the clasts would represent deposition through the basal melting of the ice sheet. As outlined in the previous text, clasts rafted from icebergs should be representative of the metasedimentary, as well as other terrains which the glacier had advanced over. The possibility that icebergs may have not developed within the lake due to the shallow depth of the lake, as indicated by the topography of the area (Figure 1.2), is another important fact which suggests deposition from basal melting was more likely within the Camp 25 succession than iceberg rafting.

The fine-grained massive beds represent suspension deposition within a small proglacial lake, as indicated by the presence of dropstones. The suspended material may come from two sources; either from a subglacial tunnel or conduit which enters the lake from the glacier (Gustavson,1975; Shaw,1985) or from eolian silt drifted in suspension by winds and deposited in the lake (see Piper and Panagos,1981, for a similar process). The rippled beds associated with the massive beds indicate that occasionally flows entering the lake from the conduit were denser than the lake water, resulting in the development of an underflow.

Detailed mapping by Kristjansson et al (1989) in the vicinity of the Camp 25 succession does not indicate large-scale, flat-lying fine-grained sediments usually interpreted as lake deposits, suggesting the proglacial lake the succession was deposited in was very small. Even though the proglacial lake was small, currents may rework bottom sediments in a similar manner to that suggested by Eyles and Eyles (1983). The sorting of the clasts within the atypical bed indicates that some amount of current reworking was taking place on the lake bottom.

(ii) Rippled Sand Lithofacies Association

This L.A. is associated with minor massive and graded beds, and is underlain by finer grained beds and overlain by coarser cross-stratified sands, in a manner similar to the rippled L.A. described in the Beardmore succession. Numerous authors have documented similar associations, and have interpreted deposition as part of a glacial deltaic system (for example Jopling and Walker,1968; Gustavson et al,1975; Smith and Eriksson,1979; Leckie and McCann,1982; and Kelly and Martini,1986). Jopling and Walker (1968) suggested ripple lamination resulted from density underflows of sediment-laden meltwater flowing into a glacial lake. The positioning and beds of the rippled L.A. suggest deposition has been primarily by underflows in the "distal" or lower section of the delta front.

The underflows were also responsible for the deposition of the graded beds interlayered with the rippled beds. Deposition of similar rippled/graded sequences has already been discussed in the rippled L.A. in the Beardmore sequence.

The massive units interbedded with the climbing ripple sequences were deposited by interflows and overflows. This is based on reasons similar to those provided in the depositional environment section discussing the reverse-graded L.A. in the Beardmore succession.

The dropstones found within the rippled beds also originated from a local source, and probably represent basal melting of the ice sheet, in a similar manner to that described in the massive L.A. The dropstones indicate the presence of an ice margin, and suggest underflows may have entered the lake through a subglacial/englacial conduit or a deep crevasse within the ice front.

Many of the climbing ripple sequences are deformed and faulted suggesting the sediments may have been deposited against an ice margin, undergoing displacement when the ice melted. Shaw (1977) attributes rotation and intense faulting within "Gilbertian" foresets of a delta to the removal of ice support, which the sediments were deposited against. Several fault types observed in glaciofluvial sediments have been attributed by McDonald and Shilts (1975) to deposition against or over ice.

(iii) Trough Cross-Stratified Sand Lithofacies Association

As described previously, the coarser grained trough cross-stratified L.A. has rippled, massive and plane-laminated beds associated with it, and overlies the rippled L.A. Based upon its position in the succession and the bed types within the L.A. the trough cross-stratified sand L.A. may be interpreted to represent deposition and reworking of distributary mouth bars in the "proximal" region of the delta front.

Documentation of distributary mouth bars associated with fine-grained deltaic systems is extensive. However, distributary mouth bars associated with coarser grained deltas such as those fed by a braided system in a glacial environment are sparse (Farquharson,1982; Dunne and Hempton,1984; Bergh and Torske,1986; Orton,1988 and Wood and Ethridge,1988). A brief discussion of the terminology and definitions applied to coarse-grained deltaic systems is warranted. Coarse-grained delta systems were formerly automatically classified as fan deltas. McPherson et al (1987) initially suggested the term braid delta defining them as "gravel rich deltas formed where a purely braided alluvial-plain system progrades into a standing body of water; they are not necessarily associated with alluvial fans." They also define a fan delta as a "coarse-grained (gravel-rich) delta formed where an alluvial fan is deposited directly into a standing body of water from an adjacent highland." The fan delta and braid delta are distinguished by their subaerial features. A fan delta is dominated by alluvial-fan facies (interbedded sheetflood, debris-flow and braided channel deposits) while a braid delta exhibits purely braided-river facies (braided-channel deposits) in the subaerial portion of the system (McPherson et al, 1988). According to McPherson et al (1988) the shoreline and subaqueous components may be similar. Subaqueously, both braid deltas and fan deltas display large-scale and coarse-grained gravelly foreset bedding.

The delineation of the deltas into fan delta and braid delta may be considered a step forward. However, to suggest that these deltas are going to develop Gilbertian foresets is too much of a generalization. This point may be exemplified by Orton (1988) who discusses 3 types of Middle Ordovician fan deltas (fluvial-dominated, wave-dominated and wave-modified) and a wave-modified braid delta. In all of the stratigraphic sections of the fan deltas and braid delta, large scale Gilbertian foresets are absent.

The wave-modified Capel Curig braid delta (Orton 1988) exhibits prodelta sediments overlain by a distal mouth bar, intermediate depth mouth bar and a barred shoreface. The distal lower facies is composed of very fine-grained sandstone units which exhibit grading, ungraded horizontal layering, low-angle planar cross-stratification and occasional ripple-lamination. The overlying or more proximal facies contains medium-grained sandstones with undulatory to horizontal stratification. The coarsening upward succession from mudstones to medium-grained sandstone within the delta front is interpreted to represent progradation of a distributary mouth-bar complex. The sequence is overlain by medium-scale, trough cross-stratified units and planar horizontally laminated beds both concentrated with heavy minerals.

These units are interpreted as a prograding barred shoreface, indicative of high nearshore wave-energy. Orton (1988) suggests that progradation of the Capel Curig braid system and the Skeidararsandur coastal braid system (a modern analogue to the Middle Ordovician Capel Curig system) results in mouth bar deposition within the delta front, which reflects localized sediment input through distributary channels. The rest of the delta front environment is characterized by shore-parallel bars and shoals representing reworking by waves of the distributary mouth bars.

During his mapping of the Camp Hill Beds in Antarctica, Farquharson (1982, Figure 6) interpreted a coarsening upward succession of thin-bedded rippled fine and medium-grained sandstone transitional to thick-bedded trough cross-stratified granular sandstone as a distributary mouth bar. The absence of an erosively-based channel sandstone or scour indicates deposition took place away from the point of discharge of the distributary channel, yet was still within the delta front.

Dunne and Hempton (1984) document Holocene mouth bar deltas within the Lake Hazar pull-apart basin. The prodelta region of the delta consists of interbedded silts, clays and fine sand. The delta front facies lacks foreset beds and is characterized by horizontally bedded gravels, sands, and silts. The coarser grained deposits of the delta plain erosively scour into the delta front facies. Similar mouth bar deltas in Paradox Basin, Colorado have been described by Wood and Ethridge (1988).

The middle member of the Proterozoic Skoadduvarri Sandstone Fromation has been mapped and interpreted as wave-reworked distributary mouth deposits truncated by stream channels with coarser sandstone fill (Bergh and Torske,1986). Coarsening upward cycles characterized by interbedded shale and mudstone units transitional to massive sandstone (with associated parallel-laminated, ripple cross-laminated and deformed sandstones), are overlain by heavy mineral parallel-laminated sandstones. These heavy mineral laminated sandstones are erosively scoured by trough cross-bedded sets grouped into cosets. The shale through heavy mineral sandstone units are interpreted to be wave-reworked distributary mouth bars. The stacked trough cross-bedded units represent deposition within the distributary channels (Bergh and Torske,1986).

Within the trough cross-stratified L.A. rippled and massive, fine-grained units are transitional to low-angle, cross-cutting, parallel-laminated units with heavy minerals. These are overlain by trough cross-stratified coarser grained sands. The trough cross-stratified sands scour into the low-angle parallel-laminated units. However, it is important to note that a large-scale erosive channel or scour filled with these trough cross-stratified sands was not observed within the succession.

The coarsening upward transitional sequence from rippled to trough cross-stratified sands within this lithofacies association may be interpreted as a distributary mouth bar deposit, analogous in some aspects to the distributary mouth bars described by Orton (1988), Bergh and Torske (1986) and Farquharson (1982).

The finer grained rippled and massive units represent the distal distributary mouth bar. Low-angle, cross-cutting (bundled), parallel-laminated sands, with heavy mineral lamination, interbedded with the rippled sequences suggest a beach environment. Examples of environments other than beach foreshore exhibiting bundled low-angle cross-bedding with heavy minerals could not be found in the literature. These beds are interpreted as wave-reworked distributary mouth bars based upon their similarity to a beach environment and position within the succession. Wave reworking affected the leading edge of the distributary mouth bar platform. Waves approaching the delta would first break on the distributary mouth bars situated furthest out in the lake. Redistribution by waves of sediment deposited in the delta front was documented in Bates' (1953) paper on the theory of delta formation. Vos (1981) records wave reworking of subaqueous distributary channel facies in an Ordovician fan delta, producing shallow submergent distributary mouth shoals and swash bars, offshore from a fluvial system. Orton (1988) documents reworking of his distributary mouth sequences by waves to produce a barred shoreface, as documented in detail in the previous text. Based upon their composition and associated lithofacies, the heavy-mineral laminated sandstones of the Koadduvarri Sandstone Formation are interpreted to have formed as a result of wave influence along delta shorelines, specifically upon distributary mouth bar tops (Bergh and Torske,1986).

The coarser grained trough cross-stratified sands would normally be interpreted to represent sedimentation within the distributary channel. However, as discussed earlier no large-scale erosive channel feature is seen, and occasionally the low-angle parallel laminated units are interbedded with the trough cross-stratified units. As indicated by Farquharson (1982), the absence of an erosively-based channel sandstone within the succession suggests a coarsening upward succesion from rippled sands to coarse-grained trough cross-stratified sandstones may represent the distributary mouth bar area within a delta front.

Faults found within this L.A. suggest close association to ice, as described in the rippled L.A. The faults in each of the lithofacies associations (rippled, trough and diamict-bearing) cross-cut more than one bed and do not show features indicating the deformation as being syndepositonal. Rare angular metasedimentary lonestones found in the three northern sections are interpreted as dropstones from basal melting of an overhanging ice sheet as discussed previously in the massive silt L.A.

(iv) Diamict-Bearing Lithofacies Association

The diamict-bearing L.A. overlies the trough cross-stratified L.A., to a restricted extent. The diamict units are interbedded or associated with all bed types within the L.A.; trough cross-stratified and low-angle plane-laminated sands, as well as finer grained rippled and massive sands. The diamict units exhibit erosional or loaded contacts where they overlie the other bed types. Due to the diamict-bearing L.A.'s restricted occurrence and the similarity of the non-diamict beds in this assemblage to the beds within the trough cross-stratified sand L.A., the diamict-bearing L.A. is interpreted to represent channelized flood events in the braided river system feeding the delta. The possibility of these diamict beds representing ice rafted units during intervals of high lake level (similar to those described at the Scarborough Bluffs by Eyles et al, 1983) is unlikely as the diamict beds are underlain by erosive bases.

Flood events are common in a glacial fed braided river environment due to the high variability and seasonality of glacial meltwater runoff (Rust,1972; Church and Gilbert,1975; and Smith,1985). It is possible to suggest high discharge events from the glacier occurred, eroding existing deposits to form water rich slurries, transitional between debris flows and high-stage discharge in a braided river system. Debris flows display plastic behaviour and are highly concentrated and highly viscous. Larger grains are supported by a matrix of interstitial fluid and fine sediment which has a finite yield strength (Middleton and Hampton,1976; Stow,1986). In contrast, flood events within braided river systems involve movement of coarser material within the traction population by grainflows, and a large proportion of finer grained material being carried in suspension. Since these water-rich slurries are transitional between debris flows and high-stage flood events, movement of material will involve interaction of processes occurring within both flow types. If there are enough clasts to interact within the slurry, movement may be partially by grainflow mechanisms. Otherwise, minor clasts may be carried in a matrix of fluid and fine sediment, not as concentrated or viscous as debris flows.

As noted in the histograms for the diamict samples, pebble, medium/coarse sand and silt grain sizes dominate. As mentioned previously, the water-rich slurry would erode away existing deposits. The source of the three populations in the sampled diamict may be exposed gravel bars existing within the braided river channel. The exposed bars would be formed of gravel beds with medium to coarse sand wedges at the bar margins. The abnormally large amount of silt may represent loess reworked from deposits formed on the gravel bar when the river was at a low stage (Rust 1972). High discharge events from the glacier resulted in flood surges which quickly become water-rich slurries as the flow eroded away existing gravel bars within the channel. The material in the slurries was dominated by pebbles, medium to coarse sands and silts and was carried downstream and deposited within and between already existing trough cross-stratified, rippled and massive sand in the proximal delta front.

