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Undergraduate course number Geol. 4K6 at McMaster University under the supervision/direction of Dr. C. Eyles, & Dr. R.G. Walker.

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THE QUATERNARY SEDIMENTOLOGY OF THE SEVERN RIVER
HUDSON BAY LOWLANDS

by

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A Thesis
Submitted to the Department of Geology
in Partial Fulfillment of the Requirements
for the Degree
Honours Bachelor of Science

McMaster University

April, 1987

Honours Bachelor of Science (Geology/Geography)

McMaster University
Hamilton, Ontario

TITLE: The Quaternary Sedimentology of the Severn River area, Hudson Bay Lowlands

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SUPERVISORS: Dr. C.H. Eyles
Dr. R.G. Walker

NUMBER OF PAGES: xi, 123

ABSTRACT

Quaternary sediments exposed in the banks of the Severn River, Hudson Bay Lowlands, are interpreted as components of four distinct types of depositional complexes. Overconsolidated massive diamicts displaying strong clast fabric orientations and containing channelized, sub-glacial fluvial deposits and glacially shaped clasts, comprise the majority of sediments in the study area. These are interpreted as components of a lodgement till complex.

Thin massive diamict units which often display random clast fabric orientations, and laminated fine-grained sediments containing dropstones and diamict clots often occur near the tops of sections. These are interpreted as components of either a glacio-lacustrine or glacio-mairne depositional complex, depending on the abundances of formainifera contained in the sediments. An uniquely marine depositional complex is composed of fossiliferous beach gravels, and estuarine silts and sands. This complex is found only at the very tops of sections, and was probably deposited in the post-glacial Tyrrell Sea.

Three distinct ice flow orientations were defined by clast fabric analysis, and measurement of striations on boulder pavements and bedrock surfaces. Three separate lodgement till complexes are identified by combining these ice flow orientations with data on formainifera abundances, erratic clast lithologies and diamict matrix colours. These lodgement complexes were deposited by ice flowing from three separate ice domes; an earlier Patrician dome, a middle James Bay dome and a younger New Quebec dome.

Acknowledgements

The author wishes to thank Harvey Thorleifson and Carolyn Eyles for their insight and advice, and for numerous interesting discussions. Thanks also to Dr. Roger Walker, who acted as a nominal supervisor, and to the Geological Survey of Canada, who hired me, and then shipped me off to the lowlands. Jack Whorwood prepared the photographs and gave advice on the presentation of figures. Special thanks to my friends and fellow thesoids who helped me survive the year.

Lastly, I would like to thank Kim Telford for her patience and generosity in the face of extreme stubbornness.

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INTRODUCTION

1.0 Overview

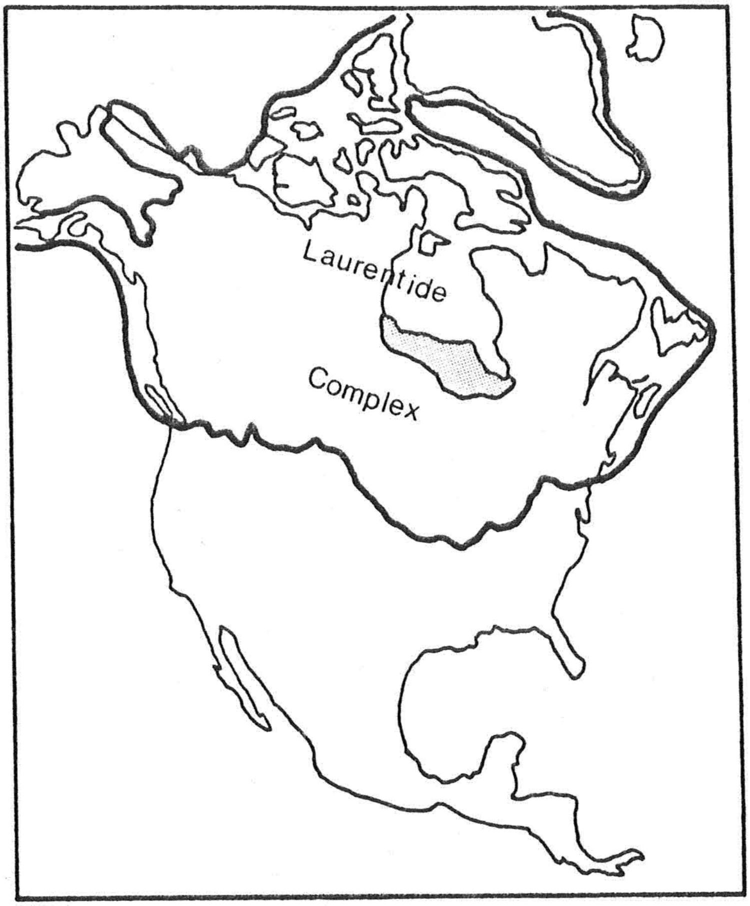
The river bluffs of the Hudson Bay Lowlands contain some of the most continuous and well exposed sections of Quaternary sediment in northern Canada. These sections are of interest not only because of their extent, but also because of their proximity to the geographical centre of the Laurentide Ice Sheet (fig. 1). Most of the information on this ice sheet, to date, has come from studies of sediments deposited at or near the ice sheet margin (eg. Great Lakes Basins, St. Lawrence Seaway), and, as such, the sedimentary processes which operated beneath the main body of the ice sheet have not been well documented. An understanding of these processes and their timing is critical for the interpretation of glacial histories further south.

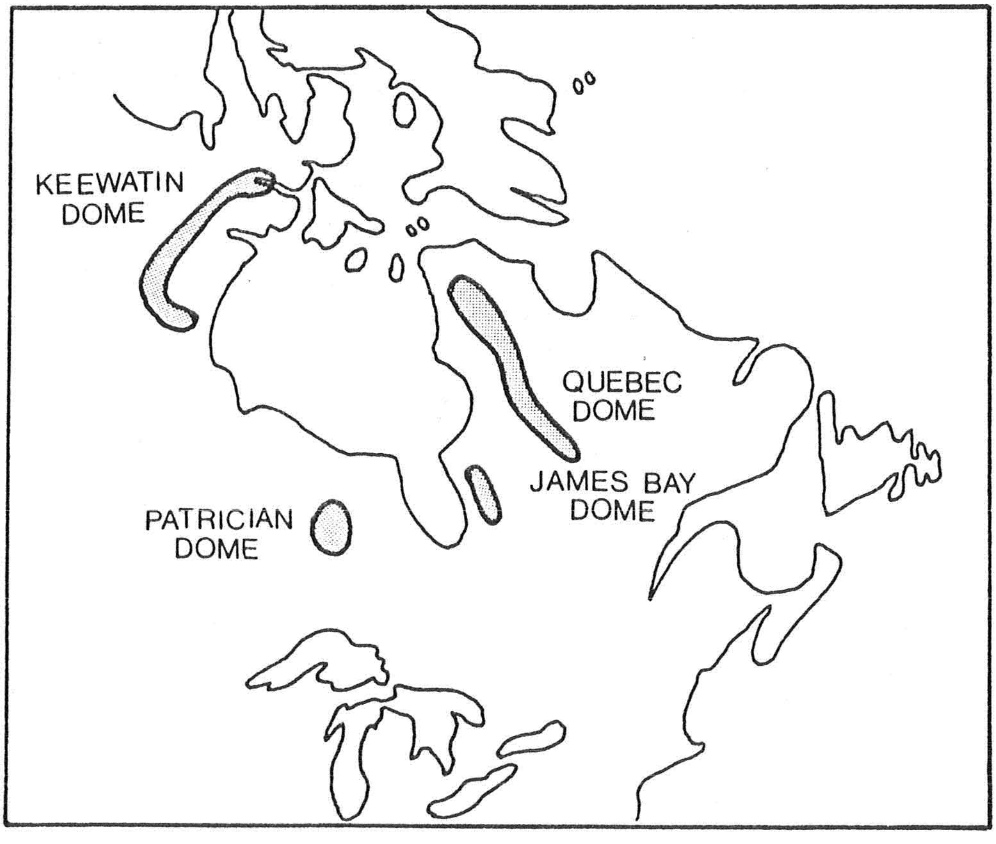
In addition, if one accepts a multidomed model for the Laurentide ice sheet (see chapter 1.3), then the central Hudson Bay Lowlands is an area which should have been affected by ice from several of these domes (fig. 2).

Because of the logistical problems associated with this field area, only the Geological Survey of Canada (GSC) and the provincial surveys have been able to finance mapping and exploration in the lowlands. Recently, there has been some

FIGURE 1: The location of the Hudson Bay Lowlands (shaded) in relation to the Laurentide ice sheet (after Peterson et al., 1980).

FIGURE 2: Approximate location of ice domes proposed by Tyrrell (1914), Shilts (1980), and Bouchard and Martineau (1985).


Laurentide
Complex


KEEWATIN DOME
QUEBEC DOME
JAMES BAY DOME
PATRICIAN DOME

drift geochemistry-type mineral exploration carried out in the James Bay Lowlands by the private sector.

The Hudson Bay Lowlands (including the James Bay Lowlands) roughly coincide with the extent of the Paleozoic rocks which cover the Precambrian basement around Hudson Bay (fig. 3). The Paleozoic strata are generally flat-lying, with a slight dip towards the centre of the bay. These are overlain almost continuously by up to 40 m of unconsolidated Quaternary sediments. The surface topography shows virtually no relief, and is essentially a flat, almost featureless bog (plate 1).

1.1 Objectives

The author was part of a small GSC field party that travelled down the Severn River in the central Hudson Bay Lowlands in the summer of 1986. The purpose of this trip was to complete a reconnaissance-scale study of the Quaternary sediments exposed along the river from the junction with the Witagoo River downstream to Limestone Rapids (figs. 4, 5 & 6). This is a straight-line distance of about 130 km, which was covered in approximately three weeks.

The objectives of this study were;

1) to obtain detailed section descriptions, clast fabric data and paleontological data from the Quaternary sediments exposed in the study area,

2) to produce a facies classification scheme for these sediments,

FIGURE 3: Distribution of Paleozoic bedrock in the Hudson Bay Lowlands.

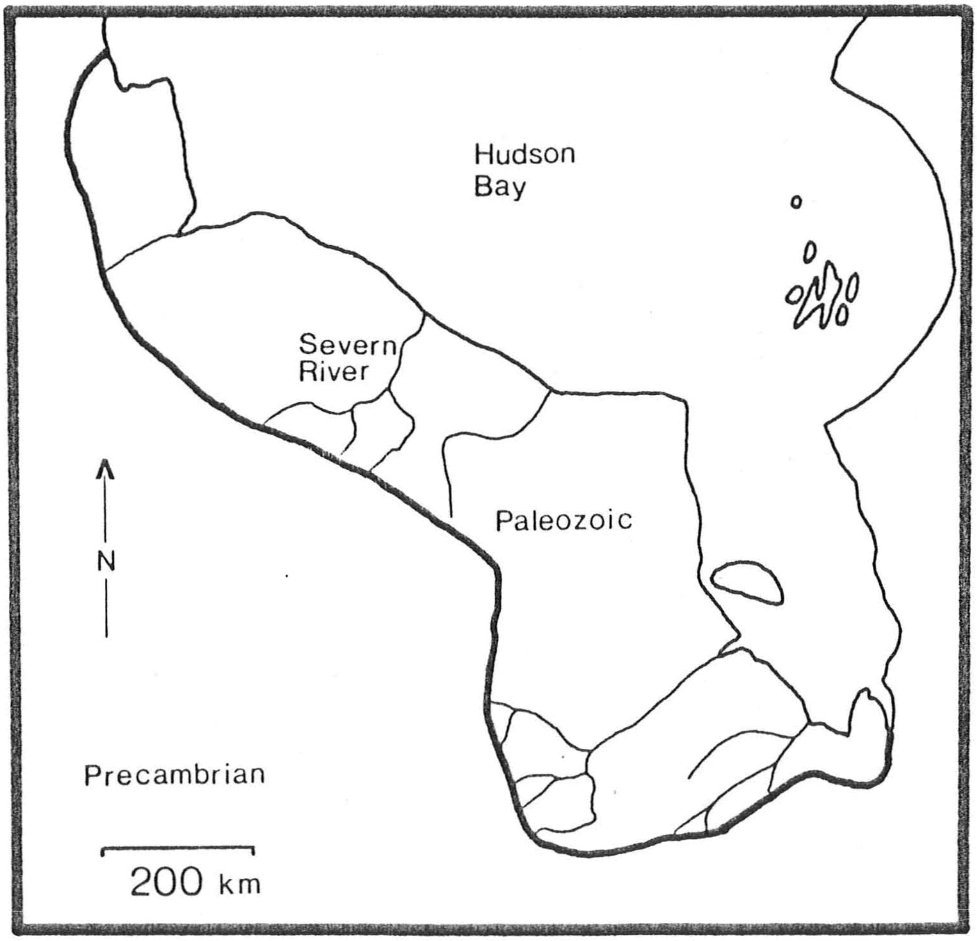
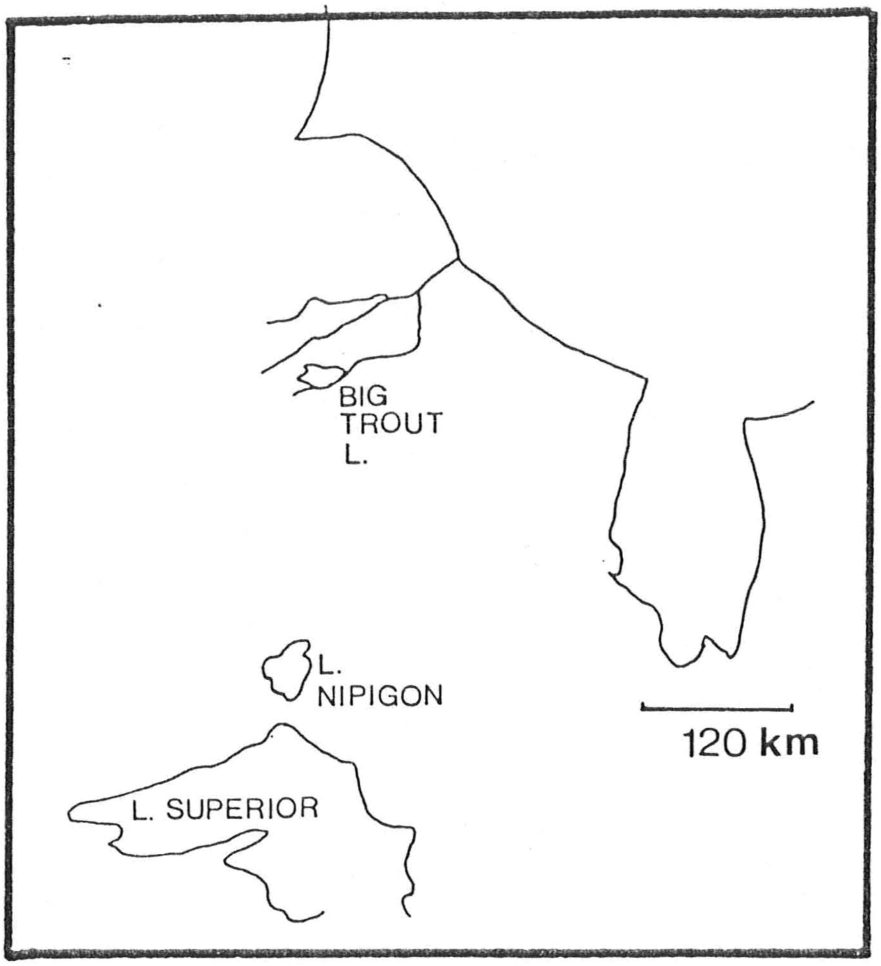

Hudson
Bay
Severn
River
Paleozoic
N
Precambrian
200 km

PLATE 1: Aerial view of the Severn River and the surrounding lowlands.

FIGURE 4: Location of Big Trout Lake and Lake Nipigon.

FIGURE 5: Location of the study area within the Hudson Bay Lowlands.


BIG
TROUT
L.
L.
NIPIGON
120 km
L. SUPERIOR

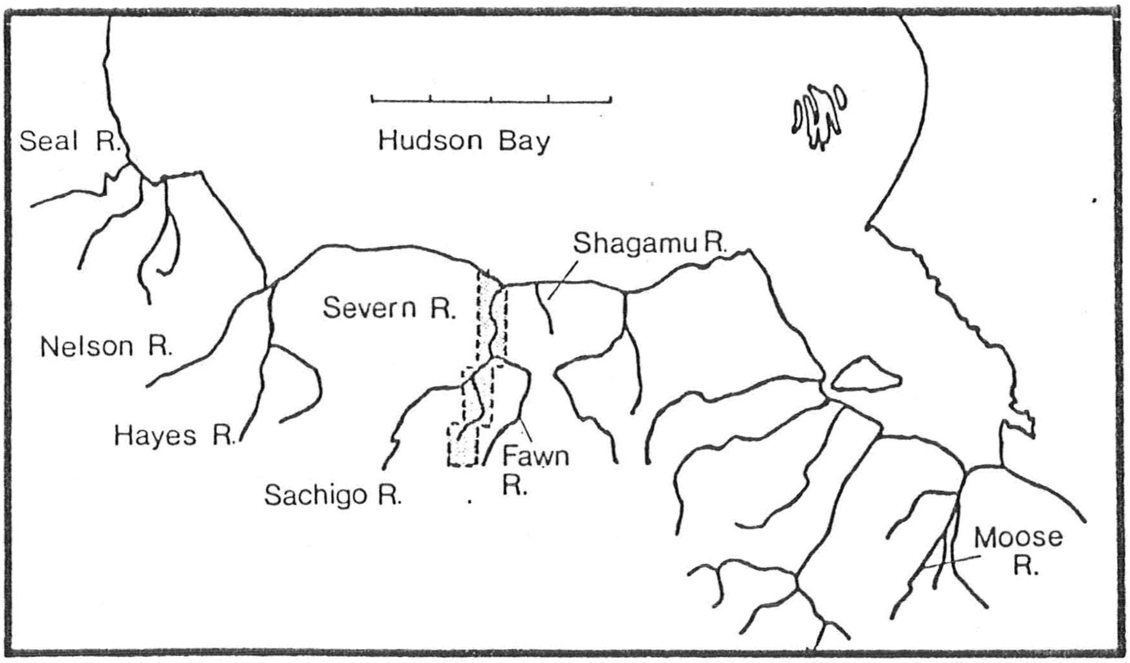
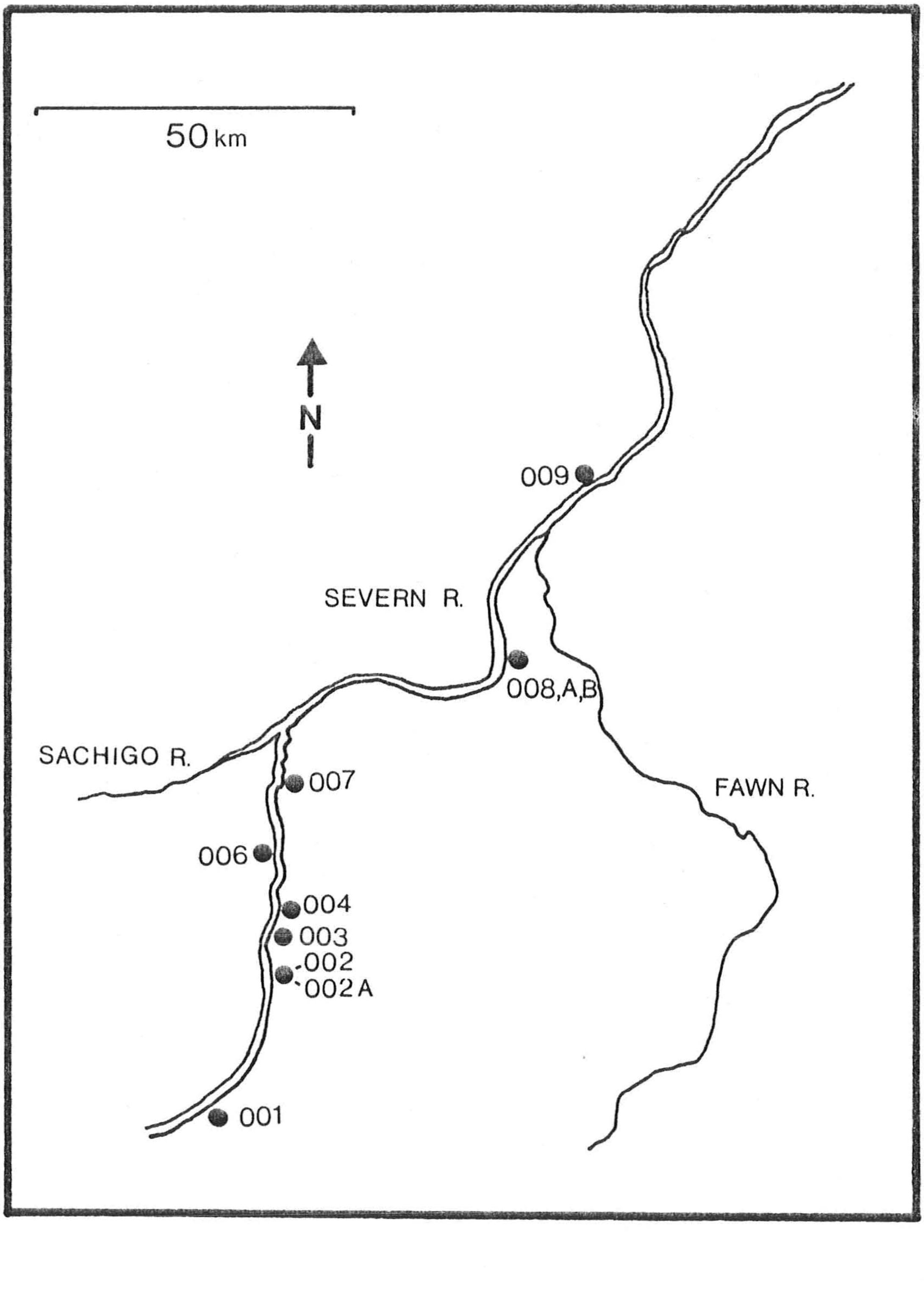

Hudson Bay
Seal R.
Shagamu R.
Severn R.
Nelson R.
Hayes R.
Fawn
R.
Sachigo R.
Moose
R.

FIGURE 6: Locations of sections within the study area.


50 km
N
009
SEVERN R.
008,A,B
SACHIGO R.
007
FAWN R.
006
004
003
002
002A
001

3) to establish the nature of the depositional environments, and develop a geologic history for the area and,

4) to briefly comment on the implications of this study for ice sheet configuration models and establish potential areas for further research.

1.2 Previous Work and Stratigraphy

The first work on the Quaternary stratigraphy of the Hudson Bay Lowlands was carried out in the late 1800's and early 1900's by Bell (1877) and Tyrrell (1912). These workers described the general nature of the sediments, but were concerned mainly with the fuel potential of non-glacial and Cretaceous organic deposits, which they lumped together under the term "lignites".

Along the Missinabi River, Bell (1877) described a stratigraphy consisting of an upper sand and gravel, a middle "till" and underlying clay and "lignite". McLearn (1927) examined these "lignites" further and was finally able to differentiate between the inter-glacial peat deposits and the true Cretaceous lignites. He also modified the Missinabi River stratigraphy to include two "drifts" separated by interglacial peat.

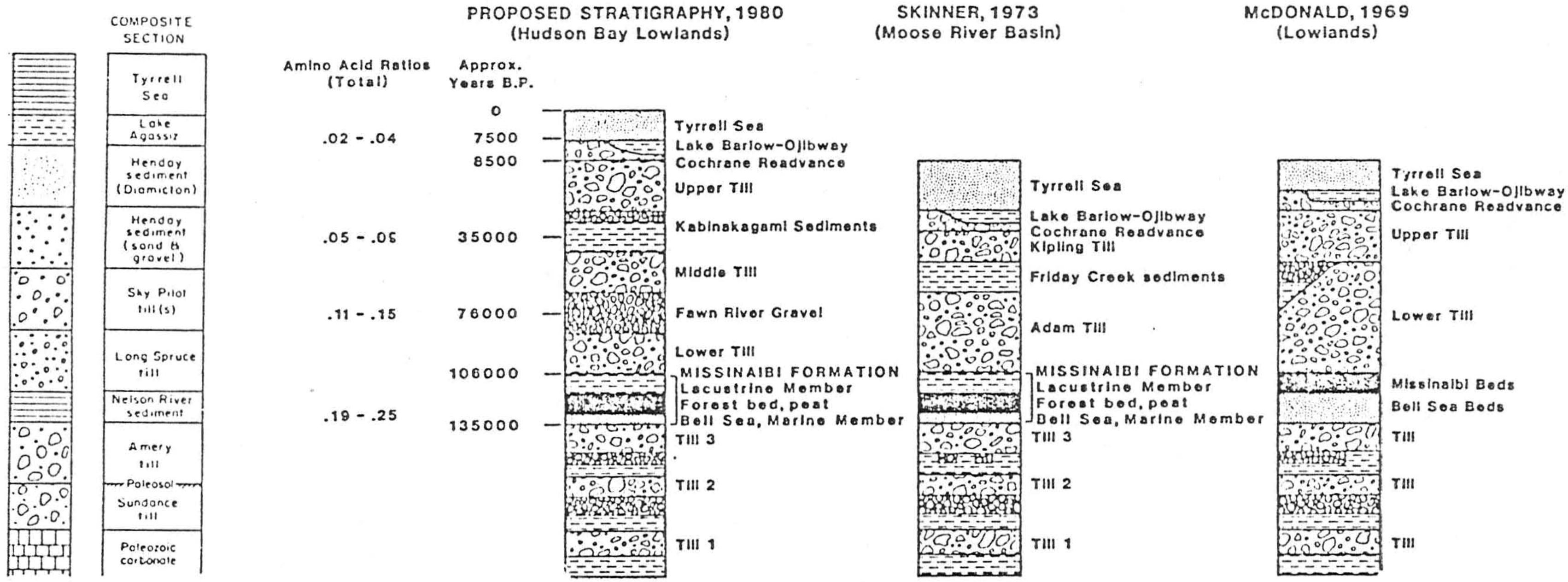
Terasmae and Hughes (1960) carried out the first modern study in the James Bay Lowlands, working along the Missinabi and Opasatika Rivers. Although they were primarily concerned with the palynology of the interglacial units, they also developed a refined stratigraphy. They identified an upper fluvial unit overlying an upper "drift unit". These were separated from two lower "tills" by an interglacial unit which they named the Missinabi beds. The palynology of these beds led them to conclude that they were deposited in a climate similar to the present. They assigned the interval a Mid-Wisconsin interstadial rank, and obtained a radiocarbon date of greater than 53,000 years bp.

Barry McDonald (1969) coordinated the Quaternary section of the GSC's **Operation Winisk**, an intensive, multi-disciplinary, helicopter-supported reconnaissance study of the entire Hudson Bay Lowlands carried out in 1967. McDonald examined sections from the Hayes River eastward to the Moose River Basin (fig. 5), and developed yet another stratigraphy for the Lowlands (fig. 7). For the Fawn and Severn River area, he proposed one pre-Missinabi and two post-Missinabi "tills". The two upper tills were separated by proglacial lake sediments in the eastern and western lowlands, but directly overlay one another in the central lowlands. McDonald reported that the two upper tills could be distinguished on the basis of colour and texture.

Skinner (1973) again expanded the Hudson Bay Lowlands stratigraphy (fig. 7) and assigned formal stratigraphic names to several of the units. He called the upper brown till the Kipling Till and the underlying grey till the Adam Till. He also named the gravels and laminated silts which

FIGURE 7: Composite stratigraphies developed by McDonald (1969), Skinner (1973), Shilts (1982) and Nielsen et al. (1986) (after Shilts (1982) and Nielsen et al. (1986).

Nielsen et al., 1986
(Nelson R.)



separated these two upper tills, calling them the Friday Creek sediments, and assigning them a mid-Wisconsin interglacial rank. Skinner argued that conditions which permitted an ice-free Hudson Bay basin represented sufficient deglaciation to warrant an interglacial rank.

In addition, Skinner also expanded the description of the Missinabi beds to include a lower marine member composed of fossiliferous sand, silt and clay, grading upwards into a fluvial unit containing current-bedded silts, sands and gravels. Overlying this was a "Forest-peat" member containing numerous plant remains and peat. This was in turn overlain by a proglacial lacustrine unit of silt and clay. He formalized the formational status of the Missinabi beds, and correlated them with the Sangamon interglacial, which placed the Adam Till in the early Wisconsin and the Kipling Till in the Late Wisconsin.

The current stratigraphy (fig. 7), was developed by Shilts (1982) and Andrews et al. (1983), using amino acid geochronometric data obtained from mollusc fragments found in tills throughout the lowlands. Amino acid geochronology is based on the assumption that, given a constant known temperature, L-isoleucine acid gradually decays to its non-protein diasteroisomer D-alloisoleucine at a consistent rate. Therefore, the L-isoleucine to D-alloisoleucine ratio can be used as an indicator of relative age (Thorleifson, 1984).

The amino acid results from the Hudson Bay Lowlands indicated that, if the Missinabi Formation represents the Sangamon interglacial (at about 135,000 years bp), than the Lowlands must have been inundated by marine waters at least twice between the Sangamon interglacial and the present. If, as Shilts proposed, an ice-free Hudson Bay represents a full interglacial, then this implied that there were two Wisconsin interglacials, post-dating the Sangamon. This was a completely new proposal, and based on this, Shilts (1982) developed a stratigraphy (fig. 7) which contained three post-Missinabi tills separated by two interglacial units and capped by the Tyrrell Sea deposits. Shilts acknowledged that three post-Missinabi tills had never been documented in the lowlands. However, Thorleifson (1984), suggested that this may be due to mis-correlation of various units by McDonald (1969) and Skinner (1973).