The concept of existing sediment being reworked due to remobilization and influx of water in a glacial environment has been documented by Lawson (1982). He outlined four types of subaerial sediment flows and their deposits on the Matanuska Glacier in Alaska. The relative availability of sediment and meltwater determines which flow type will occur, with a continuum existing between all four types. The grain support and transport mechanism varies from shear strength through localized liquefaction and fluidization, transient turbulence and bedload traction and saltation to total liquefaction. Lawson's (1982) Type III flow is the closest analogy to the processes described previously for the deposition of the diamict L.A. Type III flows are channelized, are dominated by shear and flow at rates of 0.15 to 1.25 m/sec. Lawson (1982) stated "the passage of a Type III flow down a channel is marked by an increase in meltwater flow, passage of the head, and then gradual diminishment of the body until only sediment-laden meltwater is flowing in the channel." Type III flows are the most erosive of Lawson's four types, and often erode sediments of the outer banks of the channels. Lawson's (1982) description of subaerial flows indicates reworking of existing glacial deposits by sediment flows is possible, whether they are on top of the glacier or within the proximal braidplain.

From the previous discussion, it may be possible then to question whether the diamict units represent flows from the top of the glacier, which would fall into the delta plain/delta front environment and be redistributed, or whether they represent flows occurring in the braided river channels proximal to the glacier. The flows studied by Lawson (1982) appear to be poorly sorted and contain wide ranges in grain size. In contrast, the diamict units within this lithofacies association are dominated by three distinct grain sizes composed of subround to round exotic sediment. Therefore, it appears that flood events eroding pre-existing sorted gravel bars offer a more plausible explanation for the formation of the diamict beds than flows from the top of the glacier.

(c) OVERALL SEQUENCE

The L.A.s in the Camp 25 succession represent deposition of a prograding delta against the ice margin in a small proglacial lake. Esker systems exposed as the glacier retreated are buried by a lobate mound shaped feature (Kristjansson et al,1989), in which the Camp 25 succession was excavated. This suggests the lake may originally have been subglacial, forming in a small depression beneath the glacier. The esker system may have been the source of sediment for the succession. Subglacial lakes have been inferred by Shreve (1972) and documented in the Antarctica ice sheet through radio-echo sounding (Oswald and Robin, 1973). Initially, suspension deposition in the proglacial lake dominated. The source of the sediments was from a conduit within the ice (Figure 3.2A). Smith and Ashley (1985) suggest a large amount of the sediment load within proglacial lakes represents meltwater discharged through englacial or subglacial tunnels. Interflows and overflows from

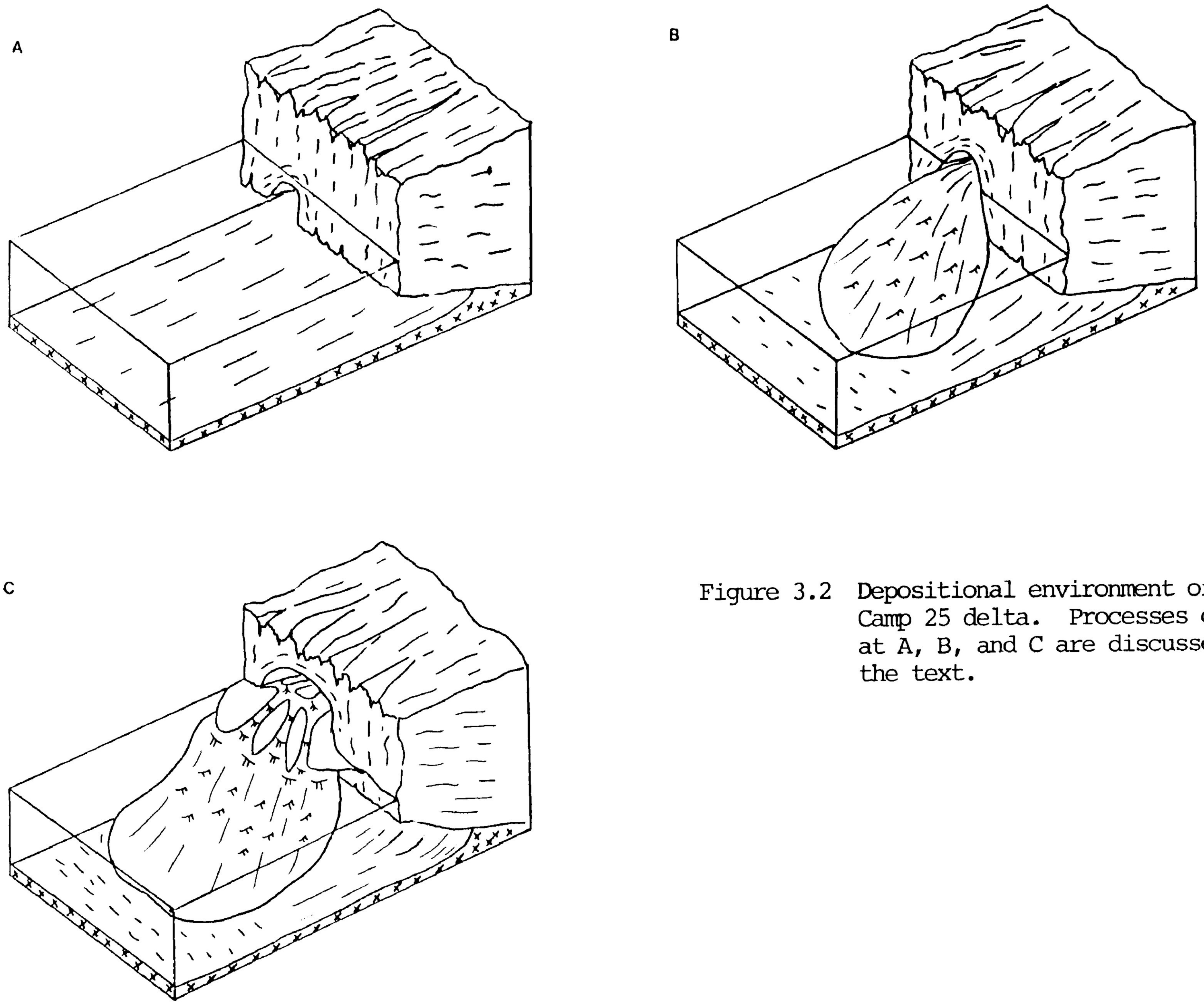


Figure 3.2 Depositional environment of the Camp 25 delta. Processes operating at A, B, and C are discussed in the text.

subglacial and englacial tunnels have been documented in proglacial Malaspina Lake (Gustavson,1975). Occasional underflows deposited rippled beds within the massive units. The rippled L.A. suggests underflow deposition became more dominant in an area previously receiving suspended sediment from interflows and overflows indicating progradation of the delta system. Due to the shallow depth of the lake, sediment buildup of the massive and overlying rippled L.A. caused the conduit within the glacier to melt upward to accommodate the sediment accumulation (Figure 3.2B). Banerjee and McDonald (1975, Figure 28) show upward melting of a subglacial tunnel due to sediment deposition. Basal melting of the overlying ice sheet deposited dropstones within the massive and rippled L.A. Thick sediment accumulation during deposition of the massive and rippled L.A.s resulted in deposition of the overlying L.A. near the lake surface. The trough cross-stratified L.A. represents distributary mouth bar deposition in the delta front. The delta was being deposited against the ice front as shown in Figure 3.2C. Rare dropstones in the northern sections of the trough cross-stratified L.A. suggest the ice margin was in close proximity. The presence of low-angle, cross-cutting, plane-laminated sands with heavy mineral laminae indicate reworking of the distributary mouth bars by waves. The outermost portions of the distributary mouth bars were subjected to the breaking waves in the small lake. This results in reworking and redistribution of the trough cross-stratified sands as low-angle plane-laminated and massive sands. Wave activity can easily form beaches within small lakes as indicated by the numerous beaches mapped on small lakes in the area by Kristjansson et al (1989). As the deltaic system prograded, the trough cross-stratified sands of the distributary mouth bars situated landward from the reworked bar margins covered the storm deposits. The restricted diamict-bearing L.A. represents channelized flood events within the braided stream system. During the flood event, a mixture of sediments were transported and deposited as wedges of diamict beds within the delta front. Due to the channelized nature of the flow, the diamict-bearing L.A. is restricted only to two sections.

Within the overall sequence, there is evidence of cycles in the southern sections. Each cycle exhibits fine-grained rippled beds at its base. The rippled units are transitional to medium-grained rippled units which are intercalated with low angle plane-laminated sands. These units are overlain by trough cross-stratified sands. Some of the cycles have diamict units interbedded with the upper cross-stratified sands. Each cycle is interpreted to represent deposition of a distributary mouth bar sequence. The different cycles indicate the switching of channels feeding the delta front, and the buildup of a new distributary mouth bar system related to the change in source of sediment.

KOA SUCCESSION

(a) INTRODUCTION

Six lithofacies associations (L.A.) were delineated in the KOA succession: diamict, massive-stratified sand and gravel, rippled sand, massive gravel, trough cross-stratified sand and trough cross-stratified gravel. The overall coarsening upward succession and lithofacies present in the rippled sand to trough cross-stratified gravel lithofacies associations strongly suggests a prograding deltaic system. This coarsening upward succession is underlain by the diamict L.A. which is interpreted to represent deposits on the bottom of a glacial lake, and the massive-stratified sand and gravel L.A. interpreted as a subaqueous outwash fan which developed at the interface between the grounded ice front and the glacial lake bottom. The topographic and geographic position of the sequence supports the suggestion that the succession represents a deltaic system prograding over glacial lake deposits and a subaqueous outwash fan. The succession is located 2 km inland of the Lake Superior shoreline, and is situated in the middle of a gently dipping slope from a topographic high, 4 km to the north of the site, down to Lake Superior. Escarpments marking former lake levels have been documented near the sequence by Burwasser (1977). Therefore, the possibility of this succession representing a delta built into a lake stage higher than present day Lake Superior is probable.

Group 1 of the rippled sand L.A. represents deposition within the prodelta and delta front areas (as defined in the introduction of the Beardmore depositional environment). The delta plain environment is represented by the trough cross-stratified sand and trough cross-stratified gravel L.A.s. The depositional environment of each of the lithofacies associations will be discussed in the following text.

(b) LITHOFACIES ASSOCIATION

(i) Diamict Lithofacies Association

The diamict L.A. is interpreted as representing the stratigraphy of a bottom of a lake based on its stratigraphic position and the composition of the beds within the L.A. As described earlier, minor sorted lenses and horizons appear within the usually massive diamict beds. Minor clean fine sand beds, trough cross-stratified sands and pebble-cobble horizons were found interbedded with the diamict units indicating the diamict units were being reworked during deposition. The massive diamict beds lack features associated with grounded ice deposition such as erosional contacts, incorporation of underlying beds, shaped, striated oriented clasts, shear surfaces, and vertical joint sets (Eyles and Miall,1986) and are interpreted to represent suspension accumulation and ice rafted debris deposition within a proglacial lake, similar to the glaciolacustrine diamicts in the Scarborough Bluffs described by Eyles and Eyles (1983). The ice margin is interpreted to be grounded in the proglacial lake (see interpretation of diamict L.A. in section S5 in following text) suggesting ice rafted debris was deposited mainly by icebergs. Deposition of poorly sorted glacial debris ranging in size from silt to boulders may take place by melting of an iceberg, or by tilting, fragmentation or overturning of an iceberg (Ovenshine,1970; Smith and Ashley,1985). These massive diamict deposits were periodically reworked by traction currents to form a continuum from massive diamict units with discontinuous ripples to more highly sorted units where most of the mud fraction was removed, such as: massive gravels and sands, rippled sands, and clast and matrix supported stratified diamict. The gradational contacts shown between the cleaner sand horizons within the diamict and the diamict itself suggest winnowing of the fines by episodic traction currents was occurring at the same time as deposition of the fine-grained sediment was taking place (Eyles and Eyles,1984). Reworking of diamict deposits is evident when comparing figures 2.24, 2.25 and 2.26. Figures 2.24, 2.25 and 2.26A indicate the poor sorting of the massive diamict beds. In figure 2.26B and C sorting of certain grain sizes is seen in the plots. In figure 2.26D development of traction, saltation and suspension populations are evidence of reworking of horizons within the diamict units.

The near vertical bedding in the diamict in section S5 is interpreted to represent a small scale push ridge or push moraine feature. Push moraines formed in proglacial water bodies have been documented by Boulton (1986), Eyles and Eyles (1984) and Powell (1981). Push moraines are composed of gravel, rubble, and diamicton, and are generally asymmetric. Powell (1981) attributes their formation to very minor advances in an ice front. The composition, shape and stratigraphic positioning of the diamict L.A. in section S5 strongly suggest it represents lake bottom rainout deposits which were formed into a push moraine by a minor glacier advance before the major deltaic progradation phase.