Recently, Nielsen et al. (1986), documented the Quaternary stratigraphy (fig. 7) exposed along the Nelson River in the western Hudson Bay Lowlands (fig. 5). They found an interglacial unit (Nelson River Sediments) which they correlated with the Missinabi Formation from the eastern lowlands, underlain by two pre-Missinabi tills. Above the Nelson River sediments they showed two further tills, the Long Spruce and Sky pilot tills, which they correlated with Skinner's Adam and Kipling tills respectively.

Because the upper Adam and Kipling tills and the Missinabi Formation have apparently been traced across the entire lowlands, it was expected that they would also be present in the Severn River sections.

1.3 Ice Sheet Configuration

The configuration of the Laurentide Ice Sheet has been the focus of much controversy since the late 1970's. In 1979, Shilts et al., revived a concept originally proposed by Tyrrell in 1912, which called for a multi-domed configuration of the ice sheet. This was in sharp contrast to the standard model of a single, stable ice dome centered over Hudson Bay that had been developed by Flint (1943) and used by most subsequent workers (eg. Denton and Hughes, 1981).

Tyrrell's original model (fig. 8) was based on bedrock forms and striations and on erratic dispersal patterns throughout the Hudson Bay Lowlands and on the surrounding Precambrian shield. He proposed three major ice domes located on high ground around the bay, and flowing into and through the Hudson Bay basin. The major dome was located somewhere in the Labrador/Nouveau-Quebec area and is referred to here as the New Quebec dome. Ice flow from this dome was to the west and south through Hudson Bay. Another very significant dome was located in the District of Keewatin on the west side of

FIGURE 8: Tyrrell's (1914) original model for the configuration of the Laurentide ice sheet (from Shilts, 1982).


GREENLAND ICE SHEET
KEEWATIN ICE SHEET
LABRADOR ICE SHEET
PATRICIAN ICE SHEET
VALLEY AND PIEDMONT GLACIERS
St Paul
Philadelphia
Topeka
St Louis
Louisville
Santa Fe
55°
45°
35°
25°
15°
115°
105°
95°
85°
75°

the bay, and is referred to here as the Keewatin Dome. This dome resulted in ice flow to the east and south. Finally, Tyrrell proposed a more short-lived dome called the Patrician dome, located in the District of Patricia, to the south of the lowlands. Ice from this dome flowed northwestward into the basin.

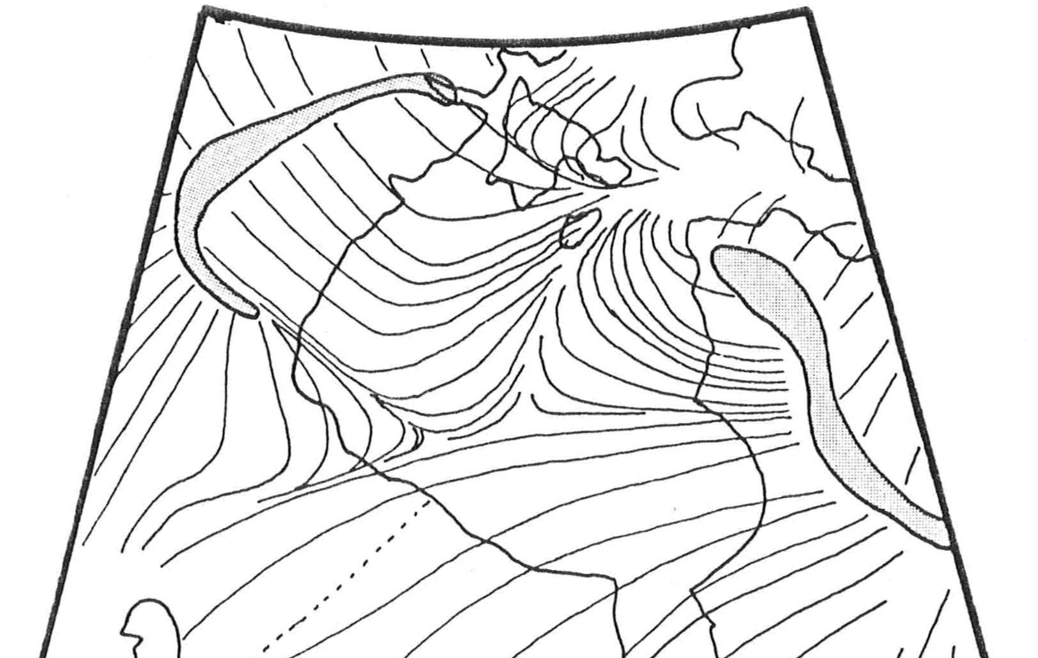
Flint (1943) dismissed Tyrrell's model and proposed instead, a model with a stable, single dome centered on Hudson Bay (fig. 9). However, this model was unable to explain geological data such as erratic dispersal patterns and ice flow orientations observed in the Hudson Bay Lowlands.

Because of problems with erratic dispersal patterns, Shilts et al. (1979) modified Tyrrell's multi-dome model to include only the New Quebec and Keewatin domes (fig. 10). Shilts felt that erratic distributions were adequately explained by these two domes, without the need for the third Patrician dome. Further evidence to support a multi-domed model has come from others working in the area of Hudson Bay, including Dyke et al. (1982), Bouchard and Martineau (1985), and Nielsen et al. (1986).

Bouchard and Martineau also provided ice flow data from the area east and southeast of James Bay which indicated a regional, pre-New Quebec dome located on the eastern side of James Bay (fig. 2). This dome will be referred to here as the James Bay dome.

FIGURE 9: Flint's (1943) single dome model for the Laurentide ice sheet (after Shilts, 1982).

FIGURE 10: Shilts' (1982) multiple dome configuration with a Keewatin dome (left) and a New Quebec dome (right).



Because of its central location, the study area might possibly have been affected by several or all of these proposed ice domes (fig. 2). Therefore, while the principal aim of this study was to interpret the sedimentology of the Quaternary deposits in the area, it was also hoped that this study could shed some light on the possible configuration of the Laurentide ice sheet.

CHAPTER 2

FIELD AND LABORATORY TECHNIQUES

2.1 Field Logging and Section Description

Ten vertical sections along the study area were examined in detail over approximately three weeks.The sections were chosen in order to maintain a fairly even spacing across the study area (fig. 6), while maximizing the vertical exposure at each site. In many cases, slumping of the unconsolidated sediments and thick slope wash made detailed logging impossible. Prior to logging the sections, steps were cut into the steep bluffs, and slope wash and weathered material were removed, in order to give a continuous vertical profile. Since priority was placed on maximizing vertical exposure, lateral control was often poor.

The sediments were logged using the lithofacies code of Eyles, Eyles and Miall (1983). The lithofacies code was used because it provides a relatively standard and non-genetic terminology for the rapid logging of sections. In addition to the lithofacies abbreviations, any significant sedimentary structures were noted. Also recorded were bed thicknesses, nature of contacts, lateral continuity and geometry of units.

Grain size was estimated in the field, as was the size, shape and abundance of clasts in the diamicts. Sediment colour was recorded using a standard Munsell colour chart. Graphic logs of the sections are shown in cross-section (fig. 11), with the Severn River used as a base level. Colour stratification of diamict matrices is shown in figure 11A. The approximate gradient of the river surface has been depicted in order to demonstrate the relative stratigraphic position of each section.

2.2 Ice Flow Direction Indicators

Information regarding former ice flow directions can provide valuable support for the interpretation of the genetic origin and depositional environment of massive diamict sequences (Dowdeswell et al., 1985). It can also be used to test various models concerning the behaviour and location of the ice dispersal centres of the Laurentide Ice Sheet. Therefore, several methods were employed to determine ice flow directions in the study area, at various locations as well as at different stratigraphic levels;

1) Whenever possible, the orientation of striations on boulder pavements, flat-iron clasts, and bedrock surfaces were measured. Although these striations give a clear and reliable indication of the line of glacier movement, they do not, by themselves, give an indication of the direction of flow, i.e. the down-ice direction.

FIGURE 11: Graphical representation of vertical sections from the Severn River study area. Correlations are based mainly on ice flow direction indicators and foraminifera abundances (see text)

Diamict

Gravel

Sand

Silt/clay

Horizontal laminations

(7) Foraminiferal abundances/100g

Mollusc valves

Trough cross-bedding

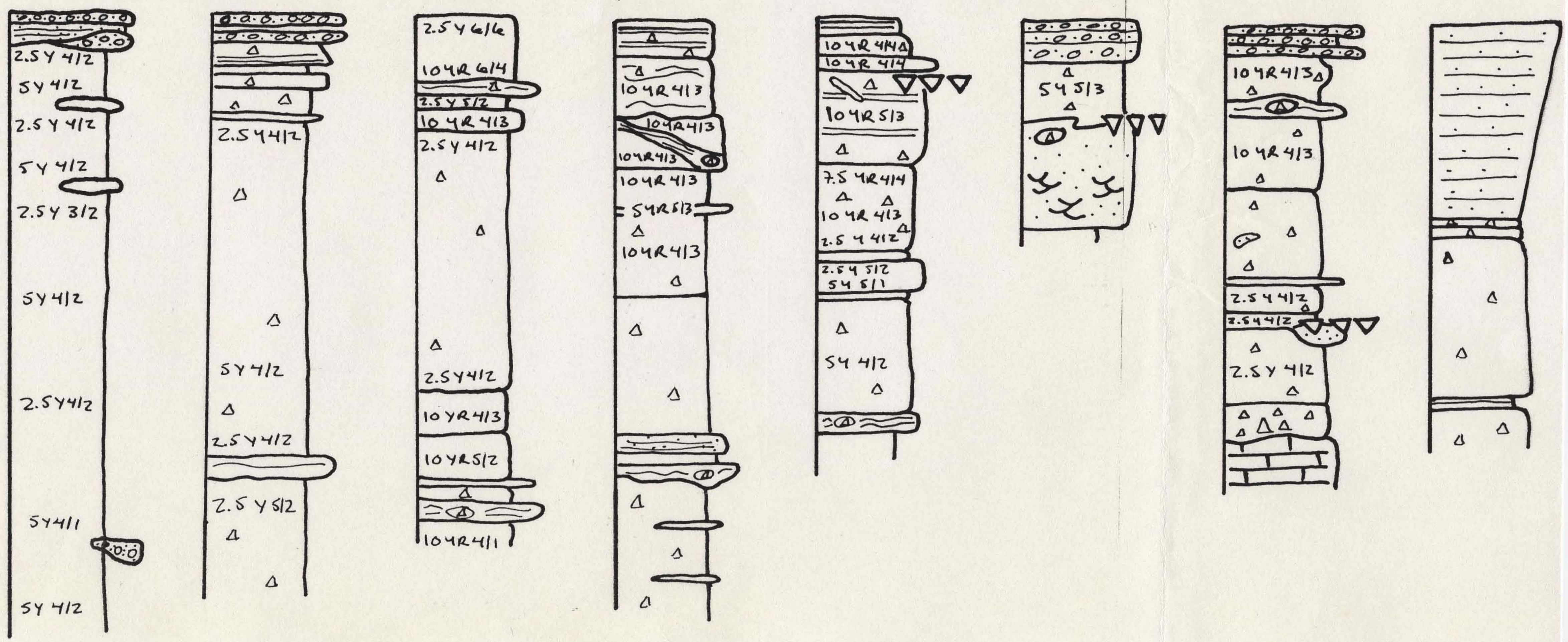
Boulder pavement

Ice flow direction

Dmm - Diamict, matrix supported, massive
Dms - Diamict, matrix supported, stratified
Gm - Gravel, massive
Gh - Gravel, horizontally bedded
Sm - Sand, massive
Sh - Sand, horizontally laminated
St - Sand, trough cross-bedded
Fm - Fines, massive
Fmd - Fines, massive, with dropstones
Fl - Fines, laminated
Fld - Fines, laminated, with dropstones

GMC - Glacio-marine depositional complex
LC - Glacio-lacustrine depositional complex
MFC - Marine depositional complex
LTC Q - Lodgement till depositional complex, New Quebec ice
LTC P - Lodgement till depositional complex, Patrician ice
LTC J - Lodgement till depositional complex, James Bay ice


001
002A
002
003
004
006
007
008A
008B
008
009
N
M-FC
GMC
LTC Q
LTC P
LTC J
LC
Sh, Gm
Gm, Dmm
Dms
Dmm
Gh
Sm, Gm, Dmm
Sh
Gm
Fld
Fl
Fmd
Bp
St
Bdrk
Sr, b
random
Covered
Surface of Severn River
5m
sand
silt
gravel
45 m.a.s.l.



2.5Y 4/2
5Y 4/2
2.5Y 4/2
5Y 4/2
2.5Y 3/2
5Y 4/2
2.5Y4/2
5Y4/1
5Y 4/2
2.5Y4/2
5Y 4/2
2.5Y4/2
2.5 Y 5/2
2.5Y 6/6
10YR 6/4
2.5Y 5/2
10YR 4/3
2.5Y 4/2
2.5Y4/2
10YR4/3
10YR5/2
10YR4/1
10YR 4/3
10YR4/3
10YR4/3
10YR 4/3
5YR5/3
10YR4/3
10YR 4/4
10YR 4/4
10YR 5/3
7.5YR 4/4
10YR 4/3
2.5Y 4/2
2.5Y 5/2
5Y 5/1
5Y 4/2
5Y 5/3
10YR 4/3
10YR 4/3
2.5Y 4/2
2.5Y4/2
2.5Y 4/2

FIGURE 11A: Stratification in the diamict matrix colours from the study area.

The shape of striated boulders and flat-iron clasts was more useful in determining the actual ice flow direction (Boulton, 1978); they frequently displayed a faceted and striated upper surface, a streamlined up-ice end and a plucked lee face.

2) At each location, at least one three-dimensional clast fabric measurement was taken. The clast fabric of a sediment refers (in this study) to the three dimensional orientation of prolate clasts supported in the matrix of a diamict. Clast fabric analysis has traditionally been used only to infer the flow direction of the ice which deposited the sediment (Nielsen et al., 1986). However, Dowdeswell et al., (1985) have used the strength of fabric orientations as an indicator of sediment genesis in diamicts of uncertain origin. Fabric data collected in the study area were used both as ice flow indicators and as supporting evidence in the genetic interpretation of diamict facies. Eighteen fabric sites were chosen in diamicts with a variety of sedimentary structures and matrix colours.

2.2.1 Theory

The two dimensional and more recently, three dimensional orientations of clasts in a diamict matrix have been used to infer ice flow direction by a number of workers (eg. Ramsden and Westgate, 1971, Nielsen et al., 1986). The basic assumption behind this method is that clasts will assume some preferred orientation within actively moving ice, that will be preserved to a greater or lesser extent when the clasts are deposited either as a component of melt-out or lodgement till.

Lawson (1979) has shown that clasts in debris-rich basal ice will normally have an orientation parallel to ice flow, often dipping in an up-ice direction. This fabric is fairly well preserved in the melt-out deposits he studied, becoming less well preserved and more variable in deposits which have undergone sediment flow. Dowdeswell et al., (1985) use data from Shaw (1982a) to show that this fabric is also developed in lodgement till, to a degree intermediate between melt-out till and glacigenic sediment flows.

Clast fabric data were also used by Dowdeswell et al., (1985) in the interpretation of various diamict units whose genesis was not clearly defined by "field appearance and relationship with other facies". The authors stated that massive and weakly bedded diamicts could be deposited by a variety of processes, including lodgement, sub-glacial melt-out, sediment flow or ice-rafting.

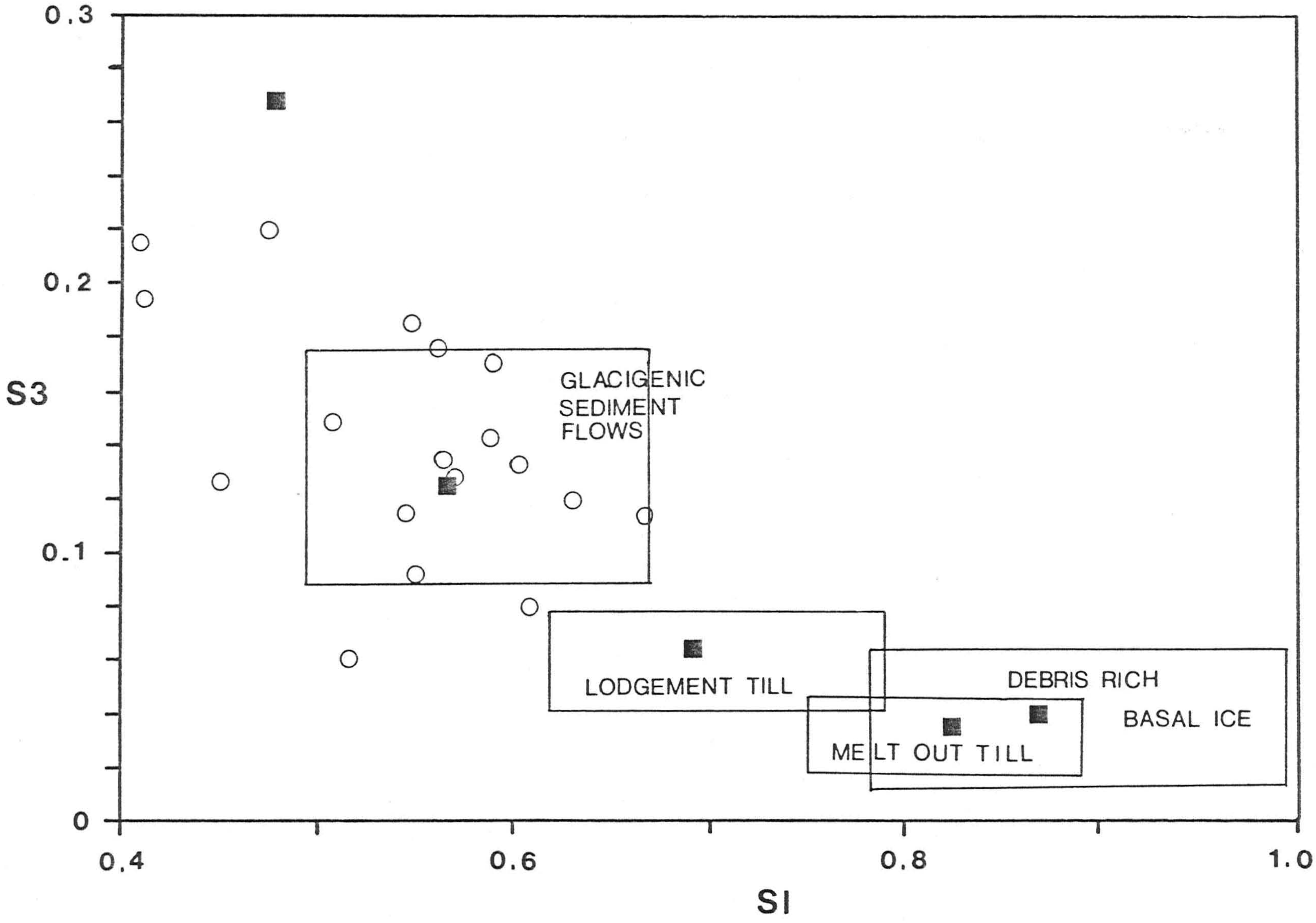
Using the method of Mark (1973), Dowdeswell et al., (1985) produced eigenvectors (V1,V2,V3) and normalized eigenvalues (S1,S2,S3) for a rather limited set of fabrics from a variety of modern diamicts whose genesis was well established. "The eigenvector V1 refers to the direction of maximum clustering, and V3 the direction of minimum clustering. The eigenvalues represent the degree of clustering or fabric strength. In particular, S1 measures the strength of clustering about the mean axis V1, while S3 is inversely proportional to the strength of the preferred plane of the fabric."

A modified plot of the S1 vs S3 eigenvalues from Dowdeswell et al., is shown in figure 12. Also plotted are the S1 vs S3 eigenvalues for the fabric data from this study area, which will be discussed later.

Dowdeswell et al., attempted to define fabric strength fields on this plot which would correspond to various depositional processes. Fabrics with high S1 values and low S3 values are considered the strongest fabrics. However, it must be noted that the data set on which these fields were based was extremely limited. Also, the clast shape criteria differs between the various data sets used in constructing this graph; this may affect the apparent strengths of the clast orientations (Thorleifson, 1987, pers. comm.).

As the authors point out, "such quantitative analysis do, however, have their limitations, manifested in ambiguity of interpretation when considered in relation to certain field observations. Caution must therefore be exercised until a much larger body of data has been assembled from modern environments where the processes of glacial deposition can be observed"

FIGURE 12: Plot of S1 vs. S3 eigenvalues for clast fabric data from Dowdeswell et al., (1985). This graph shows genetic fields defined on the basis of clast fabric strengths. Fabric strength data from the Severn River study area has been included on the plot (after Dowdeswell et al., 1985).


0.3
0.2
0.1
0
S3
0.4
0.6
0.8
1.0
SI
GLACIGENIC
SEDIMENT
FLOWS
LODGEMENT TILL
DEBRIS RICH
BASAL ICE
MELT OUT TILL

Despite these problems, it is felt that clast fabric data can not only provide strong evidence of ice flow direction, but can also be used as **supporting** evidence in genetic interpretations when combined with observed sedimentary structures and facies associations (Dowdeswell et al, 1985).

2.2.2 Method

Fabric data were obtained in the field by inserting an aluminum knitting needle into the horizontal section face, parallel to the a axis of each prolate clast. The clast was then removed in order to measure the a, b, and c axis dimensions, while the azimuth and plunge of the clast were taken from the orientation of the knitting needle. Fifty prolate clasts (a:b>3:2, b:c<3:2) were measured at each fabric location.

Fabric data were processed by computer at the GSC, using a program which produced contoured lower hemisphere projections and also calculated eigenvectors and eigenvalues. These results are discussed in chapter 4.0. The raw data and contoured projections of the data are included in appendix B.

It was hoped that fabric data would not only provide ice flow directions and support genetic interpretations, but would also help in answering questions regarding the significance of colour stratification in otherwise homogeneous diamicts, and the origin of inter-diamict stratified sediments.

Previous workers had often defined separate till units in the lowlands, on the basis of a sharp, distinct colour change between an upper brown and lower grey diamict (McDonald, 1968, Skinner, 1973). They argued that different provenances produced different colours. However, Eyles and Sladen (1981) attributed similar brown over grey colour stratification in Northumberland, to the effects of post-depositional weathering.

It was thought that by attempting to correlate the matrix colour of the sediments with their fabric orientations, it would be possible to test this weathering hypothesis.

A similar test was to be applied to the origin of packages of stratified sediments which often occur within or between massive diamict units. These packages generally consist of finely laminated silts and clays, or stratified and often channelized sands and gravels. There has been extensive discussion about the significance of similar units in other parts of the Lowlands, where they have been interpreted as interstadial or even interglacial sediments (Skinner, 1973). However, it is equally possible that they represent subglacial deposition in cavities or channels beneath stagnant or even active ice (Eyles et al., 1982).

Diamict samples and fabric data were taken immediately above and below some of the stratified packages, on the assumption that it would be unlikely (though not impossible) for two separate glacial events to produce identical deposits and fabrics (Kirby, 1969). This would help establish whether the stratified sediments belonged to one subglacial depositional episode, or whether they were deposited in an ice-marginal setting.

Overall, the results of clast fabric analysis were expected to provide useful, although not definitive, evidence for the interpretation of the genesis and depositional environment of the sediments in the study area.

2.3 Paleontology

2.3.1 Foraminifera

Twenty-seven sediment samples from both massive and stratified diamicts, as well as from one inter-diamict finely laminated unit were examined for the presence of foraminifera.

These samples were first dissaggregated by immersing them consecutively in hydrogen peroxide, a mixture of sodium hydroxide and Javex, and Quaternary "O" detergent. The samples were wet-sieved on a -4.0 phi screen between each step.

They were then dried, sieved again, and the 0.5 phi to 2.5

phi fraction was immersed in carbon tetrachloride in order to float off the lighter, air-filled foraminiferal tests. This procedure was developed by Then and Dougherty (1983) and is outlined in detail in Appendix A.

It was hoped that the relative abundances of foraminifera would be useful in correlating sedimentary units between the various sections, as well as helping to identify the genetic origin of these units.

Foraminiferal abundances should reflect the mode of deposition of the sediment. Sediments associated with a marine environment, such as marine or glacio-marine deposits and possibly lodgement tills derived from underlying marine units, may be expected to have a relatively high foraminifera content. Conversely, non-marine sediments such as lodgement tills derived from non-marine sediments, and fluvial or lacustrine sediments may have a relatively low foraminifera content.

2.3.2 Macrofossils

Both whole and fragmented mollusc valves were found in many of the sediments in the study area. Mollusc fragments were common in many of the diamicts, while reworked, less damaged shells were often present in the gravels and sands found at the top of some sections (eg. section 008, fig. 11). Whole, *in situ* mollusc valves were found in the upper sand unit at

section 009 (fig. 11); a single species collection was made of these valves for a possible radiocarbon date.
Shell fragments were tentatively identified in the field by Phil Wyatt of the GSC, who collected them for use in an amino acid geochronology study. A sample of the whole valves from section 009 were examined and identified by Alec Aitken of McMaster University.

CHAPTER 3

FACIES DESCRIPTIONS

3.1 Introduction

The use of the facies approach has become fairly standard practice in modern sedimentological studies (Walker, 1984). While developed primarily through work on fluvial and marine sediments, it is equally applicable to sediments of glacial origin, as demonstrated by several recent studies (Eyles and Eyles, 1983, Shaw, 1987).

For the purposes of this study, a facies was defined as a group of sediments distinguished by "lithological, structural and organic aspects detectable in the field" (de Raaf et al., 1965). Facies do not carry any genetic implications; they are merely descriptive classifications which are used in the subsequent genetic interpretation.

The sediments in the study area were divided into three major facies types; namely diamict facies, fine-grained facies and sand and gravel facies. These facies types were further subdivided on the basis of sedimentary structures, unit geometry and macrofossil content, and are described in detail below.

3.2 Diamict Facies

Diamicts form the majority of the sediments within the study area (fig. 11), and show a remarkable consistency in both matrix texture, clast size and clast distribution. Matrix textures are typically silty-sand to sandy-silt. Clasts are usually angular and range from 0.1 - 10.0 cm in diameter, although clasts up to 1.0 m in diameter are sometimes seen. Clast lithologies were not quantitatively determined, but appeared to consist of both Paleozoic and Precambrian rocks. Occasionally, distinctive flat-iron clasts with bullet-shaped up-ice ends and plucked lee faces were found in the thick and thin massive diamict subfacies. These were often faceted and striated on their upper surfaces.

The structure of the diamicts was usually overconsolidated and blocky, with the sandier diamicts being somewhat less competent. Clast fabric and paleontological data from the diamict facies are discussed in detail in chapters 4.0 and 5.0 respectively.

Diamict lithofacies have been divided into three subfacies; thick massive diamict, thin massive diamict, and stratified diamict. Several boulder pavements occur within the diamict facies and are also discussed below.

1A) Thick Massive Diamict Facies (Dmm)

This facies consists of massive, matrix-supported diamict with a unit thickness of greater than 1.5 m. The diamict may or may not contain a minor (<15% of outcrop area) component of thin silt or sand layers (plate 2), lenses of silt or sand or gravel (plate 3), and/or small channelized sand or gravel bodies.

These diamicts generally have sharply defined basal contacts (plate 4), which may display clearly erosive features such as striated boulder pavements (see below), and/or shearing or truncation of the underlying units (plate 5). Some thick massive diamicts have sharp basal contacts defined by a colour change from reddish-brown to grey (plate 6); these contacts do not show strong evidence of erosion.

In three instances, boulder pavements are found at the lower contact of, or within thick diamict units. At section 006, a striated boulder pavement is found within one of the upper diamict units (plate 7). The pavement consists of three visible clasts approximately 0.5 m in diameter, spaced within 10 cm vertically of each other. The upper surfaces are faceted and show striations oriented at 100 degrees, but the clasts lack any "bullet" shape which would indicate ice flow direction.

At section 007, a boulder pavement is embedded in the sheared upper portion of a thick, stratified sand (facies

PLATE 2: Unit of thick grey massive diamict from section 001. Note the silt stringer, and small clast size.

PLATE 3: Unit of thick brownish - red diamict from section 004. Note the pod of poorly sorted gravel.


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PLATE 4: Sharp basal contact of thick massive diamict at section 002 A. Diamict erosively overlies relatively undisturbed crudely bedded gravels.

PLATE 5: Sheared basal contact of thick massive diamict at section 007. The sedimentary structures in the underlying sand have been destroyed due to shearing by the overriding ice. Note the lag of clasts at the base of the diamict.


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PLATE 6: Contact between two thick diamict units at section 003. Contact is at the top of the scale card and is defined by a sharp colour change from brownish - red (above) to grey (below). The contact is not obvious in this photo.

PLATE 7: Faceted and striated boulder pavement at section 006. The pavement is contained within a thick massive diamict unit; striations are oriented approximately 100 degrees.

3A, plate 8). It consists of three visible, faceted clasts, each approximately 0.5 m in diameter, along with numerous smaller (10 - 20 cm) clasts which are not faceted (plate 5). The larger clasts are striated on their upper surfaces, with striations trending 75 degrees. The clasts are well rounded, and some appear to have a distinct plucked lee face (plate 8), indicating ice flow towards the west. Determining the exact shape of the clasts was impossible without destroying the pavement.