(ii) Massive-Stratified Sand and Gravel Lithofacies Association

The group 1 beds of this L.A. stratigraphically overlie the diamict L.A., and are overlain by the rippled sand L.A. At another location in the outcrop, group 2 beds are intercalated with the finer grained group 2 units of the rippled L.A. Based on their stratigraphic position and composition, the beds of this L.A. are interpreted to represent a subaqueous outwash fan system.

Massive, cross-bedded or parallel-bedded gravels have been interpreted as proximal deposits within subaqueous outwash fan systems (Banerjee and McDonald,1975; Rust and Romanelli,1975; and Cheel and Rust, 1982). The coarse-grained planar and trough cross-stratified pebbly sand and pebble gravel beds of group 1 represent subaqueous deposition near the mouth of a meltwater conduit within the glacier.

The massive silty-fine to coarse sands in group 1 may represent either proximal interchannel deposition from sediment flows formed during a high sediment discharge event from the glacier (Cheel and Rust,1982) or channels filled with massive sand (type B of Cheel and Rust,1982). Channel scour features in the massive sands may not have been visible in the limited face of the section (approximately 1 m wide). However, the massive beds generally did not show an erosive base or erosive contacts suggesting the massive beds are more representative of the interchannel areas as defined by Cheel and Rust (1982). The downfan transition from proximal gravels to fine to medium-grained structureless sands has been documented by Banerjee and McDonald (1975).

The group 2 association of this L.A. contains 1) massive and stratified pebbly sands and gravels, 2) clast supported granule and small pebble horizons, 3) granule and small pebble horizons in a silt matrix, 4) diamict beds with clay-poor laminated horizons and 5) deformed beds. The pebbly sands and gravels are similar to the type A channel described by Cheel and Rust (1982). The type A channel is filled with horizontally stratified medium sand containing imbricate gravel along bedding planes within the sand and along the erosional channel base, indicating repeated strong erosive currents transported the gravel as bed load (Cheel and Rust,1982). They suggest the channels bifurcate and become smaller downfan. The massive and stratified pebbly sand and gravels in group 2 have been interpreted to represent deposition within channels developing downslope from the proximal subaqueous outwash fan. As shown in Figure 2.29, some of these beds have a definite lensoid outline. The thin, well-sorted granule and pebble horizons are interpreted as small breaches of these channels, forming a small thin pebble horizon deposited within the finer grained interchannel area. The third bed type composed of pebbles in a silt matrix are interpreted to be deposited by the same process. However, in these beds admixing of the coarser pebble and silt bed took place. Banerjee and McDonald (1975) have documented a similar occurrence consisting of well rounded pebbles floating in a mud matrix near the downstream end of large gravel tongues.

Matrix and clast supported diamict beds in the interfan area of a subaqueous outwash system have been interpreted to represent deposition by debris flows and high density sediment gravity flows (Mustard and Donaldson,1987). The flows were initiated either by oversteepening of the fan and adjacent morainal bank slopes, bank collapse during glacier retreat or by the shock effects created by ice-calving (Mustard and Donaldson,1987; Powell,1981). The diamict units of group 2 can similarly be attributed to debris flows and high density sediment gravity flows deposited within the interfan area.

Deformed beds contain coarser gravels which have loaded into fine grained silts, creating ball and pillow like features. The loading is similar to ball and pillow structures found in subaqueous outwash by Cheel and Rust (1986).

(iii) Rippled Sand Lithofacies Association

The group 1 beds of the rippled sand L.A. overlie group 1 of the massive-stratified sand and gravel L.A. and are erosively scoured at their top by the trough cross-stratified sand or trough cross-stratified gravel lithofacies association. Repeated cycles from clay through rippled sand to coarse sand units occur within this L.A. Stratigraphic positioning and associated lithofacies indicate that group 1 of the rippled sand L.A represents prodelta and delta front deposition.

The finer grained group 2 units found interbedded with group 2 of the massive-stratified sand and gravel L.A. in sections S1, S2 and S3 represent interchannel and distal deposits of the subaqueous outwash fan described in the massive-stratified sand and gravel L.A. The depositional environment of each of these groups will be discussed in detail in the following text.

Group 1

The association of rippled, massive and graded units has been documented by numerous authors (for example Jopling and Walker,1968; Aario,1972; Gustavson et al,1975; Leckie and McCann,1982; and Kelly and Martini,1986) who interpreted this type of lithofacies succession as occurring within the delta front region. The rippled units within this L.A. represent deposition by underflow in the distal delta front. The grain size plots in Figure 2.33A indicate the rippled units formed from underflows composed of traction, saltation and suspension populations. As described previously in the depositional environment subchapters for the rippled L.A. of the Beardmore and Camp 25 deltas, the differences in ripple-drift cross-lamination of type A, B, and sinusoidal depends upon fluctuations in current velocity and variations in the composition and concentration of suspended sediment (Jopling and Walker,1968). Type A represents deposition dominantly from bed load, while sinusoidal lamination represents dominant fallout from suspension. The transition from A to B to sinusoidal records an increase in the ratio between suspended load and bed load. Ripple-drift cross-lamination seen in the KOA pit (A to B to sinusoidal) indicates deposition under decreasing flow strength.

The massive units found interbedded with the rippled units were deposited by interflows or overflows within the lake. This is based on data previously discussed in the depositional environment of the Beardmore reverse-graded L.A.

As discussed in the depositional environment of the rippled L.A. within the Beardmore succession, graded beds found interlayered with rippled beds may be deposited by seasonally-operating density underflows or by slump generated turbidity currents. Graded beds deposited by sediment gravity flows (such as turbidity currents) represent slumping of pre-existing units. In the KOA succession potential slump units would be the trough cross-stratified sand and gravel L.As, or the beds of the rippled sand L.A. deposited within the upper delta front. All of these units are coarser grained than the normally graded units found within the L.A. Therefore, graded beds deposited from slumping of these units should be coarser grained than those documented. The possibility that the graded beds were deposited by seasonally operating underflows appears more plausible as the rippled units interlayered with the graded beds have already been interpreted as being deposited from underflows. However, the possibility that the graded units were slump generated can not be ruled out. The grain size plots of two graded beds are given in Figure 2.33B and 2.33C.

The minor reverse-graded beds were also deposited by interflows or overflows as discussed in the depositional environment subchapter of the reverse-graded L.A. present at Beardmore. The association and interbedding of these rippled, graded and massive units points to different flow events within the glacial lake. Flows entering the lake may continue as underflows along the bottom. Mixing of these flows with lake water or sediment deposition may cause the flow to become equally or less dense than the lake water and result in its transformation into an interflow or overflow.

The clay units within this group may represent suspension deposition. In deltaic systems, clay units are generally associated with the prodelta or 'distal' region of the system. However, the clay horizons may be deposited in areas more proximal to the source as long as the water velocity is low enough to allow suspension deposition to occur. Both Gustavson et al (1975) and Reineck and Singh (1980) suggest suspension deposition of clay occurs in regions of the delta front where coarser sediment transport and deposition (i.e. from underflows) had ceased.

The coarser grained parallel-laminated, massive, trough and planar cross-stratified beds are interpreted to record deposition within the proximal delta front. As discussed previously in the depositional environment of the trough cross-stratified L.A. within the Camp 25 succession, these coarser grained units represent deposition within the proximal region of distributary mouth bars. Deposition of the coarser grained units in the proximal environment of the distributary mouth bar may be further verified if the process of deposition for the numerous coarsening upward cycles within the rippled sand L.A. is considered.

The coarseining upward cycles range in thickness from 0.25m to 1.6m and are composed of clays through fine-grained rippled sands which are transitional to coarser-grained sands. These cycles have been intepreted to represent distributary mouth bar deposits fed by multiple switching distributary channels.

The clay horizons represent areas of suspension deposition within the delta front which are not being fed by underflows. The transition from the clays to the slightly coarser grained overlying rippled, massive and graded units represents incursion of underflows and overflows into the previously quiet suspension areas. These fine-grained sands are transitional to the coarser grained massive, trough cross-stratified and plane-laminated beds. These units represent deposits directly in front of the distributary channels. These coarser grained units are not part of the distributary channels as these deposits are transitional from the rippled sands and lack the large erosional channel shaped feature associated with units deposited directly in the distributary channel (see trough cross-stratified L.A. in following text). The repetitive sequence of coarsening upward cycles may be explained if sediments were fed by multiple switching distributary channels, which are common in braid deltas (as defined by McPherson et al,1987). Vos (1981) and Fralick and Miall (1989) document complex sequences of sediments which are transitional in nature and do not resemble the thick sedimentary sequences corresponding to discrete subenvironments (i.e. mouth bar, channel etc.) found in standard river-dominated deltaic systems such as the Mississippi delta. They suggest these deposits are evidence of small, temporary shifting environments such as those fed by braid deltas, which are characterized by braided transitory channels on the delta plain (see trough cross-stratified sand and troucgh cross-stratified gravel L.A.s in following text). It is possible to suggest in a similar manner that these coarsening upward cycles were fed by multiple switching distributary channels of the braidplain.

Group 2

The finer grained group 2 units found interbedded with group 2 of the massive-stratified sand and gravel L.A. in sections S1, S2 S3 represent interchannel and distal deposits of the subaqueous outwash fan described in the massive-stratified sand and gravel L.A. Mustard and Donaldson (1987) record the transition of rhythmites dominated by clay, to silt-rich rhythmites with normally graded beds and rare ripple lamination. They interpret these lower rhythmites to correspond to Group I of Ashley (1975) and suggest deposition in the distal fan area. The silt-rich rhythmites represent Group II of Ashley (1975) and were deposited dominantly by underflows in what they describe as the "fan bottomset area". The rippled and rhythmically bedded units found in sections S1, S2 and S3 may represent deposition by underflows in the distal fan area. Some of the flows reaching the distal fan area from the conduit within the glacier carried fine-grained sediment in suspension. The massive beds in the lower sections would represent sedimentation of this material. The lenticular silts and clays are found only in one of the lower sections, and are situated beneath the other beds in group 2. The lenticular bedding represents mainly suspension deposition of clay, with rare underflows carrying silt into the area. Rare dropstones within the lenticular silts and clays indicate the presence of floating ice.

Fine-grained silt units with rare dropstones within section S7A are extremely deformed. Associated with these silts are minor clay laminae and laminated silt and silty fine sand. These fine-grained units are interbedded with diamict units from group 2 of the massive-stratified sand and gravel L.A. The succession of beds within section S7A is similar to the units in sections S1, S2 and S3 which were interpreted as distal fan deposits. The location, attitude, and deformation of the beds within section S7A suggest they were originally part of the distal outwash fan system and have been thrust or pushed by a local advance in the ice sheet. The formation of glacial-thrust structures is relatively easy in unconsolidated clay-rich glacial lake sediment due to its very low shear strength (Moran et al,1980). Glacially thrust lacustrine sediment has been documented in ice marginal complexes in eastern North Dakota (Bluemle,1975, in Moran et al, 1980).

(iv) Massive Gravel Lithofacies Association

The steeply dipping pebble to boulder gravel beds of this L.A. are interpreted to represent the core of an esker. Deposition of stratified sands and gravels within subglacial and englacial tunnels of glaciers forming linear steep sided ridges of this type have been documented by Shaw (1972), Saunderson (1975), and Banerjee and McDonald (1975). Samples taken from the esker indicate the dominance of bedload transportation (Figure 2.41A).

Pebble clast grain sizes dominate these samples as shown by the histograms in Figure 2.45B.

Wedges extending from this mound are finer grained, being composed of pebble and cobbly pebble gravels in the proximal region to fine sands in the distal wedge. The wedges fine away from the esker, as can be seen by the decrease in average grain size from plot 1 to plot 6 in figure 2.42. The plot of sample 6, which was taken the farthest away from the core of the esker shows development of only two populations; it lacks a traction population. The histograms for the samples in the wedge also indicate the decrease in the pebble content from proximal (sample 1, Figure 2.43) to middle section (sample 4, figure 2.43) of the wedge. In samples 1 to 4, coarse sand and very fine sand also form important populations. In samples 5A, B, C, and 6, very fine sand and fine sand become the dominant population. The grain size decrease from sample 1 (esker proximal) to 6 (esker distal) along the wedge, suggest the wedges were originally material in the esker that has been reworked, and redistributed. One possible method for reworking and remobilization of the gravel into wedges from the esker are waves produced by a storm. Waves in a large lake, such as Glacial Lake Minong, may have been strong enough to cause the erosion, transportation and redeposition of material from the esker.