At section 008 a boulder pavement lies between an upper thin massive diamict and a lower thick diamict (plate 9). Here the pavement contains eight visible boulders over a distance of about 40 m. The boulders are larger in this pavement, with some boulders up to 1.0 m in diameter. Upper surfaces are faceted and striated with striations trending approximately 234 degrees. In this pavement, the clasts had a distinct plucked lee face indicating ice flow towards the SW (plate 10). A small isolated channel (1.0 m across) filled with fine sand is found at the same stratigraphic horizon as the pavement.

1B) <u>Thin Massive Diamict Facies</u> (Dmm)

This is also a massive, matrix-supported diamict, which may or may not contain a minor component of reworked silt, sand or gravel, but has a unit thickness of less than 1.5 m.

PLATE 8: A faceted and striated clast which forms part of a boulder pavement at section 007. The clast is embedded in the sheared upper surface of a well bedded sand unit. Ice flow is from right to left (approximately 75 degrees).

PLATE 9: Faceted and striated boulder pavement approximately half way up section 008. Striations trend approximately 234 degrees.

PLATE 10: Faceted and striated upper surface of a clast from the boulder pavement at section 008. The plucked lee face indicates ice flow from left to right (approximately 234 degrees).

PLATE 11: A sequence of several thin massive diamicts at the top of section 009. Part of the distortion of these units is due to the cut of the face and the camera angle.

Unlike facies 1A, this facies does not display clearly erosive basal contacts. The units are most often distinguished by sharp colour or textural changes (plate 11), or simply by sharp linear contacts whose nature is difficult to determine (plate 12). Clast size and content, as well as matrix texture are not significantly different from those of facies 1A.

1C) Stratified Diamict Facies (Dms)

The third diamict facies consists of matrix supported diamicts, displaying stratification of some type over more than 15% of their outcrop area. Stratification may be due to thin (<5.0 cm) silt laminations within these diamicts, or thin alternating bands of diamicts of different colours or textures. Individual beds may be slightly undulatory. Stratified diamicts are similar to massive diamicts in terms of texture, clast size and clast content. These units do not contain any reworked sand or gravel.

Stratified diamict units are found only at or near the tops of sections in the study area (fig. 11).

3.3 Fine-Grained Facies

These sediments are composed mainly of interlaminated silts and clays; these are not perfectly sorted and generally

PLATE 12: A thin massive diamict unit at section 004. The upper contact of this unit is at the hammer head, while the lower contact is approximately 75 cm below this. The contacts are defined by sharp linear disconformities whose exact nature is difficult to determine.

contain varying amounts of admixed sand. Sedimentary structures are quite variable, and are therefore used as the basis for further subdivision.

2A) Fine-Grained Laminated Facies (Fld, Fl)

The first subdivision consists of horizontally interlaminated clays and silts (plate 13) which may contain dropstones and diamict clots (plate 14). These clots appear similar to the sediment in the diamict facies. Laminations appear to be sharply defined and are typically 0.1 - 1.0 cm thick, but may reach up to 10.0 cm in thickness. Laminations are deformed around diamict clasts and larger dropstones (plate 14). In some cases, the laminations are extremely folded and contorted (plate 15). Dropstone sizes range from 0.2 - 5.0 cm, while diamict clots can be up to 10.0 cm in diameter. Total unit thickness never exceeds 1.0 m, and these units do not seem to be laterally continuous for more than about 100 m (fig. 11).

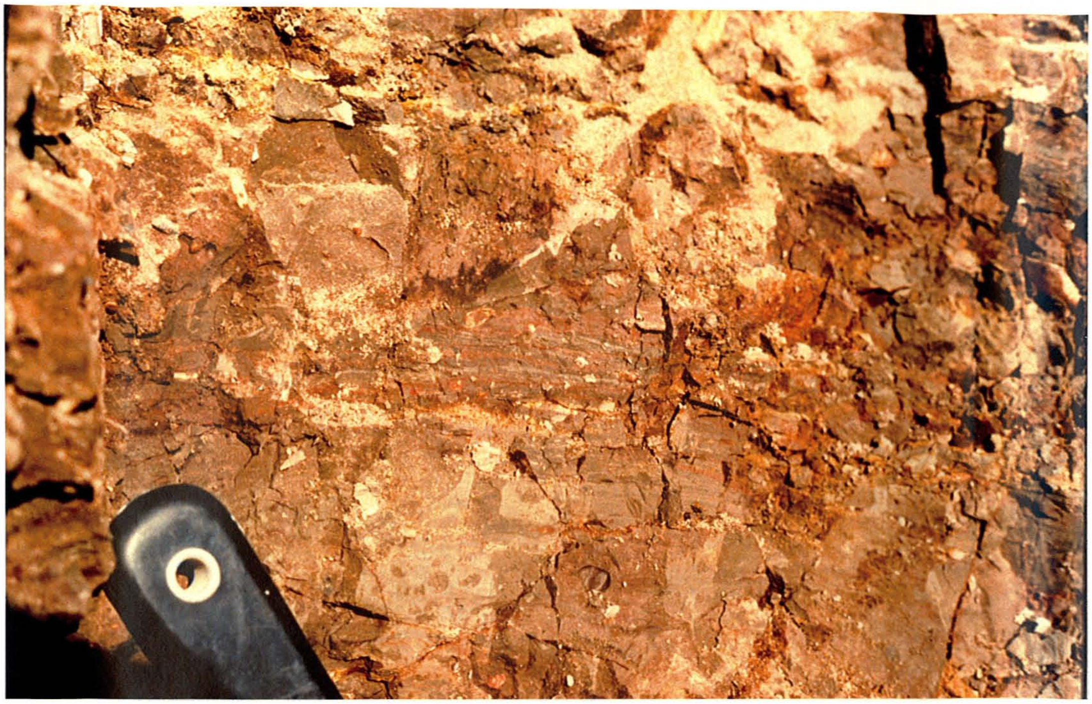
Fine-grained laminated facies often occurs within or between thick massive diamict units (plate 14). Upper contacts in this case are usually sharp, but may be gradational over 5.0 -10 cm. Laminations often dip slightly near the upper contacts and are truncated by the overlying diamict unit (plate 16). This may indicate that these upper contacts with overlying diamicts are erosional.

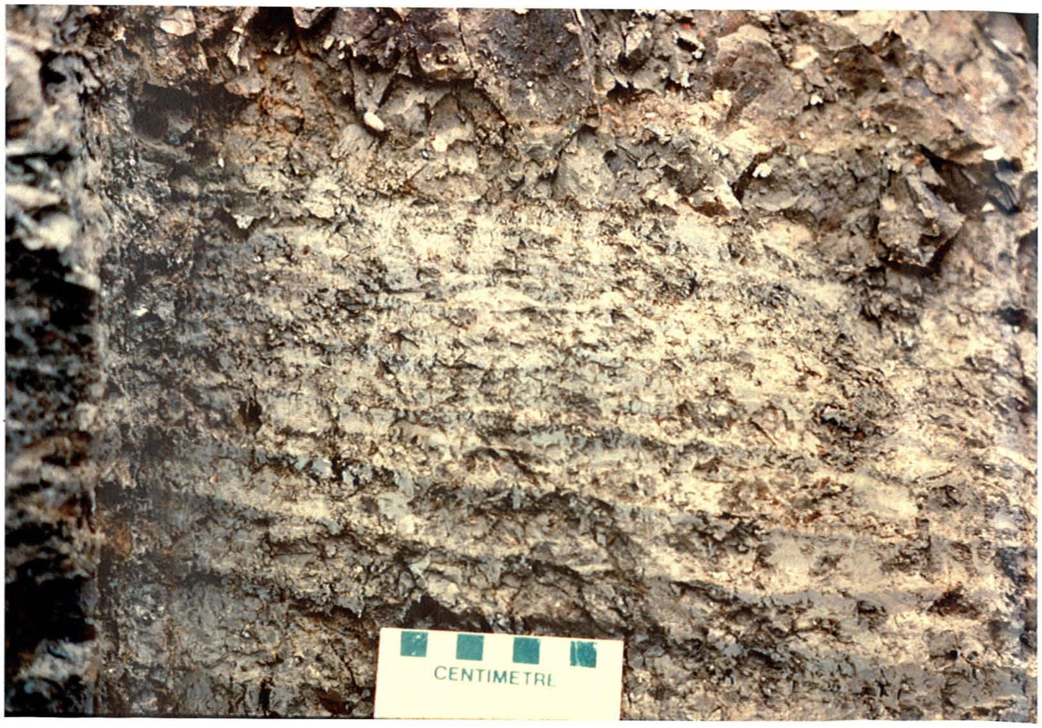
PLATE 13: Horizontally laminated silts and clays at the top of section 006. These contain no dropstones or diamict clots and are barren of foraminifera.

PLATE 14: Rhythmically laminated silts and clays which occur between two massive diamicts at section 009. Note the distortion of the laminations around the large diamict clot, to the upper right of the pencil.

PLATE 15: Contorted laminations of silt and clay from section 004. Disruption of these laminations is much more extensive than shown in this photograph.

PLATE 16: Truncation of rhythmically laminated silts and clays by the overlying massive diamict unit at section 006.

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2B) Fine Grained Massive Facies (Fmd)

Massive, blue-grey clay containing about 10% dropstones is found at the base of sections 006 and 007 (fig. 11). This facies differs from the diamict facies in that it displays a much greater degree of sorting, and contains fewer clasts. These clays are extremely dense and are usually poorly exposed. The dropstone sizes range from 0.5 - 2.0 cm in diameter. Upper contacts were not seen in either section due to extremely thick slump deposits.

3.4 Sand and Gravel Facies

This facies consists of poorly to moderately sorted sands and gravels, with well rounded pebbles and cobbles. Sedimentary structures are variable, as are unit geometry and lateral continuity. Facies subdivisions are based on these variables.

3A) Variably Bedded Sand and Gravel Facies (St, Sh, Gm, Gh)

Relatively large, laterally discontinuous channels (>15 m across, 4.0 m deep), filled with medium to coarse sands or gravels are commonly found between thick, massive diamict units (plate 17). Gravels are usually crudely bedded to massive (plate 18), while sands are more structured and

PLATE 17: Channelized gravels within a massive diamict unit at the composite section 002 and 002A. Note the truncation of the upper channel surface by the overlying diamict. The gravels contain interbedded diamicts at the channel margins.

The accompanying sketch shows the geometry of the channel feature.

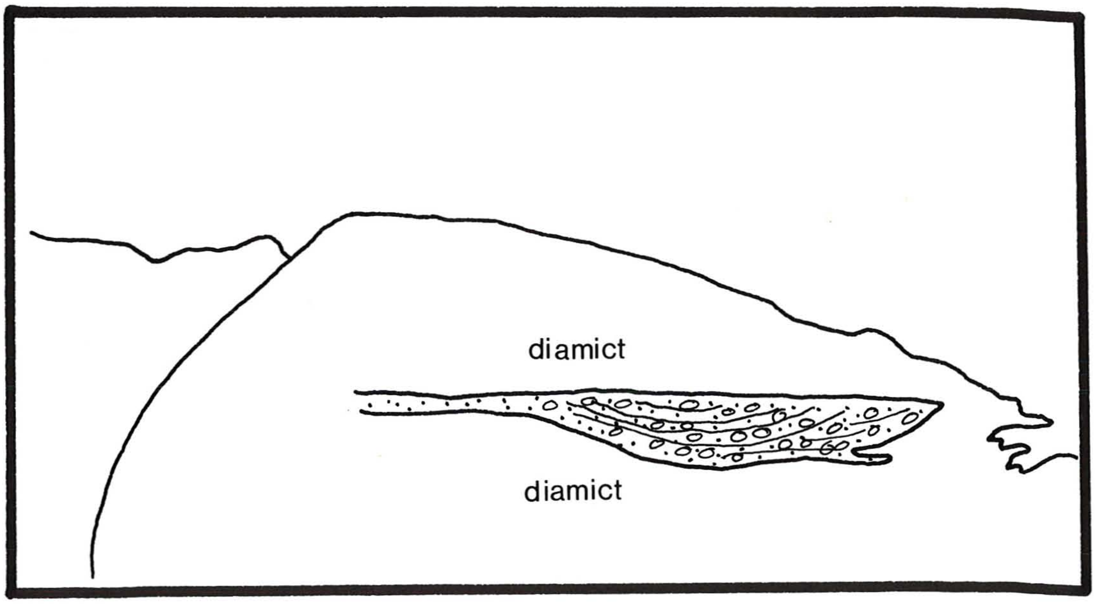
diamict
diamict

PLATE 18: Crudely developed bedding in channelized gravels from section 002A.

PLATE 19: Well developed trough cross-bedding in sand at section 008B. The upper contact of the sands shows truncation, but not disruption by the overlying massive diamict unit. Cross-beds are somewhat distorted by the camera angle.


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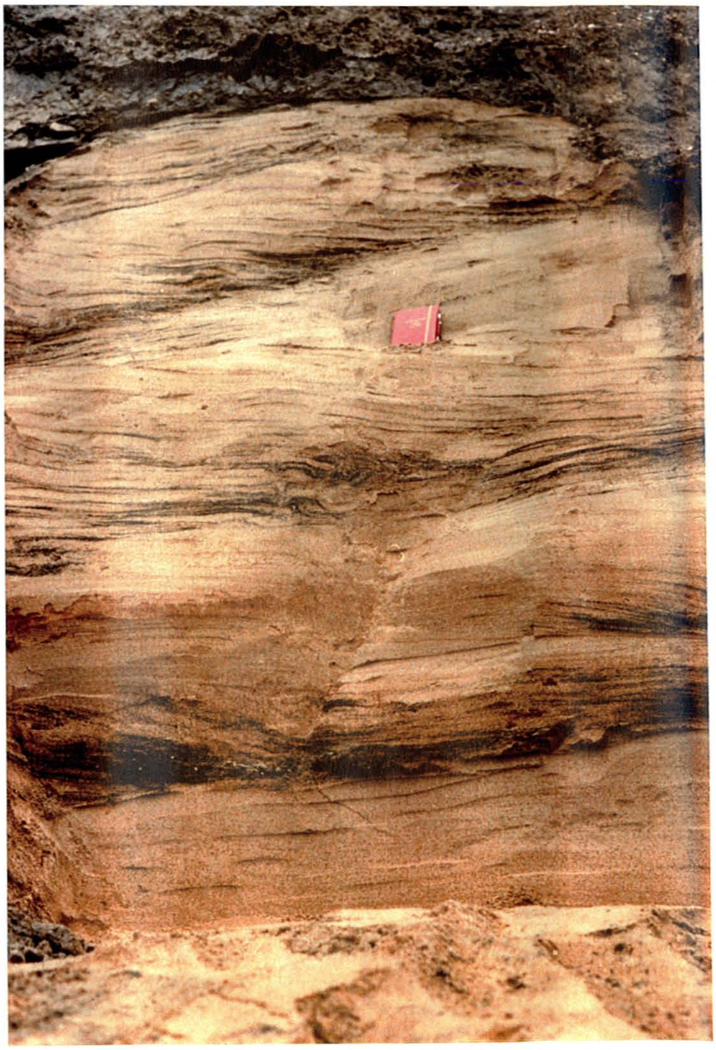


typically show large (0.5 - 1.0 m across) trough cross-beds (plate 19). The sediments are poorly to moderately sorted while clasts are well rounded, with a maximum size of about 10.0 cm in diameter.