(v) Trough Cross-Stratified Sand Lithofacies Association

The trough cross-stratified beds within this L.A. erosively scour into the rippled sand L.A., and are transitional to the overlying trough cross-stratified gravel L.A. The channel-shaped bedforms filled with stacked trough cross-stratifed units lead to interpreting this L.A. as distributary mouth channel deposits of a braided river system eroding into the delta front deposits. These larger scale bedforms with their channel-shaped appearance contrast to the coarser-grained cross-stratified sands which cap the coarsening upward cycles within the rippled sand L.A., and have been interpreted as part of distributary mouth bar sequences, as described previously. Clemmensen and Houmark-Nielsen (1981) document distributary channels occurring in the transition zone between foreset and topset regions of a delta. The channels vary in width from 0.5 to 3 m, and are infilled by pebbles and granules to fine sand which exhibit channel-fill cross-bedding. Clemmensen and Houmark-Nielsen (1981) interpret these channels as anastomosing small distributary channels representing the most distal part of the braided river system feeding the delta. Kelly and Martini (1986) attribute trough and planar cross-stratified sands with ripple and parallel-laminated drapes to migration of subaqueous dunes within a braided stream system. The braided system has eroded channels up to 50 m wide into underlying upper delta front deposits. Farquharson (1982) documents a distributary river channel cutting down through delta front sediments exposed at Camp Hill, northern Antarctica Peninsula. The erosively based channel is filled by a thick fluvial sandstone with trough and planar cross-bedding.

Bergh and Torske (1986) interpret cosets of trough cross-bedded sandstones which commonly rest on a basal scour as deposits within distributary channels. The channels erosively scour into the finer grained delta front deposits. Stacked, trough cross-bedded sandstones with a sharp erosive base in the Capel Curig braid delta have been interpreted to represent deposition within distributary channels of a braided stream feeding the delta front (Orton,1988).

Channels of variable width and depth are found within sandy braided systems (Walker and Cant 1984). Within deeper channels (> 3 m) sinuous crested dunes form which produce trough cross-bedded deposits. Sands within the channels are carried mainly as bedload. The plots in figure 2.49A indicate samples from the trough cross-stratified sands have well developed traction, saltation and suspension populations.

Within this L.A., two "architectural elements" as defined by Miall (1985) are present.

The trough cross-stratified beds represent sandy bedforms. The second architectural element is represented by the channels the trough cross-stratified sands are deposited within. As described earlier, the trough cross-stratified beds are often stacked, forming larger scale units deposited within channels. This is similar to multistoried units infilling channels as described by Miall (1985).

The trough cross-stratified sands may have been formed by migration of subaqueous sinuous crested dunes within distributary channels branching from the braided river system. The trough cross-stratified sand L.A. represents the initial phase or "distal" deposits of the delta plain braided river system prograding over the delta front deposits. The distributary channels the trough cross-stratified sands are deposited in may be subaerial within the delta plain, or subaqueous, and extend into the lake. The deposits within the distributary channel, whether they are subaerial or subaqueous, will be very similar. In fine-grained systems, trough cross-stratified sands which scour into the underlying rippled sands, are interpreted to represent delta plain deposition, and subsequently the strandline. However, these deposits may have been deposited within a subaqueous channel. Therefore, the first appearance of coarser grained cross-stratified sands does not necessarily indicate the strandline location. In the KOA succession, the exact position of the strandline is difficult to determine.

(vi) Trough Cross-Stratified Gravel Lithofacies Association

The gravel beds within this L.A. are transitional from underlying trough cross-stratified sands. In sections where trough cross-stratified sands are absent, the gravels erosively scour into the rippled sand L.A. Based on their position and composition, the trough cross-stratified gravels represent deposition within braided distributary channels.

Three main categories of bars have been documented in braided river systems; longitudinal, linguoid or transverse and point, side or lateral (Miall,1977). Longitudinal bars are gravel dominated and internally are massive or show faint parallel-bedding. Linguoid and transverse bars form through avalanching of sediments to produce large scale high angle planar cross-stratification and trough cross-stratification and are typical of sandy braided rivers. Trough cross stratified gravel beds are rare in the literature (Smith,1974; Hein and Walker,1977; and Miall, 1985). Hein and Walker (1977) document the changes in a braided river system dominated by one main channel upstream and numerous smaller channels downstream. In the main channel upstream, high discharge carries gravels in sheets, forming predominantly longitudinal bars. As the channel bifurcates, discharge and the rate of gravel transport decreases. A lag deposit will aggrade vertically, and eventually avalanching may occur as gravel rolls across the top of the deposit, developing bars with cross-bedding. The higher discharge within the main upstream channel does not allow development of a lag deposit, and subsequent bar growth by avalanching. Therefore there is an increase in cross-bedding of the gravels from the proximal to distal reaches. This sequence has also been documented by Church and Gilbert (1975) and Boothroyd and Ashley (1975).

It is possible to suggest the trough cross-stratified gravels within the KOA succession represent deposition within bifurcating distributary channels branching from the main channel. The bifurcating channels do not have a high enough discharge to form coarse-grained horizontally stratified gravels deposits, typical of longitudinal bars. Bifurcation of the channels would be expected within the delta plain as flow from the river system feeding the delta is not confined. The dominance and lateral continuity of the trough cross-stratified gravels suggest deposition of this L.A. took place within rapidly switching bifurcating distributary channels of the braided river system feeding the delta.

(c) OVERALL SEQUENCE

The lithofacies associations in the KOA succession represent deposition of a delta into a proglacial lake. Initially, the diamict L.A. was deposited by glacier or iceberg rainout (Figure 3.3A). The sedimentary structures present and relative lack of fines indicate traction currents reworked the deposits as they were accumulating. A small advance of the glacier formed some of these diamict units into a push ridge. As the glacier began to retreat, a subaqueous outwash system was developed (Figure 3.3B). Combination push-ridge subaqueous outwash systems have been documented by Powell (1981), Eyles and Eyles (1984) and Boulton (1986). Proximal to the ice front, stratified pebbly sands and gravels of group 1, massive-stratified sand and gravel L.A., were deposited. Slightly downfan, massive finer grained sands, also of group 1, were deposited. The distal environment of the fan is represented by the interbedding of group 2, massive-stratified sand and gravel L.A., and group 2 of the rippled sand L.A. Massive and stratified pebbly sands and gravels were deposited within bifurcating channels which extended from the proximal area of the outwash fan. Occasionally, breaches from these channels formed thin clean pebble horizons, or pebbles loaded into silt horizons, in the finer grained sediments of the interchannel areas. Deposits within these distal interchannel areas were either formed by suspension accumulation or by rare overbank flows from the subaqueous system. The unstable nature of the fan building in the glacial lake may have triggered sediment gravity flows which deposited silt rich diamict deposits within the finer grained deposits. Rarely, the coarser grained deposits carried in the channels loaded into the fine grained silts causing deformation. Dropstones within the finer grained distal fan deposits indicate the presence of floating ice. Glacial retreat exposed an esker in the eastern section of the pit (Figure 3.3C). Flooding of the lake accompanied retreat of the glacier. Initiation of a deltaic system into the glacial lake

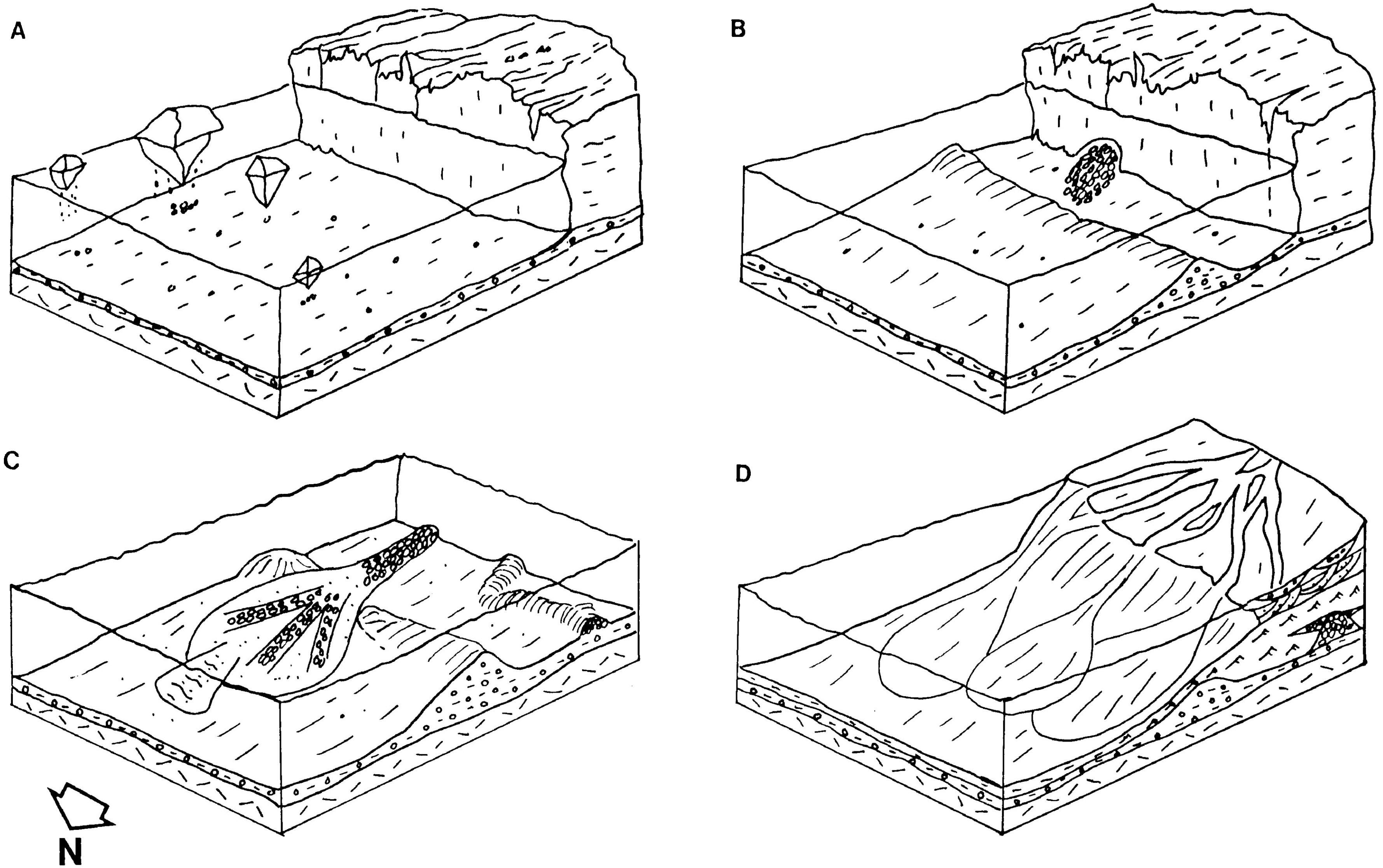


Figure 3.3 Depositional environment of the KOA delta. Processes operating at A,B,C, and D are discussed in the text.

began at this time. Fine-grained clays within the rippled L.A. represent suspension deposition in the prodelta region. Eventually, underflows began to reach into the portion of the basin examined, forming rhythmites. As the system prograded, the dominantly clay rhythmites became silt rich, as more underflows entered the area. Rippled, massive and graded sands were deposited in the distal delta front by underflows, interflows and overflows. Coarser grained deposits of distributary mouth bars deposits cap the rippled sequences in the proximal delta front. This coarsening upward cycle from silts through rippled sands to coarse grained sands repeated numerous times within the rippled sand L.A. suggests channel switching within the delta plain environment. Progradation of the deltaic system, possibly combined with isostatic uplift resulted in a regressive sequence. The top of the esker was levelled during storm events with remobilized material deposited as wedges in the rippled sand L.A. A wedge of distal outwash fan sediments was thrust up into the delta front sediments by a localized readvance or ice surge within part of the glacial margin still present in the lake basin. As the delta topset advanced through the area, offshore, sand dominated distributary mouth channels were cut into the distributary bar sands. These are overlain by trough cross-stratified gravels deposited within distributary channels probably proximal to the main braided fluvial channel feeding the delta (Figure 3.3D).

The proximal gravels of the outwash fan indicate a paleocurrent trend to the west (268°). The rippled sand L.A. of Schuster (1985) trends to 252°, while the deposits further west trend 284°. Overall these rippled deposits trend almost due west (262°), similar to the subaqueous outwash. The trough cross-stratified sands show a wide range in trends from 106°, to 016° to 306°, and average 044°. The trough cross-stratified gravels trend to the northwest (323°). The topography of the region to the north of the delta is higher and slopes down to the succession. The paleocurrents indicate deposition of the deltaic sequence was predominantly in a west and northwesterly direction. This suggests that part of the ice margin is trending approximately east-west (see Figure 3.4A). This orientation is needed to supply sediment for the delta topsets which prograded out in a northwesterly direction. This configuration of the ice front may seem unusual, since overall general trends for the Lake Superior basin suggest the ice sheet retreated generally to the northeast. However, Saarnisto (1974, Figure 3) indicates an embayment within the ice margin near the Black Bay Peninsula, showing a similar trend. Also, Zoltai (1965b) documents glacial striae and movement of the Marks Phase ice sheet that agree with this ice configuration (see Figure 3.4B).