The tops of these units are usually flat and truncated, and often show evidence of having been planed off by the overlying diamict. Sedimentary structures immediately below the upper contact may be destroyed by shearing (plate 5), or may be completely undisturbed (plate 19).

Basal contacts are defined by the channel sides and bottom, and are clearly erosive (plate 17).

3B) <u>Interbedded Sand, Gravel and Diamict Facies</u> (Sm, Gm, Dms)

Also occurring between thick massive diamict units are sub-horizontal, laterally discontinuous interbeds of sand, gravel and diamict (plate 20). These interbeds are sharply defined and do not appear to grade into one another. Individual interbeds are less than 0.5 m in thickness and are frequently contorted and folded. This facies often underlies facies 5A (plate 17) and the contacts between the two usually show evidence of erosion. Overall facies thickness is less than 2.0 m, and sand and gravel textures are similar to those in facies 5A.

PLATE 20: Chaotically interbedded sand, gravel and diamict found at the channel margin in section 002A.

PLATE 21: Bioturbated coarse silts and fine sands with *in situ* marine molluscs at the top of section 009. Note mollusc shell to the upper right of the pencil.

3C) Fossiliferous Sand and Gravel Facies (Sh, Sm, Gh, Gm)

This facies occurs only near the tops of sections (fig. 11), and consists of massive or horizontally bedded coarse sands and gravels. Clasts are generally well rounded with a maximum gravel size of about 6.0 cm. Reworked marine molluscs are common, and range from damaged unidentified single valves, to small broken fragments of shell. This facies has a maximum thickness of about 4.0 m.

3D) Fossiliferous Coarsening-Upwards Sand Facies (Sh, Sr)

This is a thick (>5.0 m) coarsening upwards facies which grades from coarse silt at its base to fine sand at its top. Sedimentary structures are common, but are too extensively bioturbated to identify (plate 21). *In situ* marine molluscs are frequent throughout the unit. These are dominantly *Hiatella arctica*, *Macoma balthica*, , *Mya truncata*, and *Mytilus edulis*, with minor *Macoma calcarea*, *Mya psuedoarenaria*, *Axinopsida orbiculata*, *Serripes groenlandicus*,and *Clinocardium ciliatum* (Aitken, pers. comm., 1987). This facies occurs only at the top of section 009 (fig. 11).

CHAPTER 4

CLAST FABRIC ANALYSIS

4.1 Results

Fabric data from the study area were processed by computer at the Geological Survey of Canada, and a printout was produced for each fabric site (Appendix B). This printout included the calculated eigenvectors and eigenvalues, as well as a test of randomness (Woodcock and Naylor, 1983). In addition, a lower hemisphere projection, contoured in units of two standard deviations was also included.

Woodcock (1977) warned that bimodal or multi-modal orientations can produce eigenvectors which fall between the modes. To test for this, each contoured projection was examined and an approximate vector was fitted by eye (Appendix B). In most cases this compared very well with the calculated eigenvectors. However, in some instances, bimodal or strongly asymmetric distributions produced eigenvectors which were suspect (F13 and F14). In these cases the vectors that had been fitted by eye were used. As well, three fabric sites produced essentially random orientations (F5, F16, F17). Ice flow directions are included as arrows on the cross-section (fig. 11).

Examination of the clast fabric data showed three dominant ice flow directions; a stratigraphically highest NE-SW orientation, and two lower orientations, one which trends approximately E-W and another which trends NNW-SSE (fig. 11). The stratigraphic relationhip between these two lower orientations is uncertain in the study area because they are never found in the same sections. However, Thorleifson (pers. comm., 1987) has found the NNW-SSE flow direction to be older than the E-W orientation on the Shagamu River, approximately 80 km east of the study area (fig. 5). Clasts from most of the fabric sites were generally flat lying and thus did not indicate in which direction the ice was flowing, ie. they did not display an up-ice dip. However, stoss and lee features of clasts found in boulder pavements at sections 006 and 007 (fig. 11) indicate ice flow toward the west and southwest respectively. It was noted that when fabrics were taken from units overlying or containing a striated boulder pavement, the fabric orientations and the striation orientations always agreed.

The strength of the fabrics (S1) was quite good, with only three fabrics being non-random at a 99% confidence level. There did not appear to be a significant variation in fabric strength (S1) between thick diamicts, thin diamicts or stratified diamicts. Nor was there a significant variation in fabric strength between the three fabric orientations, or between diamicts of different colours.

Sediment colour did seem to vary with ice flow direction. Southwestward ice flow produced mainly brownish-red diamicts with some grey diamicts, while the NNW-SSE ice flow orientation produced mainly grey diamicts with some brownish-red diamicts. The westward ice flows produced approximately equal amounts of both brownish-red and grey diamicts.

When the S1 vs S3 eigenvalues from the study area were plotted on the graph from Dowdeswell et al., (1985), it was found that they plotted mainly within the **glacigenic sediment flow** field (fig. 12). The points which plotted outside the sediment flow field did not fall within any other genetic field.

CHAPTER 5

PALEONTOLOGY

5.1 Foraminifera

Foraminifera are protozoa characterized by a test of one to many chambers, composed of calcite or agglutinated particles (Dic. of Geol. Terms, 1985). They are predominantly marine dwellers and, not surprisingly, have been found in glacigenic sediments in many glaciated marine basins, including the Hudson Bay Lowlands (Nielsen et al., 1986).

Samples from eighteen thick massive diamicts, four thin massive diamicts, four fine-grained laminated units and one stratified diamict from the study area were examined for foraminifera using the method outlined in appendix A. Foraminiferal abundances are shown on the cross-section (fig. 11) and are given as the number of undifferentiated foraminifera per 100 grams of matrix (>-1.0 phi) material. The numbers of foraminifera per sample ranged from 0 to 74, although most samples contained less than 20. The foraminifera found within the sediments were generally very well preserved, and did not appear to be extensively damaged or abraded and very few broken tests were found.

While the results were not broken down into specific foraminifera species and sub-species, a cursory examination revealed the following trends;

- Elphidium sp. (?) comprised the vast majority of foraminifera found within every sediment type
- Islandellia sp. (?) and Oolinas sp. (?) along with several other unknown species made up the rest of the foraminifera in the samples.

Foraminiferal abundances were compared with fabric orientation and sediment colour in order to determine if any significant trends existed. Stratigraphically, sediments which were higher in the sections generally contained higher foraminiferal abundances than sediments lower in the sections.

No correlation was found between the abundance of foraminifera in a sediment and its matrix colour. However, there was some correlation between the number of foraminifera per sample, and the fabric orientation of that sample. Diamicts with a NNW-SSE fabric orientation had consistantly low abundances (x=7.2 foram./100g), sediments with a westward ice flow orientation had intermediate abundances (x=11.8 foram./100g), while sediments with southwestward ice flow orientations had the highest abundances (x=18.6 foram./100g).

5.2 Macrofossils

Mollusc fragments found in many of the diamict units in the study area were identified by Phil Wyatt of the GSC, both visually and by utilizing the characteristic signatures from thirteen amino acids analyzed as part of the amino acid geochronology process. The fragments from the study area were predominantly Hiatella arctica (74%) with various other marine molluscs comprising the rest of the fragments (Wyatt, pers. comm., 1987). Mollusc fragments were found only rarely in diamicts with a NNW-SSE fabric orientation.

Wyatt also identified the reworked molluscs found in the upper fossiliferous sands and gravels (fig. 11) as being marine in origin, although a positive species identification was not posible, since the shells were extremely weathered and fragile.

Alec Aitken of McMaster University identified the mollusc samples from the sand unit at section 009 (fig. 11). He found that the molluscs were dominantly Macoma balthica, Mya truncata, Mytilus edulis, and Hiatella arctica. Also present were Macoma calcarea, Mya psuedoarenaria, Axinopsida orbiculata, Serripes groenlandicus, and Clinocardium ciliatum (Aitken, pers. comm., 1987). Aitken noted that all of the molluscs in the sample appeared stunted in their growth.

CHAPTER 6

INTERPRETATION

6.1 Facies Interpretation and Depositional Environments

Facies interpretations are based on several lines of evidence which are not limited to lithological descriptions alone. Paleontology, clast fabric data, and perhaps most importantly, the stratigraphic context and relationship to other facies (Walker, 1984), are also of value in interpretation.

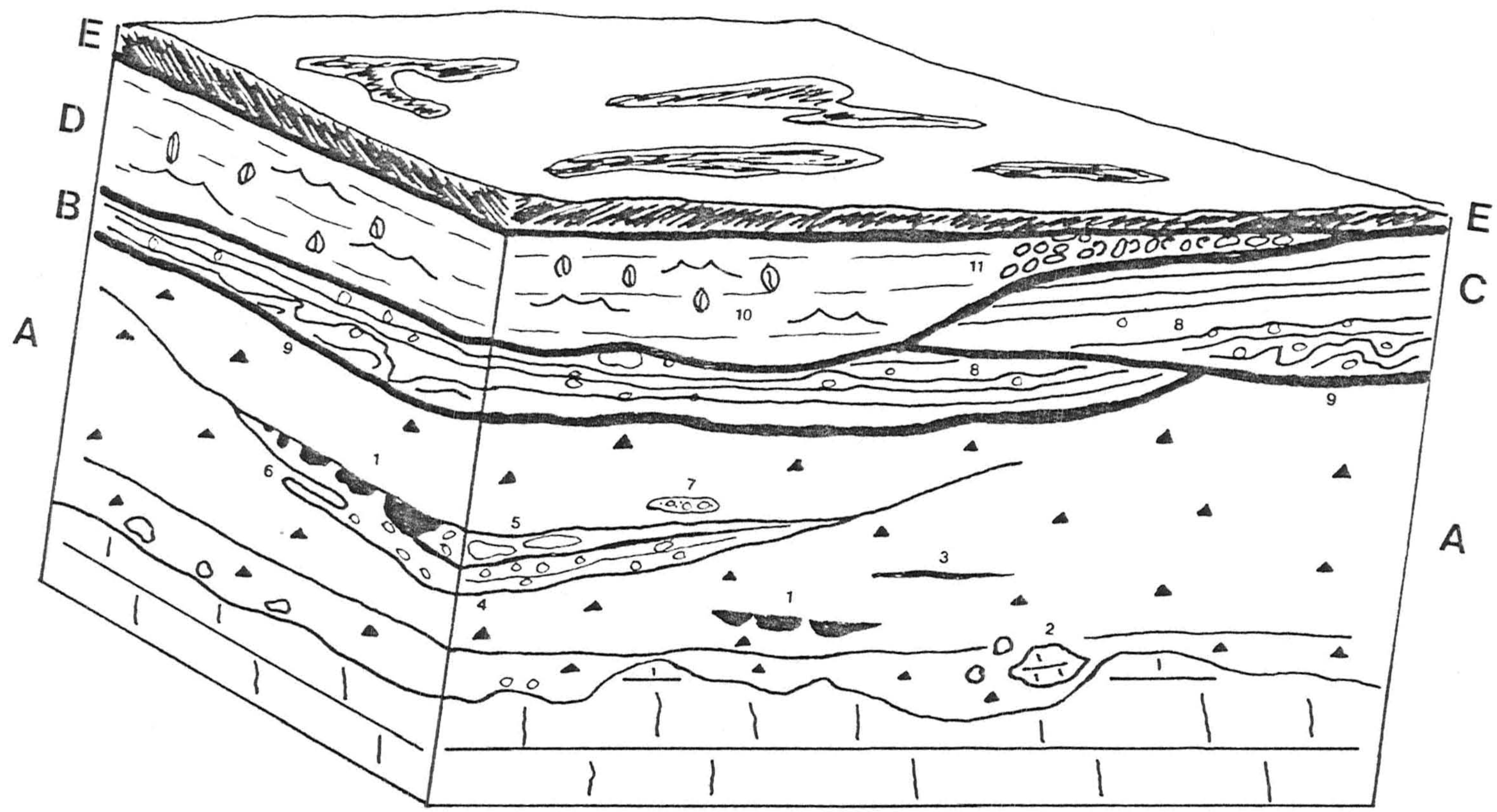
Because of the considerable lateral and vertical variability in the nature of glacigenic sediments, it was decided to interpret the facies defined in the study area, by grouping them into genetic complexes in the manner of Eyles et al., (1982). Because of the limited lateral control and the considerable lateral variation between sections, correlations are made only between the various genetic complexes, and not between individual lithological units (fig. 11).

Four types of depositional complexes are defined; a lodgement till complex, a glacio-lacustrine complex, a glacio-marine complex and a marine complex. These are described in detail below, and are summarized in a block diagram in figure 13.

FIGURE 13: Composite block diagram of Quaternary sediments in the study area (after Eyles et al., 1983). Lodgement till complex (A) shows; (1) distinctive glacially-shaped clasts, often occuring as boulder pavements, (2) bedrock rafts plucked from bedrock highs, (3) sheared-out incompetent clasts forming "stringers", (4) channelized, subglacial "cut and fill" deposits, (5) often planed off or sheared at their upper surfaces, (6) with diamicts remobillized into the channels by fluvial erosion of the diamict banks. (7) Rafts or pods of fluvial sediment are eroded from "cut and fill" deposits.

Glacio-marine (B) and glacio-lacustrine (C) complexes show (8) laminated fine-grained sediments probably deposited from density underflows, with larger dropstones and diamict clots melted out of debris-bearing icebergs. (9) Disruption of laminated sediments is caused by sediment gravity flows.

Marine depositional complexes (D) produce (10) bioturbated, fossiliferous silts and sands, and (11) beach gravels containing reworked marine molluscs.


E
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6.2 Lodgement Till Complex

This type of complex was first identified by Eyles et al., (1982), in sequences of massive diamict and associated glaciofluvial sediments found in southeast Northumberland. The majority of the sediments exposed in the Severn River study area can also be interpreted as components of several lodgement till complexes (fig. 11). The reasons for defining three different lodgement till complexes will be discussed at the end of this section.

Components of the lodgement till complex include the thick massive diamict facies, along with certain units of the thin massive diamict facies. These facies are interpreted as lodgement till (see below). Also included are the Fld division of the fine-grained facies, the thinly bedded sand, gravel and diamict facies, and the variably bedded sand and gravel facies; these last three facies make up the "cut and fill" component of the lodgement till complex (see below).

6.2.1 Lodgement till

The massive diamict facies were probably deposited subglacially by the successive frictional retardation and pressure melt-out of individual debris particles and/or debris aggregates from the basal debris layer of the actively flowing Laurentide ice sheet (Boulton, 1975; Eyles, 1983). These diamicts display several characteristic features which, when combined, tend to support a lodgement till interpretation.

One of the strongest lines of evidence for deposition by lodgement is the presence of faceted and striated clasts, which often display distinct stoss and lee features (plates 8 & 10),(Boulton, 1978; Eyles et al., 1982). These clasts sometimes form boulder pavements at the base of massive diamicts units (plate 9); these pavements are discussed in more detail below.

The massive, overconsolidated nature of the diamicts also argues for a lodgement till interpretation. The absence of sedimentary structures, and the poor sorting indicates a lack of extensive fluvial reworking of the sediments. The overconsolidated structure of the sediment is likely due to the high effective stresses encountered at the ice-bed contact. High effective stresses are required for the lodgement processes to operate (Eyles, 1983). Stringers of silt and sand within the massive diamict units (plate 2) may be due to the "smearing out" of incompetent clasts (Kruger, 1979), or alternatively, they may be lag horizons resulting from water released during pressure melt-out (Eyles, 1983).

The consistency of clast fabric orientations in the massive diamicts, within individual lodgement till complexes (plate 11) provides further evidence for a lodgement interpretation (Boulton, 1978, Kruger, 1979). As was noted previously in chapter 4, the strengths of the majority of clast fabrics from massive diamict units interpreted as lodgement tills, fall within the "glacigenic sediment flow" field of Dowdeswell et al (1985) (fig. 12). This, however, seems to be due to the paucity of data used by these authors in constructing this diagram, rather than indicating a sediment flow origin for all of the massive diamict facies.

It is important to note that units of the thin massive diamict facies are included in the lacustrine complex and the glacio-marine complex (sections 6.3 & 6.4), as well as in the lodgement till complex (fig. 11). Those thin massive diamicts included in the lodgement till complex were identified by their strong clast fabric orientations and their relatively low foraminiferal contents (see below). Also supportive of this interpretation was the lack of sedimentary structures indicative of resedimentation by mass movement (eg. flow noses) in these units.

Sequences of multiple thin massive diamict beds often occur near the boundaries of successive lodgement till complexes (eg. sections 008 & 009, fig. 11). These may have been deposited by relatively rapid alternations between erosion and lodgement deposition at the base of the ice sheet (Eyles, 1983), possibly caused by unstable ice conditions accompanying a change in ice flow direction.

The laterally discontinuous, lens-like geometries of the lodgement till complexes and their component beds (fig. 11), are also likely due to alternating erosional and depositional conditions. This type of lateral geometry has been documented by Eyles et al. (1982) in lodgement till complexes in England (section 6.8).

Further evidence for alternating erosion and deposition is the presence of faceted and striated boulder pavements associated with several of the thick massive diamict units (fig. 11). The formation of boulder pavements has been discussed by Boulton (1976). He suggested that large clasts being transported at the ice-bed interface would plough up a ridge of unconsolidated sediment in front of them, eventually providing enough resistance to cause the clast to become lodged in the bed. Further clasts would become "jammed up" behind the original clast, forming a horizontal boulder pavement.

Other workers (Dreimanis and Reavely, 1963; Flint, 1971; Sauer, 1974), have suggested that the clasts are concentrated as a fluvial lag, either sub or pro-glacially, which is then overridden and shaped by the ice.

Of the three pavements in the study area, two of them (sections 007 and 008, fig. 11) are embedded in or associated with underlying glaciofluvial "cut and fill" deposits (plate 8, see below). In addition, the clasts do not seem to be in close proximity to each other, as would be expected with a "traffic-jam" origin. These two pavements appear to have been formed as subglacial lag deposits, as shown in fig. 14. The clasts were probably carried as bedload in subglacial meltwater channels, or were dropped out of the ice roof of the channel. When flow in the channel waned, the clasts were deposited on channel bed; as the ice re-attached to its bed, the tops of the clasts were faceted and striated.

The third pavement (section 006, plate 7) does not appear to be associated with any sort of fluvial "cut and fill" beds. Instead, it is contained within a massive diamict unit, and the clasts are in close proximity to each other. In this case, Boulton's "traffic-jam" model may be applicable.

The presence of foraminifera in the massive diamicts of the lodgement till complexes, apparently indicates that at least some foraminiferal tests can survive the high effective stresses that accompany the lodgement process. This has also been documented by Nielsen et al. (1986), who found foraminifera in most of the lodgement till units exposed along the Nelson River, in the western lowlands.

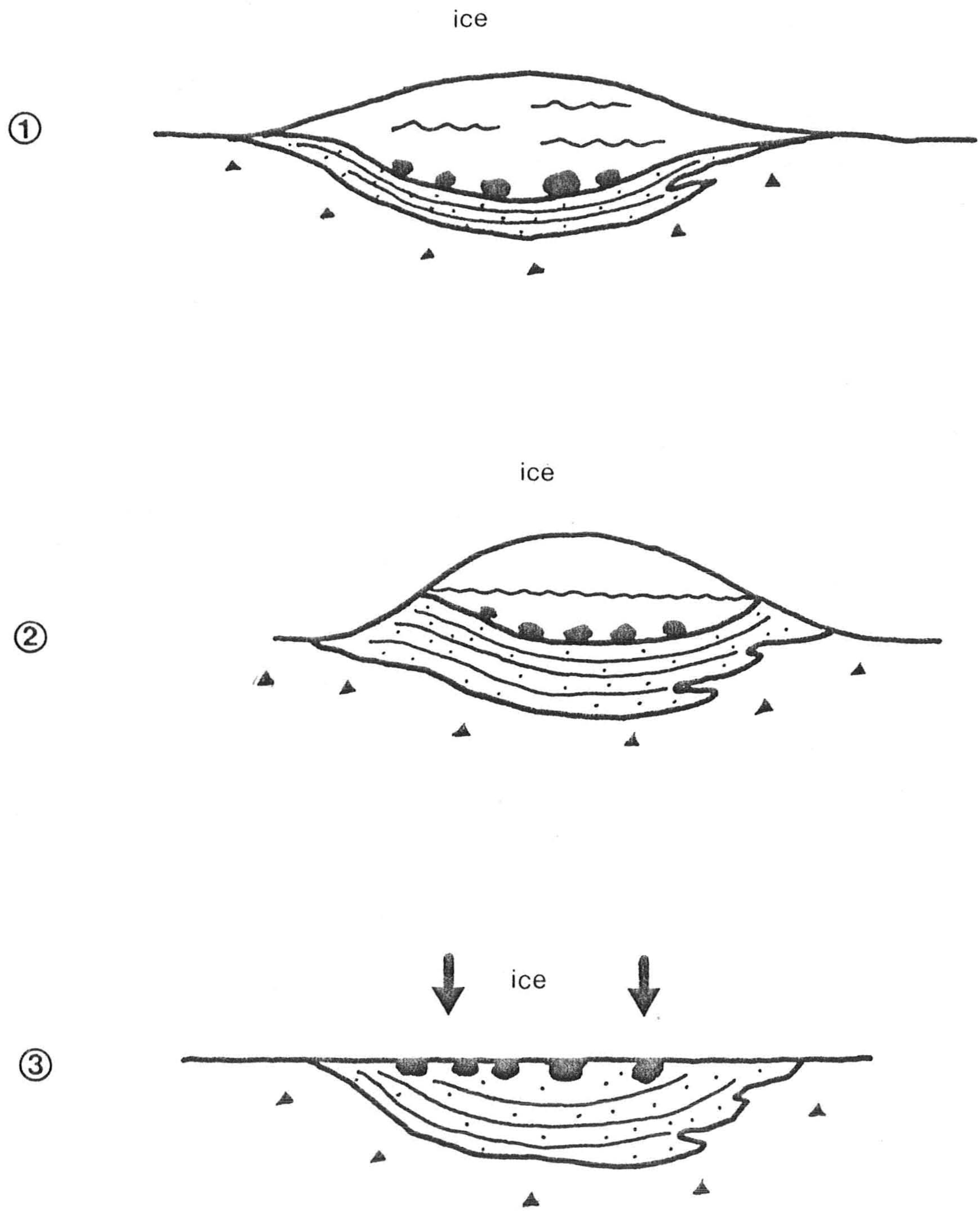
When clast fabric data were not available for thin massive diamict units, these units were often interpreted as components of a lodgement till complex on the basis of a foraminiferal content that was similar to adjacent thick massive diamict units.

FIGURE 14: Proposed origin for "lag-deposited" boulder pavements; (ice-flow out of page)

1) Large clasts are moved as bedload in subglacial drainage channels,

2) As flow in the channel wanes, the clasts are deposited as a lag on the channel bed,

3) As the ice reattaches to its bed, a period of erosion planes off the top of the channel deposits, and creates the faceted and striated boulder pavements.



ice
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ice
②
ice
③

6.2.2 "Cut and fill deposits"

The Fld division of the fine grained facies (facies 2A), the variably bedded sands and gravels (facies 3A) and the thinly bedded sand, gravel and diamict facies (facies 3B) make up the "cut and fill" component of the lodgement till complex (Eyles et al., 1982). Channelized sands and gravels were probably deposited in subglacial drainage channels eroded into the underlying lodgement till. The presence of sedimentary structures such as large scale trough cross bedding in the sands (plate 19), and sub-horizontal bedding in the gravels (plate 18), the relatively greater degree of sorting than in the diamicts, and the geometry and stratigraphic context of these beds seems to indicate a fluvial origin for these sediments. No attempt was made to analyze the paleo-hydraulics of these fluvial units. Diamict interbeds within the channelized sand and gravel facies (plate 20) probably represent erosion and collapse of diamict from the channel walls, or melt-out from the overlying ice roof (Eyles et al, 1982).

Laminated silts and clays found within and between lodgement till units (plate 14) are interpreted as having been deposited in subglacial standing water, probably in abandoned subglacial channels closed by ice movement downstream (Shreve, 1972). In this environment, fine-grained sediments such as silts and clays presumably settled out of suspension from the water column, or were deposited by density underflows. Alternations of silt and clay found in several of these deposits may have been caused by fluctuations in the meltwater supply to these cavities, or may represent graded bedding caused by density underflows. Clasts and clots of diamict found within the fine-grained laminae probably melted out of the ice roof of the cavities, and were dropped into the water body. Deformation of individual laminations around these dropstones and diamict clots seems to support this hypothesis (plate 14).

The upper surfaces of these sandy or fine-grained "cut and fill" deposits are usually truncated by gently undulating, erosional contacts with the overlying lodgement till (plate 17). Sedimentary structures in the upper portion of these units may be disrupted to varying degrees due to shearing by the overriding ice (plate 5). This appears to indicate that the tops of the "cut and fill" units were planed off as the ice re-attached to its bed, and lodgement till deposition resumed.

The channelized "cut and fill" sediments discussed above are interpreted as sub-glacial rather than ice-marginal deposits for a number of reasons. The main opposition to an ice-marginal interpretation for the "cut and fill" sediments is the lack of correlation of these units between the various sections (fig. 11). Where the entire "cut and fill" unit is visible in a section (as in sections 002 & 002A, fig. 17), the geometry is clearly a channel form and not a laterally extensive body as would be expected with an ice-marginal deposit (eg. Skinner, 1973).

In addition, these "cut and fill" units lack characteristics which have been used to identify ice-marginal or entirely non-glacial deposits elsewhere in the Hudson Bay Lowlands. The interglacial sequence which Skinner (1973) describes in the Missinabi Formation from the eastern lowlands includes a fossiliferous marine unit, overlain by a fluvial unit. These are in turn overlain by an organic-rich "Forest peat" unit and an upper pro-glacial lacustrine member.

None of the deposits interpreted as subglacial "cut and fill" sediments from the Severn River study area resemble the Missinabi Formation.

6.2.3 Definition of lodgement till complexes

Within the study area, three or possibly four, separate lodgement till complexes are defined (fig. 11). As was discussed in chapter 4, three distinct ice-flow orientations can be defined in the study area from clast fabric analysis of the diamicts; these orientations are supported by striations on boulder pavements and bedrock surfaces. The boundaries between the three lodgement till complexes are defined primarily by contacts between diamicts with differing ice flow orientations (fig. 11). Where ice flow orientations are poorly defined due to a lack of fabric data, the boundaries are based on a combination of foraminiferal and mollusc fragment abundances in the diamicts, diamict matrix colour and erratic provenance data. The exact position of the lodgement till complex boundaries is somewhat uncertain in most cases, due to the limited amount of fabric and foraminiferal data which was available. The lodgement till complexes are referred to as the Patrician complex, the James Bay complex and the New Quebec complex, after the areas where the ice which deposited them originated (section 6.7). The distinguishing characteristics of each lodgement till complex are also discussed in section 6.7.

At the base of section 003 (fig. 11) a fourth lodgement till complex is tentatively defined. This complex is composed of a sequence of massive diamicts, and a bed of horizontally laminated sand and gravel containing clots of the underlying diamict. It directly underlies the Patrician lodgement till complex (see below) and is differentiated by anomalously high foraminiferal abundances (fig. 11). However, this may simply represent reworking of older foraminifera-rich sediments by Patrician ice flow (section 6.7). Because of the limited amount of data on this group of sediments, they will be treated as part of the Patrician lodgement till complex.

barren of foraminifera. It is largely the barren nature of this unit that suggests its lacustrine rather than marine origin.

It is assumed that the glacio-lacustrine complex was deposited in Lake Agassiz, a giant proglacial lake created by the damming of the northward drainage system of central Canada and the north-central United States by the retreating late-Wisconsin ice sheet. The glacio-lacustrine deposits at section 006 are well within the northern limits of Lake Agassiz given by Teller et al. (1983).

6.4 Glacio-marine Complex

This complex is found at the top of several sections (fig. 11) and is overlain only by deposits of the marine complex (chapter 6.5). Components of the glacio-marine complex include the fine-grained laminated facies (facies 2A), the thin massive diamict facies (facies 1B) and the stratified diamict facies (facies 1C). These facies are interpreted as glacio-marine, rather than subglacial or glacio-lacustrine in origin because of their relatively high foraminifera abundances.

The often rhythmically laminated silt and clay units may have been deposited from suspension through the water column, influenced by seasonal fluctuations in sediment input (Domack, 1983). However, a more likely origin is deposition by density underflows, generated by sediment-laden subglacial meltstreams entering the marine environment from the glacier margin (Mackiewicz et al., 1984). The apparent rhythmic laminations may in fact be successive, graded density current deposits. The dropstones and diamict clasts in these fine-grained sediments probably represent material rafted in, and melted out of icebergs calving from the glacier margin.