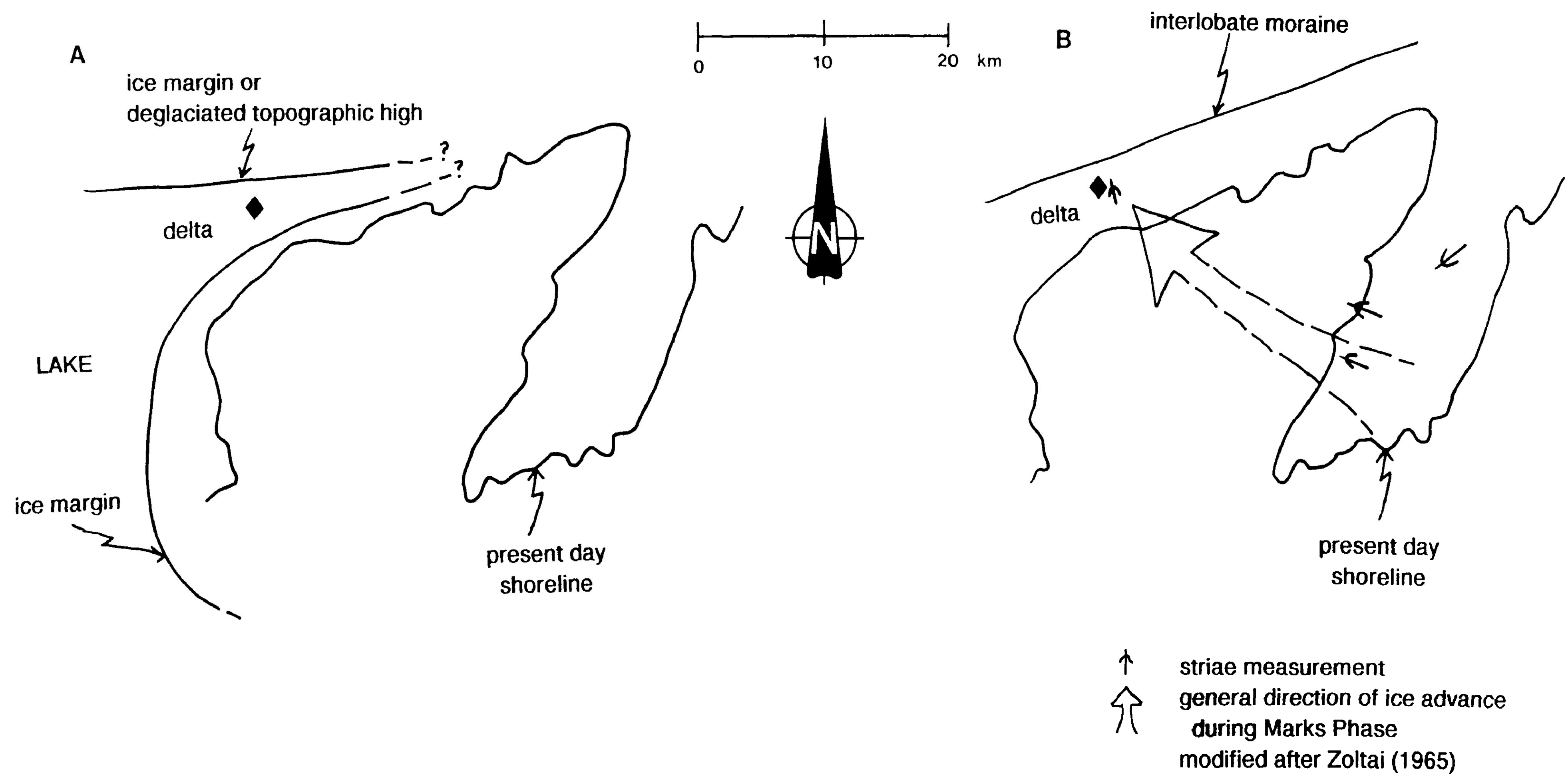


Figure 3.4 A) Plan view of ice margin positions during the deposition of the KOA delta.
B) Ice advance and position during Marks Phase (after Zoltai, 1965).

CHAPTER IV

CONCLUSION

This chapter will be divided into three sections. The first part will outline the depositional environments of the glacial deltas mapped. The second section will discuss the similarities and differences of these deposits to glacial deltas documented in literature. The third section will outline the significance of the study and a model for glacial sedimentation.

(1) DEPOSITIONAL ENVIRONMENTS

The following text will briefly outline the depositional environments of the three glacial deltas mapped.

(i) Beardmore

The beds within the Beardmore succession represent a deltaic system prograding into a glacial lake. Prodelta deposition is represented by the reverse-graded lithofacies association (L.A.). The glacial lake was dominated by numerous pulsating discrete interflows and overflows which deposited thin, stacked reverse-graded beds. These interflows and overflows occasionally deposited nongraded beds. The presence of a few rippled beds interlayered with the reverse-graded units suggest periodically the plume water was denser (probably due to sediment concentration) than the lake water, and underflows developed. The flows which deposited the reverse-graded L.A. trended in an easterly direction. As the delta began to prograde underflows became more common depositing ripple cross-laminated and ripple-drift cross-laminated beds and minor graded beds within the lower delta front. Rare massive beds indicate development of intermittent interflows and overflows. The presence of restricted parallel-laminated and planar cross-stratified beds within the finer grained units is attributed to the development of subaqueous distributary channels down the delta front. The paleocurrent direction noted for the rippled units trends easterly, similar to the reverse-graded beds. Coarse-grained planar cross-stratified beds represent avalanching within the upper delta front. The flow appears to have taken on a more northerly course for deposition of the coarse-grained units.

At this time, the locus of deposition switched and another similar deltaic sequence began building into the lake. Interflows and overflows deposited reverse graded units to the northwest. These deposits are overlain by rippled units deposited by underflows as described earlier. Discrete, discontinuous massive, parallel-laminated and diamict units found interbedded with the finer grained rippled units are attributed to sediment gravity flows within an unstable delta front. The overlying coarse-grained planar cross-stratified beds represent upper delta front deposits, and were deposited forming a general arcuate or lobe shape.

(ii) Camp 25

The four lithofacies associations (L.A.) within the Camp 25 succession represent deposition of a delta against the ice margin in a small proglacial lake. The succession is excavated within a lobate hill. Esker systems appear directly to the north and south of the hill, and disappear where the mound of sediment is present,suggesting the lake the succession built into was subglacial.

Deposition of the massive silt L.A., the lowest in the succession was mainly by suspension deposition within the lake. Numerous dropstones within the L.A. suggest the lake is proglacial, and therefore flows entered the lake through subglacial or englacial tunnels. Flows were periodically dense enough to become underflows and deposit rare rippled units. Current reworking along the bottom of the lake was taking place as evidenced by the sorting and layering of clasts within one unit. The massive L.A. is overlain by the coarser grained rippled sand L.A. Dropstones within the L.A. suggest the depositional environment was similar to the massive L.A. Flows carrying sediment probably entered the lake from the same englacial or subglacial tunnel acting as the conduit during deposition of the massive silt L.A. The rippled L.A. represents progradation of the delta system, such that underflow deposition became more dominant in the prodelta area examined. Massive beds indicate the formation of intermittent interflows or overflows within the lake. Sediments within this L.A. are deformed or faulted suggesting close proximity to the ice margin. The rippled L.A. has been interpreted to represent the lower delta front deposits. The trough cross-stratified L.A. which overlies the rippled L.A. represents the upper delta front and possible delta plain deposits. The beds within this L.A. coarsen up from rippled sands through parallel-laminated sand to trough cross-stratified sands, and are interpreted to represent coarse-grained distributary mouth bars. Heavy mineral laminae associated with massive and parallel laminated beds in lower sequences of the distributary mouth bar represent wave reworking and redeposition of trough cross-stratified sands present within the distributary mouth bars. Rare dropstones indicate the influence of an ice margin. The subglacial tunnel within the ice margin melted upwards and back to accommodate the buildup of sediment. The restricted extent and interbedding of the diamict-bearing L.A. with units similar to the trough cross-stratified sand L.A. indicate that the diamict-bearing L.A. may represent channelized flood events within the delta plain which eroded existing barforms and deposited them within the delta front environment.

Coarsening upward cycles from fine-grained rippled sand through interbedded rippled and plane-laminated sands to trough cross-stratified sands are present within the overall succession. These cycles have been interpreted to represent distributary channel switching within the delta plain.

(iii) KOA

The lithofacies associations in the KOA succession represent deposition of a delta into a proglacial lake. The two lowest L.A.s indicate the presence of an ice margin within the lake. Ice rafted debris from floating ice accumulated with fallout of suspension material to form the basal diamict L.A. Traction currents periodically reworked the deposits as they were accumulating as indicated by the development of massive diamict units with discontinuous ripples to more highly sorted units such as massive gravels and sands, rippled sands, and clast and matrix supported stratified diamict beds. A small localized advance of the glacier formed some of these diamict units into a push ridge feature. As the glacier began to retreat the second L.A., massive and stratified sands and gravels, was deposited. These sediments represent a subaqueous outwash system. Stratified pebbly sands were deposited proximal to the ice front while massive finer grained sands accumulated slightly downfan. Bifurcating channels extending from the proximal area of the outwash fan contained massive and stratified pebbly sands and gravels. Periodically, channel breaches deposited thin clean pebble horizons, or pebbles which loaded into silt horizons of the interchannel area. The silt deposits accumulated by suspension fallout from interflows or overflows in the interchannel areas. The presence of floating ice is indicated by rare dropstones within the finer grained distal fan deposits. Silt-rich diamict deposits within the fine-grained distal-fan sediments are interpreted as sediment gravity flows generated by the rapid sedimentation of unstable, loosely consolidated coarser grained units within the fan. As the glacier continued to retreat an esker within the eastern section of the succession was exposed on the lakebed. The coarsening upward succession present in the rippled sand, trough cross-stratified sand and trough cross-stratified gravel L.A.s suggest a deltaic system built into the glacial lake. Clays deposited from suspension plus silts brought into the delta front area by occasional underflows formed couplets. The rhythmites became more silt rich as stronger flows entered the area. Ripple cross-laminated and ripple-drift cross-laminated beds were deposited by underflows that were entering the area previously dominated by suspension deposition. Occasionally, these underflows deposited graded beds. Minor massive beds suggest the presence of rare interflows and overflows into the area. Coarser grained parallel-laminated, massive, trough and planar cross-stratified deposits are transitional from the rippled sequences and are interpreted to represent distributary mouth bars deposited adjacent to the inflowing, laterally confined water jet. These distributary mouth bars represent deposition proximal to the distributary channels. This cycle of sedimentation from prodelta clays through rippled sands to coarser grained distributary mouth bars is repeated within the vertical sequence. The cycles have been attributed to changing sources of meltwater input due to switching of distributary channels within the delta plain. Progradation of the deltaic system, possibly combined with isostatic uplift, resulted in a recession of the lake. The top of the esker was levelled during storm events with remobilized material sedimented as wedges in the rippled sands of the delta front. Deformed deposits of the distal outwash fan appear near the top of the delta front sediments. This wedge of sediments was thrust up onto the delta front sediments by a readvance or localized ice surge within the section of the glacial margin still present in the lake basin. As the delta plain advanced through the area trough cross-stratified sand was deposited in subaqueous/subaerial distributary mouth channels cut into distributary bar sands. These are overlain by trough cross-stratified gravels deposited within distributary channels proximal to the main braided fluvial channel feeding the delta.

(2) DISCUSSION

The following text will compare and contrast the three glacial deltas mapped with descriptions of glacial deltas found in the literature. For ease of discussion, the deposits of the deltas will be divided into four regions; lake sediments, prodelta, delta front and delta plain environments. According to Smith and Ashley (1985) glacial lakes are either glacier fed or proglacial. Glacial deltaic deposits have been documented within both lake types. Therefore I suggest the terms distal-fed delta and ice-contact delta be applied to infer deposition of deltas in distal-fed lakes and proglacial lakes (against the ice margin) respectively. Most deltas recorded are distal-fed deltas. In the following discussion the deltas are distal-fed, unless otherwise indicated. The deposits of the outwash fan associated with the KOA succession are not considered part of the glacial delta, and will not be discussed within this section of the text.

(i) Lake Sediments

Numerous papers have been written on glacial lake sedimentation, and lake bottom stratigraphy. Since the purpose of this thesis is to discuss glacial deltaic sedimentation, this part of the discussion will briefly focus on glacial lake sedimentation associated with glacial-deltaic deposition. The majority of sediments in lake basins associated with glacial deltaic deposition are laminated fine-grained material deposited from interflows, overflows and occasional underflows (for example Jopling and Walker,1968; Ashley,1975; Gilbert,1975; Harrison,1975; Smith,1978; Lambert and Hsu,1979; and Leckie and McCann,1982). In contrast to the laminated bottom sediments, the deposits underlying the KOA deltaic succession include deposition of diamict units by glacial rainout and fallout of suspension material, as well as a subaqueous outwash fan system. Similar diamict deposition on a lake bottom has been documented by Eyles and Eyles (1983). Their reinterpretation of the Scarborough Bluffs stresses progradation of sandy deltaic systems over glaciolacustrine diamicts deposited below floating ice. A deltaic system prograding over diamict deposited within ground moraines associated with a retreating ice sheet has been documented by Smith and Eriksson (1979). The KOA delta is the first known example in the literature of a subaqueous outwash system overlain by a deltaic sequence.

(ii) Prodelta

The massive and laminated beds in the prodelta regions of the three deltaic successions mapped were deposited by suspension fallout from interflows or overflows within the lake. Occasional underflows into the prodelta area formed rippled beds. Similar suspension deposition in prodelta regions of glacial deltas has been documented in distal-fed deltas by Smith and Eriksson (1979), Jorgensen (1982), Leckie and McCann (1982), and Kelly and Martini (1986), and in ice-contact deltas by Theakstone (1976). Multiple reverse-graded beds similar to the deposits found in the Beardmore prodelta section are unusual, and have not been documented elsewhere. As discussed previously only minor rare reverse- graded units have been recorded in prodelta areas (Aario,1972; Jorgensen, 1982). The two coarser-grained atypical beds found interbedded with the fine-grained reverse-graded and minor massive and rippled beds in the prodelta region of the Beardmore succession have been attributed to development of a subaqueous distributary channel down the delta front. Clemmensen and Houmark-Nielsen (Figure 14B, 1981), Vos (1981), Kostachuk and McCann (1987) and Prior and Bornhold (1988) all document development of subaqueous distributary channels or 'chutes' within the delta front of deltas fed by braided systems. As can be seen from Clemmensen and Houmark-Nielsen's diagram, rare scoured pockets of coarser material would be expected interbedded with the delta front and prodelta sediments.

Dropstones in the prodelta area of the Camp 25 ice-contact delta were deposited by floating ice. Dropstone deposition within prodelta regions of ice-contact deltas (Cohen,1979; Jorgensen 1982) as well as distal-fed deltas (Smith and Eriksson,1979) has been documented. Smith and Eriksson (1979) suggest the pebble-sized dropstones found within winter clay deposits represent pebbles trapped in the winter ice cover of the lake which were transported and deposited as the ice cover melted in early summer. In the prodelta region of the Camp

25 delta sorted layers of dropstones have been attributed to currents reworking the deposits on the lake bottom. This is similar to traction current reworking recorded by Eyles and Eyles (1983).

(iii) Delta Front

The discussion involving the delta front will be divided into two sub-regions; the lower and upper delta front.

(a) Lower Delta Front

Ripple cross-lamination and ripple-drift cross-lamination were documented in all three glacial deltaic successions mapped, and interpreted to represent deposition by underflows. Similar rippled sequences in the lower delta fronts of distal-fed deltas have been documented by Smith and Eriksson (1979) and in the lower to mid delta foresets by Smith and Ashley (1985). The sequences have also been recorded in lower delta fronts of ice-contact deltas by Orombelli and Gnaccolini (1978) and Jorgensen (1982). Similar rippled sequences form the complete delta front succession in the distal-fed deltas of Jopling and Walker (1968), Gustavson et al (1975), Leckie and McCann (1982), Kelly and Martini (1986) and in the ice-contact deltas of Aario (1972) and Gustavson et al (1975). The graded beds found intercalated with the rippled units may be deposited by turbidity currents formed by seasonally-operating density underflows or discrete-event slumps. Turbidity currents produced by slumps are usually associated with unstable delta fronts formed by avalanching of coarse-grained sediments (for example, in distal-fed deltas of Gilbert,1972; 1975; Lambert and Hsu,1979; Pharo and Carmack,1979; Pickrill and Irwin,1983; and in ice-contact deltas of Orombelli and Gnaccolini,1978; and Jorgensen,1982). However, they have also been associated with failure in fine-grained, low-angle delta fronts (Leckie and McCann 1982). Seasonally operating density underflows/turbidity currents depositing graded beds in the lower delta front have been documented by Ashley (1975), Gustavson (1975) and Harrison (1975).

In the Beardmore succession, the massive L.A. is composed of laterally discontinuous massive, diamict and parallel-laminated beds. Deposition of these units is attributed to sediment gravity flows within the delta front. Jorgensen (1982) and Leckie and McCann (1982) have interpreted similar units within glacial deltaic successions mapped as representing deposition from sediment gravity flows within the delta front. The initiation of the sediment gravity flows can not be determined, but may have been caused by slumping within the delta front.

Dropstones found within the rippled lower delta front deposits of the Camp 25 succession suggest the presence of overlying ice. Other references to dropstones in delta front deposits were not found.

(b) Upper Delta Front

Coarse-grained planar cross-stratified foresets documented in the Beardmore succession are interpreted to represent deposition within the upper delta front region. Foreset deposits caused by avalanching of coarse-grained sediments were first documented in 1885 by Gilbert. Steeply dipping coarse-grained foresets have been documented in both distal-fed glacial deltas (for example Gilbert,1972; 1975; Ashley,1975; Smith,1978; Lambert and Hsu,1979; Pharo and Carmack,1979; Pickrill and Irwin,1983; Weirich,1986) and in ice-contact glacial deltas (for example Shaw and Archer,1979; Orombelli and Gnaccolini,1978; Smith and Eriksson, 1979; Jorgensen,1982; and Cohen,1979; 1983). In most of these articles the planar cross-stratified beds compose the entire delta front environment, and are underlain by prodelta beds, with no lower delta front environment defined. However, a few authors record planar cross-stratified units overlying finer grained lower delta front deposits. Smith and Eriksson (1979) record large scale planar cross-beds overlying rippled and massive sandstones.

They have assigned the rippled and massive sandstones to the proximal prodelta area of the delta. Due to their similarity to lower delta front deposits as described here it is reasonable to suggest these units formed in this environment. Cross-bedded gravels in the upper delta front overlying rippled sands in the middle to lower delta front have also been documented within an ice-contact delta (Orombelli and Gnaccolini,1978). Cross-bedded sands and gravels of the upper delta front overlying rippled finer grained deposits have been recorded in a model of a distal-fed glacial delta by Smith and Ashley (1985). In Beardmore, planar cross-stratified upper delta front beds overlie finer grained rippled lower delta front units similar to the sequences outline by Orombelli and Gnaccolini (1978), Smith and Eriksson (1979), and Smith and Ashley (1985).

In the Camp 25 and KOA sequences rippled sands are transitional to coarse-grained trough cross-stratified, planar cross-stratified, parallel-laminated and massive beds which have been interpreted to represent deposition within distributary mouth bars. These deposits have not been interpreted as channel-fill deposits as they do not exhibit the typical erosive channel base scour as seen in the units which have been assigned to the delta plain division (see following text). Rippled sands transitional to coarser grained trough and planar cross-stratified sands, as well as parallel-laminated sands within delta front areas have been interpreted by Farquharson (1982), Dunne and Hempton (1984), Bergh and Torske (1986), Orton (1988) and Wood and Ethridge (1988) to represent distributary mouth bars. The deltaic sequences mapped by these authors are not glacial deltas yet they are important as the papers describe coarse-grained distributary mouth bar sequences, a deposit type which has received little attention.

Kelly and Martini (1986) suggest landward dipping horizontally stratified beds represent possible bars. Orton (1988) and Bergh and Torske (1986) interpret heavy-mineral laminated sandstone units a wave reworked bars. Low-angle parallel-laminated sands and fine-grained massive beds with heavy mineral laminae in the Camp 25 succession are interpreted to represent reworking and redeposition of the distributary mouth bars by waves. The Red River Delta fed by the Red Glacier shows extensive wave reworking in the upper delta front/delta plain transition zone (Hayes and Michel 1982). Smith and Ashley (1985) briefly note the shape of the delta shoreline may be altered by varying intensities of waves.

The diamict units interbedded with the distributary mouth bar deposits in the Camp 25 delta are interpreted to represent channelized flood events within the braided system feeding the delta. Flood events associated with outwash from glaciers have been extensively documented, yet descriptions of material deposited from these floods within the delta front has not been provided in the literature.

Rare lonestones were found within the lower section of the upper delta front deposits in the Camp 25 succession suggesting the presence of glacial ice. Dropstones in any part of delta front environments have not previously been documented in the literature.

Faults have been documented within the coarse-grained steeply dipping foresets of ice-contact deltas (Shaw,1977; Shaw and Archer,1979; Cohen,1979; and Jorgensen,1982). The faults represent melting of ice buried or supporting the deltas or gravitational movements towards the unsupported side of the delta.

(iv) Delta Plain

Trough cross-stratified sands and gravels were recorded within the delta plain of the KOA succession. Most papers describing glacial delta plain deposition note the similarity between the deposits and an alluvial outwash plain. Coarse-grained longitudinal bars and minor cross-bedded sand wedges have been documented by Gustavson et al (1975) and Leckie and McCann (1982). Cross-bedded sands and gravels interpreted as linguoid and transverse bars have also been documented (Smith and Eriksson,1979; McPherson et al,1987). Few papers discuss the development of distributary channels of the braided system feeding the delta front. Channels in the transition zone from foreset to topset deposition have been recorded in an ice-contact delta by Theakstone (1976) and in a distal-fed delta by Clemmensen and Houmark-Nielsen (1981). The channels have been interpreted as representing anastomosing small distributary channels of the main delta-building system. Both of these systems show overlying coarser grained topset beds interpreted as longitudinal bars deposited within a braided river system. Bergh and Torske (1986) and Orton (1988) have documented similar distributary channels in the transitional area from foreset to topset in braid deltas. The coarsest materials in the delta plain of the distal-fed delta documented by Kelly and Martini (1986) are trough cross-stratified sands, formed by the migration of dunes within distributary channels. In these papers, it is not stated whether the sediments documented represent subaerial or subaqueous channels. The trough cross-stratified sands found in the KOA succession have been interpreted in a similar manner as representing deposition within distributary channels. These sands are transitional to the trough cross-stratified gravels. The gravels represent deposition in distributary channels proximal to the main braided river system. Documentation of similar distributary channels in a glacial delta plain filled with trough cross-stratified gravels has not been found in the literature. Distributary channels may develop over fine-grained low slope delta fronts, as seen in Theakstone (1976), Kelly and Martini (1986) and the KOA succession; or over coarser grained steep slope delta fronts, similar to Clemmensen and Houmark-Nielsen (1981).

Within the Beardmore succession there are two main coarsening upward cycles with different paleocurrent trends. In the Camp 25 and KOA deltas repetitive coarsening upward cycles are common within vertical sequences. It seems appropriate to discuss the cycles seen within the Beardmore, Camp 25 and KOA successions as they are interpreted to represent deposition due to channel switching within the delta plain environment. Active channel switching has been documented on the Balfour delta within Hector Lake (Smith,1978). Cycles of sedimentation have been noted in distal-fed deltas by Gustavson et al (1975) and Clemmensen and Houmark-Nielsen (1981). Clemmensen and Houmark-Nielsen (1981) interpret the occurrence of angular unconformities and thick fining upward sedimentary sequences in coarse-grained planar cross-bedded delta front foresets as delta progradation taking place in several episodes. They suggest the fining upward sequences represent decreasing flow strength and may possibly be seasonal. Smith and Ashley (1985) however, suggest fining upward sequences within coarse-grained foresets are probably not seasonal but represent either a high discharge event or distributary channel switching. Overlapping lobes of sediment deposited by density currents have been attributed to migration of distributary channels across a subaerial delta plain (Gustavson et al,1975).

Cycles of sedimentation have also been documented in ice-contact deltas (Cohen,1979; Jorgensen,1982). Cohen (1979) suggested abrupt change of dips between foreset and bottomset sediments is due to shifting directions of meltwater input over the delta.

There may be controls on cycles other than switching of channels or sources feeding the delta. Coarsening upward deltaic cycles alternating with deltaic-lacustrine cycles can be caused by fluctuating positions of the ice margin (Jorgensen,1982).

(v) Other Related Deposits

As the glacier retreated in the KOA succession, an esker was exposed. Eventually the esker was reworked by waves to deposit wedges of gravel within the fine-grained delta front deposits. The possibility of reworking and redeposition of earlier sediments deposited directly by the glacier must be considered when studying glacial deltas.

(3) SIGNIFICANCE OF THE STUDY

Renewed interest in processes of glacial sedimentation in the past few years has not included a detailed study of glacial deltas. Recent summaries on glacial deltas have examined certain aspects of glacial deltaic sedimentation, yet they have not presented an overall flexible model. For example, Smith and Ashley (1985) suggest deltas formed at the mouth of glacial streams are similar to non-glacially fed deltas. This suggestion appears to oversimplify glacial deltaic sedimentation. Also, Smith and Ashley (1985) do not discuss the possibility of deltaic deposition against the ice margin within proglacial lakes, even though ice-contact deltas have been extensively documented (Theakstone,1976; Orombelli and Gnaccolini,1978; Cohen,1979; Shaw and Archer,1979; and Jorgensen,1982). Glaciers are dynamic systems which are continuously changing. Processes such as daily and seasonal meltwater fluctuations associated with glaciers should affect sedimentation within a glacier fed delta. These proccesses and their effect on sedimentation have not been specifically considered in glacial deltaic studies. Most recent studies on glacial sedimentation have arisen due to the realization that glacial systems are complex, and that the simple models defined earlier may not apply. As Leckie and McCann (1982) stated "existing models of glaciolacustrine sedimentation need to be refined to incorporate situations where a low slope, prograding glaciofluvial delta advances over glaciolacustrine sediments."

The previous discussion has outlined the similarities and differences within the prodelta, delta front and delta plain regions between the three deltaic successions mapped and glacial deltas found in the literature. The following text will describe some of the important additions this study has made to our understanding of glacial deltaic depositional systems.

(i) Multiple processes of sedimentation within the delta front

Two main types of delta front deposition have been documented. The first is deposition by avalanching, forming steeply dipping coarse-grained foresets. The second is underflow deposition forming rippled or ripple-drift sequences. In this study, both deposition by underflows and avalanching have been documented within the same delta front succession. The possibility that more than one process of deposition may occur within the delta front should be considered when studying glacial deltas.

(ii) Presence of distributary mouth bars

Within both the Camp 25 and KOA successions, coarse-grained distributary mouth bars were recorded. The bars are formed of fine-grained rippled sands through plane-laminated sands to coarser grained trough, and planar cross-stratified sands. Documentation of distributary mouth bars within coarse-grained braid or fan deltas (Farquharson,1982; Dunne and Hempton,1984; Bergh and Torske,1986; Orton,1988; and Wood and Ethridge,1988) suggest distributary mouth bars may be present in glacial deltas which are fed by braided systems.

(iii) Large scale cyclic sedimentation

Small scale (cm) cycles of sedimentation have been documented in glaciolacustrine and glacial deltaic successions. However, larger scale cyclic sedimentation has not. In the Camp 25 and KOA succession these cycles have been attributed to channel switching of the distributaries feeding the delta. Larger scale cyclic sedimentation has been documented within deltas, yet has not been considered within glacial deltas. The possibility of distributary channel switching creating large scale cycles should be considered in glacial deltas.

(iv) Inability to define a strandline position

The discussion of distributary channels leads to one of the problems found within glacial deltaic discussions. In glacial deltas dominated by avalanching, a definite erosional surface and change in dip between the foresets and topsets indicate the division of the succession into delta front and delta plain. In fine-grained systems deposited by underflows, generally the coarser grained topset units help distinguish the delta front and delta plain. In both these situations it is possible to delineate the approximate strandline position. The delta front deposits of the Camp 25 succession are represented by rippled and trough cross-stratified sands of the distributary mouth bar. Beds within the distributary channels in the delta plain may also be trough cross-stratified sands. Large erosive scours, typical of meandering distributary channels were not documented, making it impossible to distinguish the upper delta front from the delta plain, and define the strandline position. The development of complex systems which include distributary mouth bars makes the distinction between delta front and delta plain difficult.

The next two points deal with relict deposits associated with active glaciation.

(v) Presence of subaqueous outwash system

The KOA glacial deltaic succession partly overlies a subaqueous outwash system which developed when the ice margin was grounded within the lake. As the ice margin withdrew, a deltaic system built into the lake. In the KOA succession, the delta prograded over the subaqueous outwash system. The KOA succession is the first known example in the literature of a subaqueous outwash system overlain by a deltaic sequence.

(vi) Reworking of previous glaciogenic deposits

An esker system within the KOA succession was exposed as the glacier retreated. Wedges of gravels which fine away from the esker core were found interbedded with the delta front sands. The wedges represent reworking and redistribution of the esker by storm waves within the lake. Eskers are just one of the many positive relief features associated with glaciation. The possibility of reworking and redeposition of earlier sediments deposited directly by the glacier must be considered when studying glacial deltas.

(vii) Glacial deltaic sedimentation against an ice margin which began subaqueously

The Camp 25 succession has been interpreted to represent originally subaqueous deltaic sedimentation against an ice margin. The shallow depth of the lake combined with rapid sediment accumulation resulted in subaerial deposition of the delta against the ice margin. Numerous small shallow ice-contact lakes develop in front of retreating ice margins. The shallow depth of small, proglacial lakes and rapid sedimentation rates, typical of glacial environments suggest development of subaerial deltaic sequences from initially subaqueous deposits should be considered when studying glacial deltas.

The discussion of the Camp 25 succession raises the problem of models of glacial deltaic sedimentation. As outlined earlier, no comprehensive model of glacial deltaic sedimentation has been developed. The previous discussion of the three glacial deltas of this study and glacial deltas in the literature involved comparing and contrasting the processes of deposition within the different regions of a delta. In this discussion it was evident that similar processes may occur within both distal-fed deltas and ice-contact deltas. Deposits such as ripple-drift sands on the delta front are representative of both delta types. Definition of the terminology applied to glacial deltas is needed. The following definitions are proposed for glacial deltas. The two main delta types, distal-fed and ice-contact, may be divided further into two subcategories. This results in four main glacial type end members. It is important to note that these four delta types are end members, and that a continuum exits between them. Distal-fed deltas may be divided into (i) deltas far removed from the glacier, such that no direct effects of the glacier are felt, defined here as nonglacial distal-fed deltas, and (ii) deltas in which the ice margin is close to the delta, and may influence the sedimentation, defined here as ice-influenced distal-fed deltas. Subglacial ice-contact deltas may be defined as ice-contact deltas fed by englacial or subglacial tunnels, which are deposited against the ice margin. Similarly, supraglacial ice-contact deltas are deposited against the ice margin and are fed by supraglacial and occasionally englacial sources. Generally, supraglacial ice-contact deltas build into lakes formed at the junction of an active and stagnant ice margin, and are deposited on top of the stagnant ice. The settings of the four delta types are shown in Figure 4.1.

Description of the various processes operating within a glacial delta combined with application of one of the four delta type definitions outlined previously, would make it possible for better understanding of the setting and depositional environment of glacial deltaic successions.

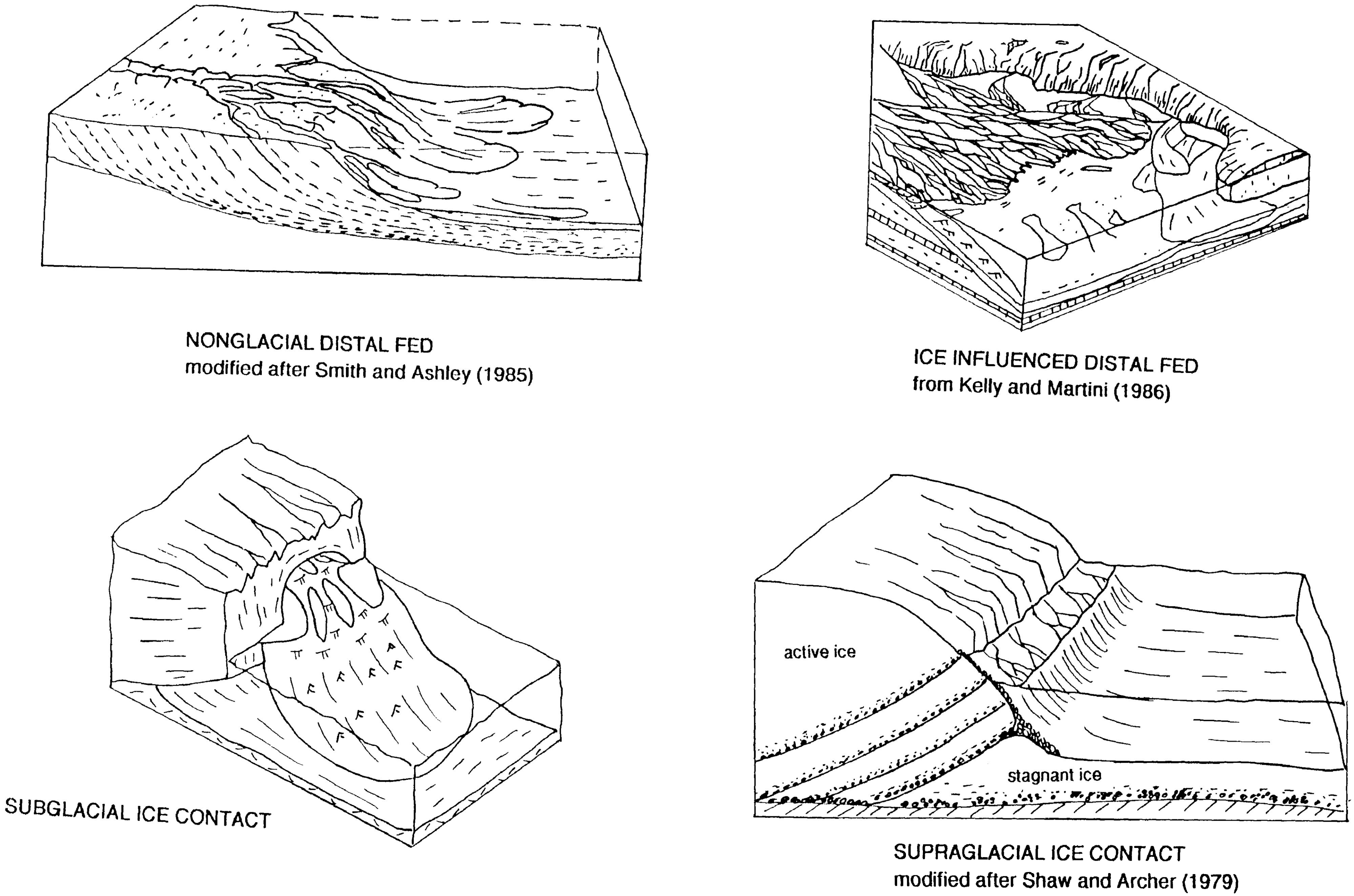


Figure 4.1 Models of deposition of the four main glacial delta types.

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FIGURE 2.20C KOA DETAILED STRATIGRAPHIC COLUMNS

SECTIONS POSITIONED ON TRUE RELATIVE ELEVATION

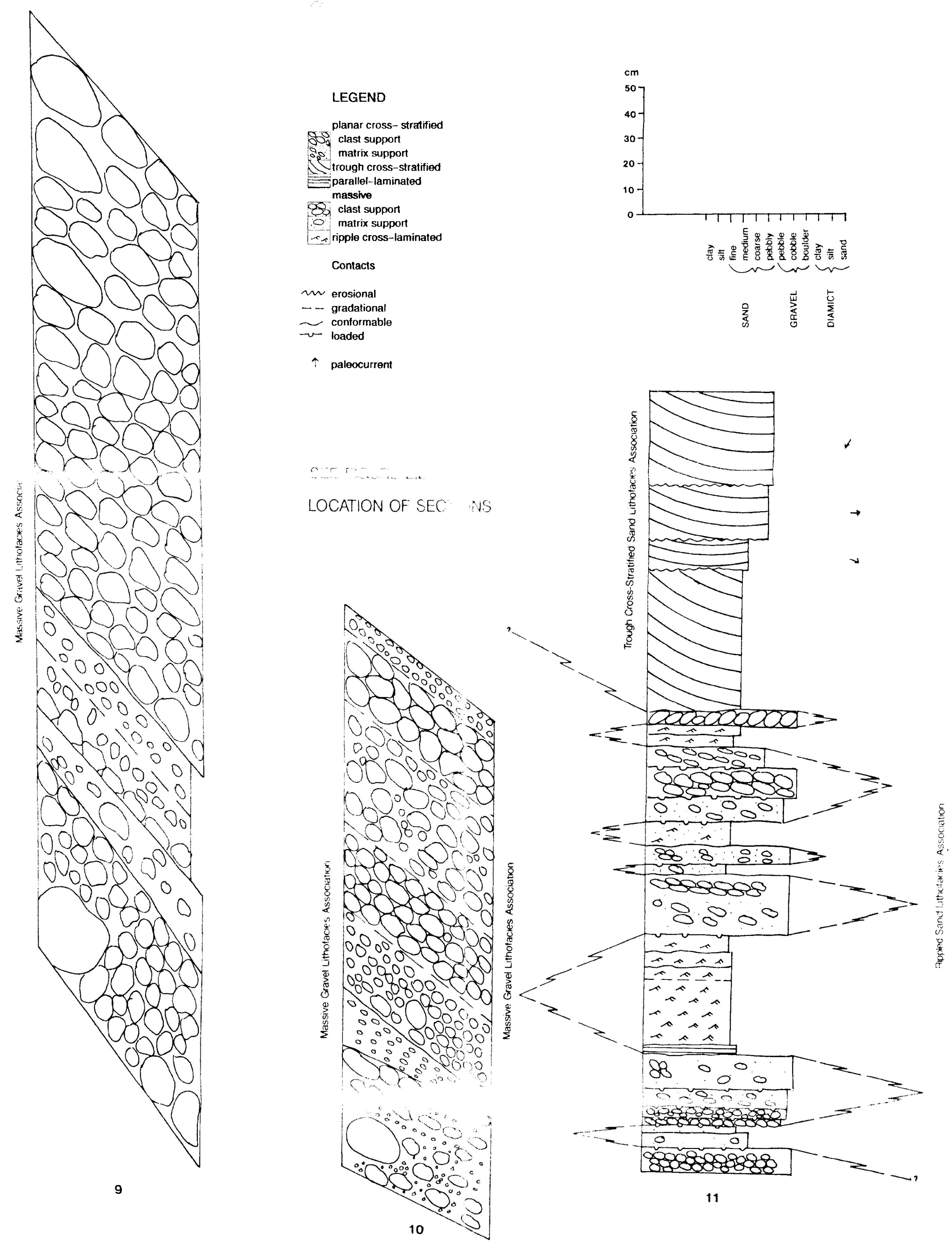
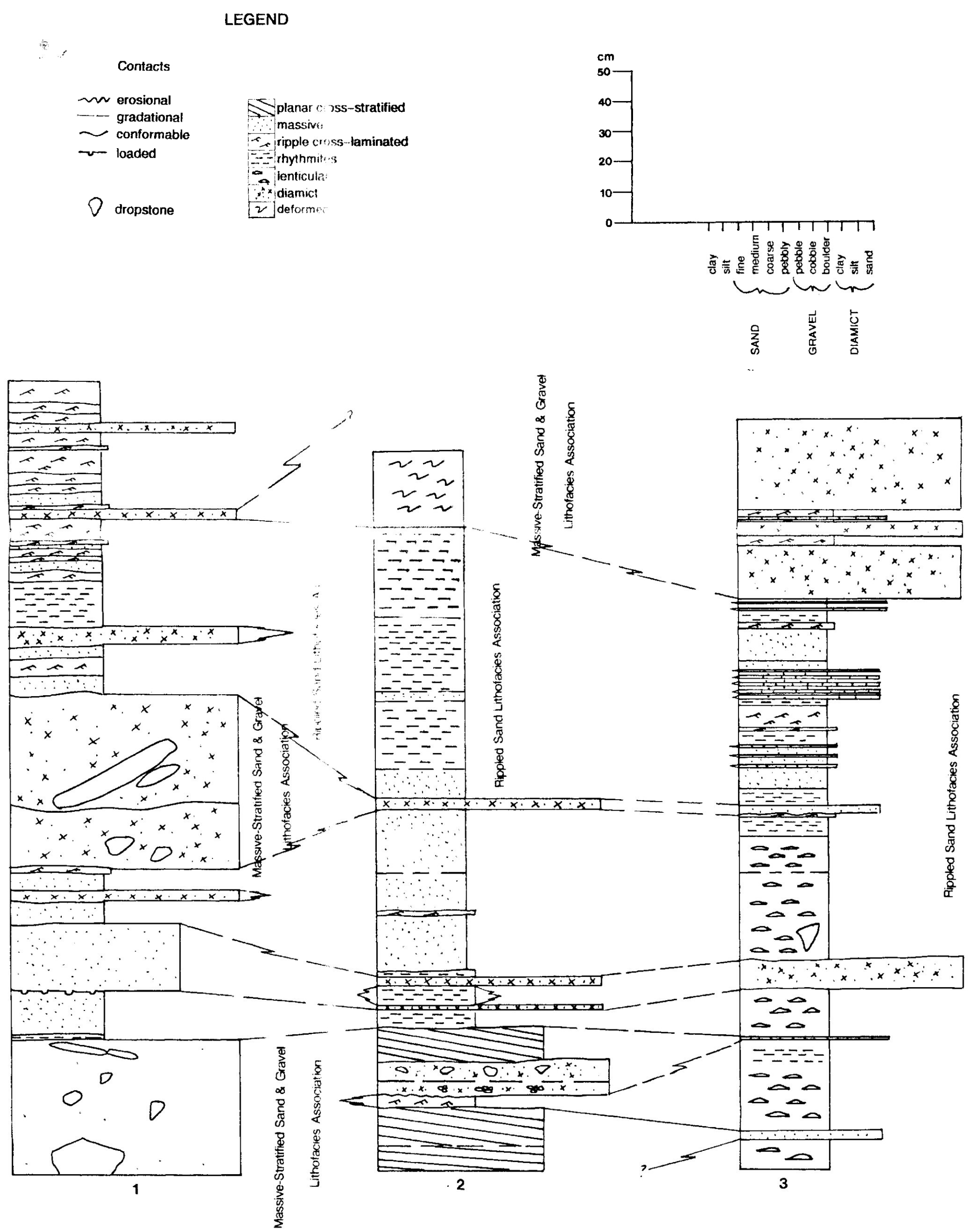


FIGURE 2.20A KOA DETAILED STRATIGRAPHIC COLUMNS



SEE FIGURE 2.20B FOR

LOCATION OF SECTIONS

SECTIONS POSITIONED ON TRUE RELATIVE ELEVATION

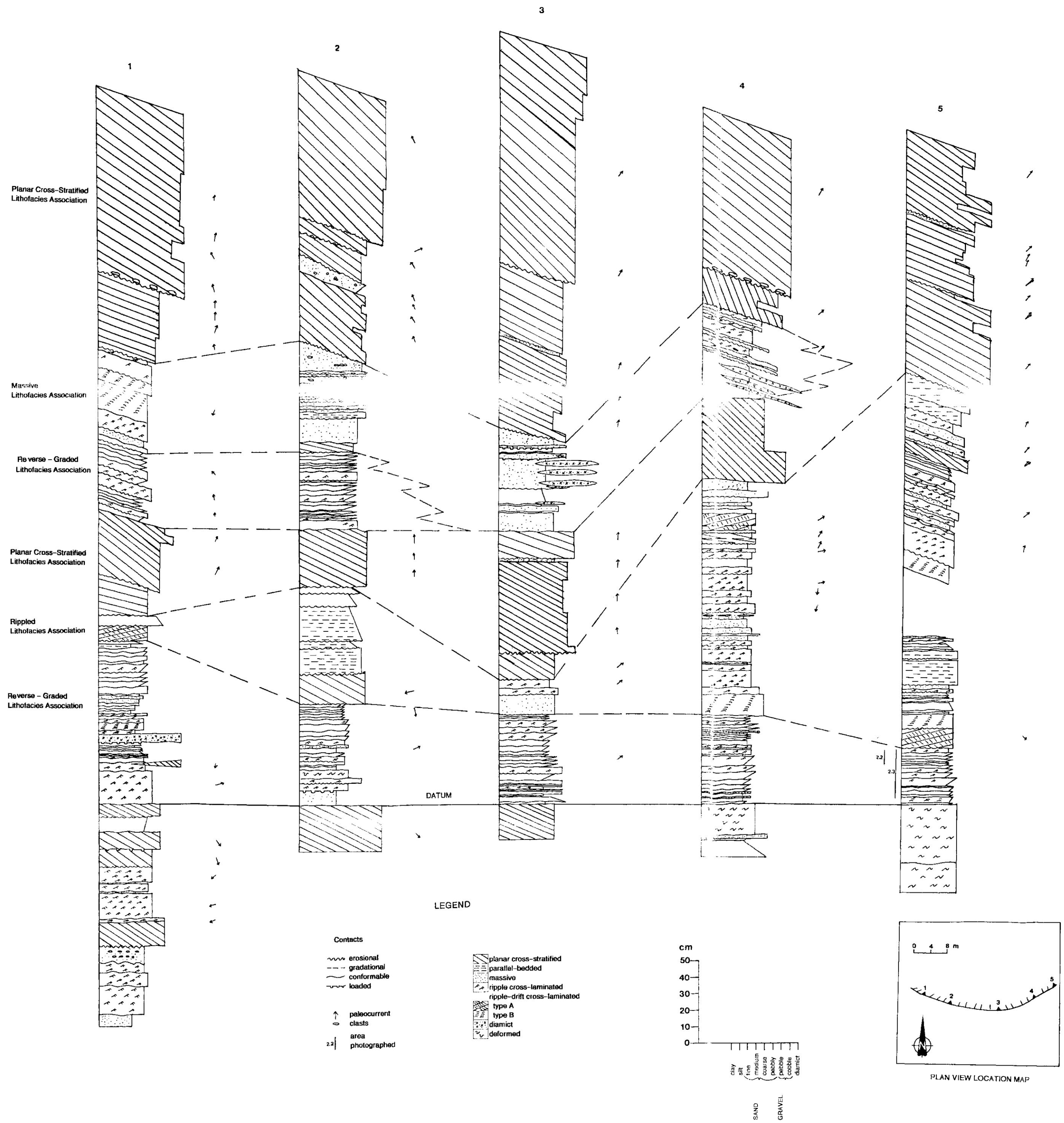


FIGURE 2.1 BEARDMORE DETAILED STRATIGRAPHIC SECTIONS

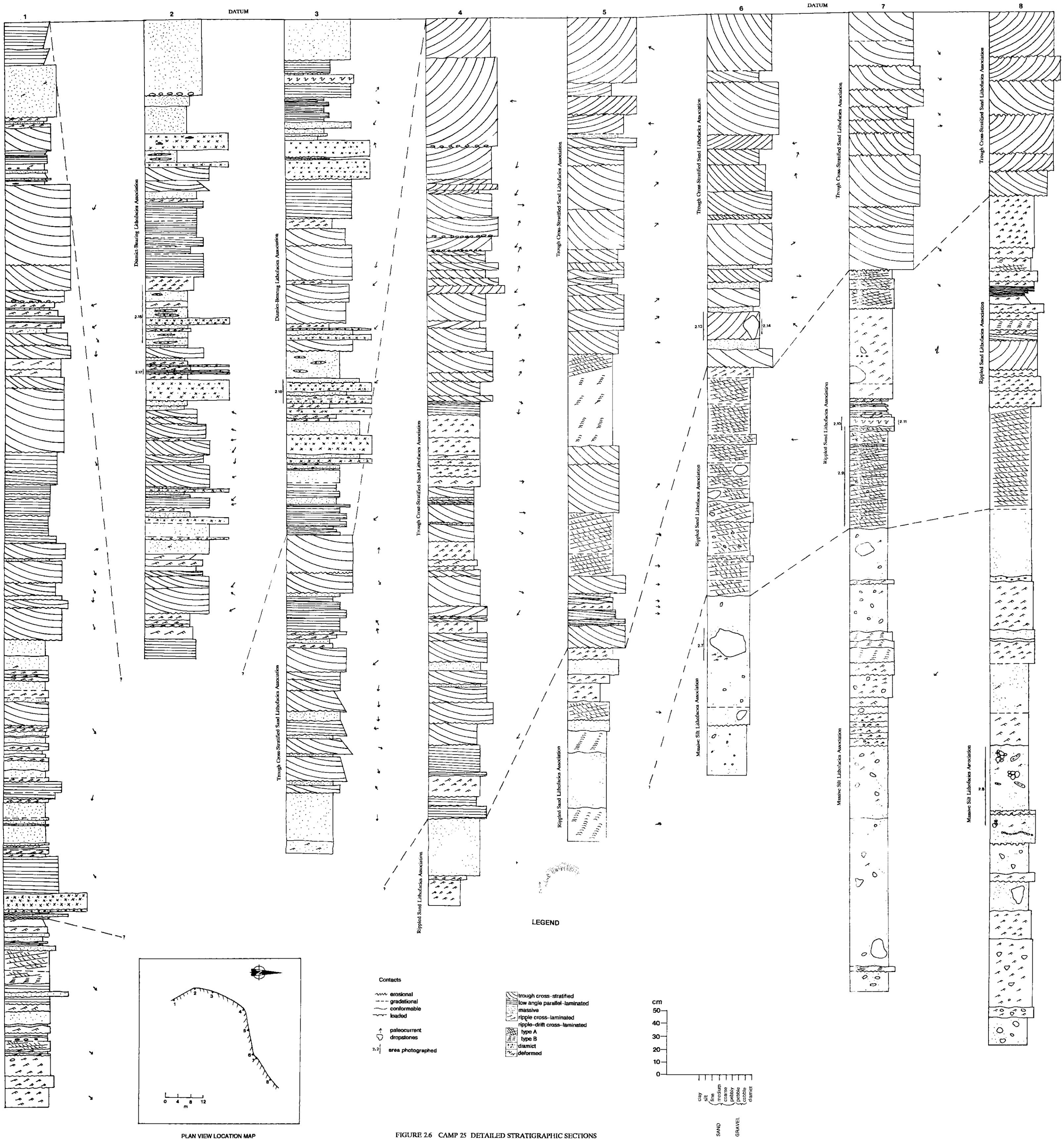


FIGURE 2.6 CAMP 25 DETAILED STRATIGRAPHIC SECTIONS

FIGURE 2.20B KOA DETAILED STRATIGRAPHIC COLUMNS