The frequent disruption of these laminated sediments is likely due to sediment gravity flows or slumping of some sort; this type of resedimentation would require only very low slopes, due to the unstable nature of rapidly deposited fine-grained sediments (Walker, 1984). Resedimentation of unstable fine-grained sediments is probably also responsible for the thin massive diamict and stratified diamicts in this complex. The random clast fabric orientation in the thin massive diamict at the top of section 004, supports this resedimentation hypothesis (Dowdeswell et al., 1985).

6.5 Marine Complex

Facies in this complex include the fossiliferous sand and gravel facies (facies 3C) which caps several of the sections (eg. section 008, fig. 11), and the fossiliferous coarsening-upwards sand facies (facies 3D) at the top of section 009 (fig. 11). This complex is differentiated from the glacio-marine complex by the lack of glacially-derived sediments such as ice-rafted debris.

The fossiliferous sand and gravel facies are probably beach deposits, but may represent a fluvial system which flowed on the surface of the lowlands - possibly a proto-Severn River. Those containing reworked marine molluscs are most likely beach deposits.

The coarsening-upwards sand at section 009 (plate 21) contains abundant in situ marine molluscs. This mollusc assemblage and the stunted nature of the molluscs indicates a shallow (less than 10 m) water estuarine depositional environment, with high sedimentation rates (Aitken, pers. comm., 1987). The coarsening upward trend was probably caused by the regression of the sea due to isostatic uplift following deglaciation.

The marine complex was probably deposited in the Tyrrell Sea. The name Tyrrell Sea refers to the extensive, early Holocene epieric sea which covered the Hudson Bay basin. Flooding of the basin commenced when retreat of the Laurentide Ice Sheet had progressed far enough to allow seawater to enter the glacio-isostatically depressed basin, about 8,000 years b.p.. Sediment supply to the basin probably came from either the retreating ice sheet, or, assuming relatively debris-poor ice, from the post-glacial erosion of previously deposited glacigenic sediments.

It is very interesting to note the apparent rapid transition from the subglacially deposited lodgement till complexes to the non-glacially influenced marine complex (section 6.5). In most sections, the lodgement till complexes are directly overlain by relatively thin glacio-lacustrine or glacio-marine complexes, which are in turn overlain by deposits of the marine complex (fig. 11). This appears to indicate a rapid retreat and disintegration of the Laurentide ice sheet at the end of the Wisconsin glaciation. In addition, there is no evidence of a supraglacial debris complex in any of the sections (Eyles and Miall, 1984), and the actual volume of ice-rafted debris in the glacio-lacustrine and glacio-marine complexes is quite low. This seems to imply that the Laurentide ice sheet was very clean, with very little englacial and probably no supraglacial debris. This is not surprising, considering that compressive flow with subsequent shearing of debris upwards into the ice is required to produce large volumes of englacial or supraglacial debris in an ice sheet (Eyles, 1983). It is difficult to imagine compressive flow occurring on such a smooth, obstructionless bed as the Hudson Bay Lowlands. In addition, there would have been no source of supraglacial debris from rock walls as in a valley glacier, since this would have required an extensive topographical high protruding through the surface of the Laurentide ice sheet.

6.6 Summary of Depositional Environments

Stratigraphically, the genetic complexes identified in the area comprise three lodgement till complexes overlain successively by a glacio-lacustrine, a glacio-marine and a marine depositional complex. These sediments reflect the interaction of ice from three distinct ice domes (see below), followed by the apparently rapid retreat of the Laurentide ice sheet at the end of the Wisconsin glaciation. The features of and relationships between the genetic complexes are summarized in a block diagram in figure 14. Not all of these complexes are represented in any one section (fig. 11).

6.7 Implications for the Configuration of the Laurentide Ice Sheet

Various lines of evidence from the Severn River area, and the Big Trout Lake area (fig. 4), point to a Late Quaternary depositional history which has interesting implications for the configuration of the Laurentide ice sheet. By combining ice flow orientations from the study area, with data on erratic lithologies, relative foraminifera abundances in diamicts, and diamict matrix colours, it is possible to define three distinct lodgement till complexes in the Severn River area (chapter 6.2; fig. 11). The three ice flow orientations seem to indicate that ice flow during deposition of these complexes originated outside of Hudson Bay, and flowed into and across the basin. This is supported by the fact that all diamicts within the study area contain a variable mix of Precambrian and Paleozoic erratic clasts (Thorleifson, pers. comm. 1987). This implies that ice must have flowed across both Precambrian and Paleozoic outcrops (fig. 3) before reaching the study area, which suggests that ice flowed into and across the basin, rather than radially out of the basin.

Recent observations from the area of Big Trout Lake (fig. 4) appear to indicate a period of ice flow northwestward from the Precambrian shield into the Hudson Bay basin (Thorleifson and Wyatt, pers. comm., 1987). These workers re-measured bedrock striations and roche moutonee features originally cited by Tyrrell (1912), as evidence for an ice dome referred to as the Patrician dome. Thorleifson and Wyatt confirmed Tyrrell's data and feel that an ice dome located somewhere north of Lake Nipigon (fig. 2), with ice flow toward the northwest, is responsible for the features found at Big Trout Lake.

Evidence from the Severn River area seems to support the possibility of a Patrician dome. Component diamicts of the NNW-SSE lodgement till complex (ie. Patrician flow) differ from other diamicts in the study area in several ways. These "Patrician" diamicts have relatively low foraminifera and mollusc fragment abundances, and are enriched in Precambrian erratic clasts. In addition, the matrix colour of "Patrician" diamicts is typically grey (see chapter 6.8). These factors appear to indicate that "Patrician" diamicts contain a much smaller component of sediment derived from the Hudson Bay basin, as would be expected if the ice which deposited these diamicts was flowing northwestward into the basin from a Patrician dome located on the Precambrian shield. The Paleozoic component of these diamicts can be explained by reworking of older glacial sediments derived from the Hudson Bay basin.

The existence of a lodgement till complex deposited by westward flowing ice (James Bay complex; fig. 11) has interesting implications for the Laurentide ice sheet configuration. Diamicts in this complex contain foraminifera abundances intermediate between "Patrician" diamicts and diamicts which display a southwestward ice flow orientation (New Quebec lodgement complex; fig. 11). In addition, westward flowing ice deposited diamicts with both grey and brownish-red matrix colours.

The only ice dome which appears to be able to produce westward ice flows is the James Bay dome of Bouchard and Martineau (1985, fig. 2). Since ice from this dome would have to flow through the James Bay basin, its deposits should contain reworked foraminifera, although not as many as diamicts deposited by southwestward flowing ice (see below). Precambrian erratics in the James Bay diamicts could be derived from the Precambrian shield east of James Bay (fig. 3), or from reworked deposits of the older Patrician ice. The mix of diamict matrix colours is discussed in section 6.8.

Ice which deposited the third lodgement till complex flowed approximately towards the southwest (New Quebec complex; fig. 11). This complex contains predominantly grey diamict matrix colours, a mix of Precambrian and Paleozoic erratic clasts, and the highest relative foraminifera abundances of the three lodgement complexes. These features can best be explained by ice flow from a dome located in New Quebec (fig. 10, Shilts, 1980). Ice flowing from this dome would cross both Precambrian and Paleozoic outcrops (fig. 3) and would also cross a larger marine basin than the James Bay dome, thus producing the higher foraminifera abundances. The predominantly grey diamict matrix colours are discussed in section 6.8.

The above evidence from the Severn River and Big Trout Lake areas suggests a configuration for the Laurentide ice sheet that is not explained by any of the current models. The ice flow orientations and erratic clast lithologies are in total disagreement with Flint's (1943) model of a single dome centered in Hudson Bay, producing outward radial ice flow. Nor are these features completely explained by the multi-domed model proposed by Shilts et al. (1979) and subsequently modified by other workers (eg. Dyke et al., 1982, Bouchard and Martineau, 1985).

However, a modification of Shilts et al.'s (1979) original model to include not only the two major domes in Keewatin and New Quebec, but also two minor domes located on the east coast of James Bay (James Bay dome, Bouchard and Martineau, 1985), and to the north of Lake Nipigon (Patrician Dome, Tyrrell, 1914) seems to adequately explain the features of the depositional complexes identified in the Severn River area (fig. 2). This modified configuration also seems to agree with the large scale distribution of distinctive Proterozoic erratics documented by Shilts (1980, 1982), provided that the two minor domes precede the Keewatin and New Quebec domes, and are relatively short lived.

It is interesting to note that ice flowing from a Keewatin dome does not seem to have influenced the Severn River area. This seems to agree with the findings of Shilts (1980), that Keewatin ice probably reached only as far southeast as the Seal River in Manitoba (fig. 5).

6.8 Origin of Colour Stratification

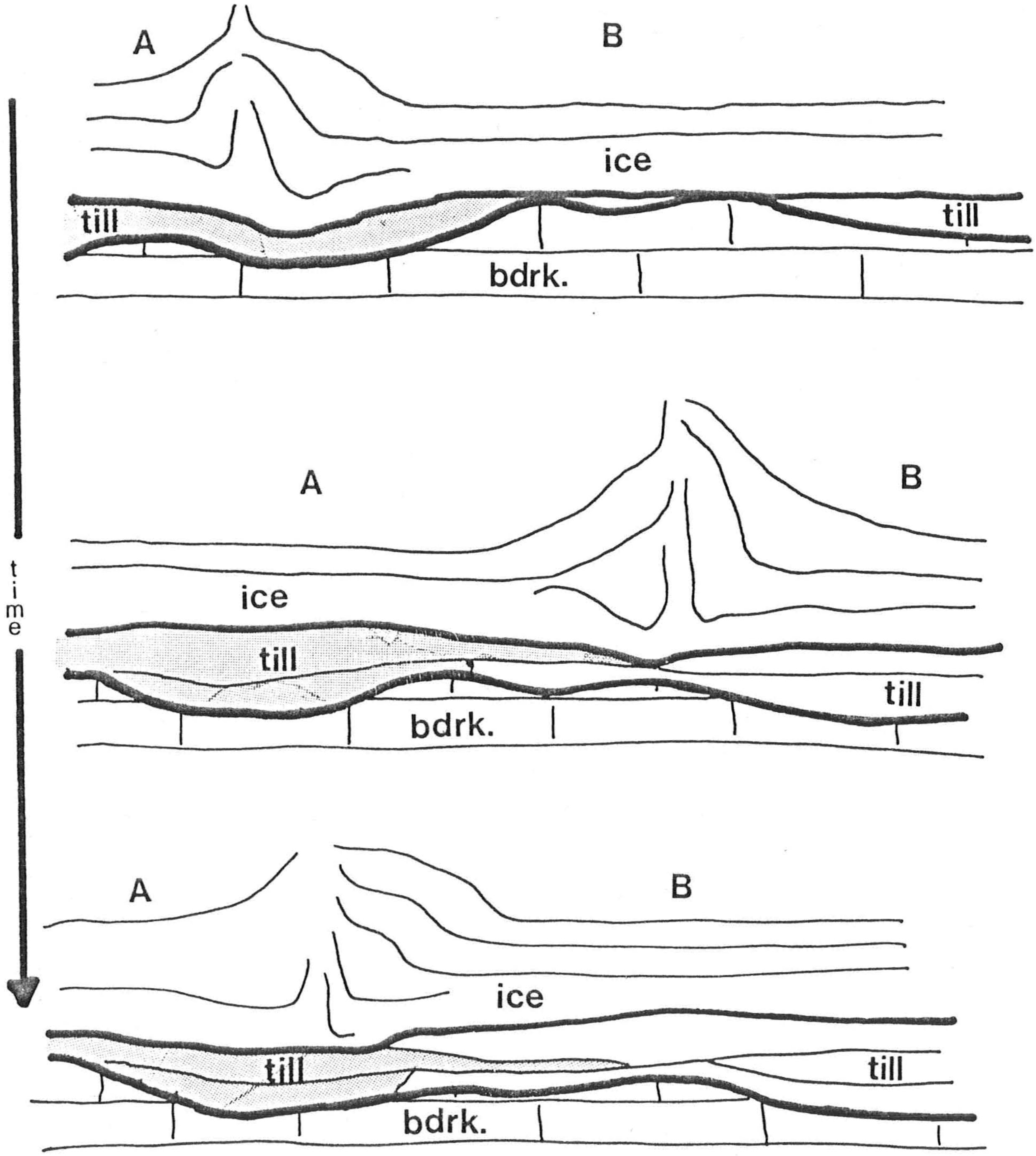
Another important feature of the sediments which may be explained by a multi-domed ice sheet, is the colour stratification which often defines the various diamict units in the study area (fig. 11A). An upper till stratigraphy consisting of a younger brownish-red till overlying an older grey till has been developed in the Hudson Bay Lowlands by many previous workers including McDonald (1969), Skinner (1973) and Nielsen et al., (1986). However, Eyles and Sladen (1981) have demonstrated that a brown over grey till stratigraphy is often a misinterpretation of a single weathered lodgement till complex.

In this case, there are several lines of evidence indicating that neither separate glaciations nor a weathering model are able to explain the colour stratification within the study area. Eyles and Sladen (1981) proposed a mechanism in which summer moisture deficits caused cracking of the upper portion of the till, allowing water to permeate the substrate to a maximum depth of about 8.0 m. Weathering of sulphide minerals caused the brownish colour of the till; this weathering zone was sharply defined where the till was drained by permeable "cut and fill" deposits, and less distinct in areas of homogeneous diamict. Evidence for this model included the presence of only a brownish till in areas where drift cover was shallow, and the fact that grey till was never seen outcropping at the surface.

The nature of the colour stratification in the study area does not appear to fit this model. Brownish till extends to a minimum depth of 27.0 m in some areas (section 009), while in other areas only a grey till occurs, extending to within 1.0 m of the surface (section 001). As well, in section 003, Each of these flow units was assumed to incorporate underlying lithologies into their basal debris layer; because of the varied bedrock geology in northern England, each flow unit would have a debris load which varied in colour, texture and/or clast lithology. Successive or alternating dominance of the various flow units could produce apparently unconformable deposits during a single glacial event (fig. 15). The colour of the sediments in the study area appear to be related to the matrix composition, which is determined by the composition of the source rocks or sediment (Thorleifson, pers. comm. 1987). Lithologies within the Hudson Bay basin are predominantly Paleozoic carbonates with minor clastics. The colour of these rocks is mainly light brown to buff except for the Upper Silurian Kenogami River Formation which consists of red-coloured carbonates and fine-grained clastic rocks (Norris and Sanford, 1968, Sanford, pers. comm., 1987). The distribution of this formation is shown in figure 16. This formation is quite possibly the source rock for the brownish-red sediments found in the study area. The soft, fine-grained nature of this rock would allow for rapid disaggregation and erosion by the ice sheet, to produce the silt and clay size fraction which makes up most of the matrix of the diamicts. Grey diamicts are probably derived from the other Paleozoic rocks within the basin, which appear grey when disaggregated and deposited as lodgement till.

FIGURE 15: Idealized depositional model for unconformable facies superimposition in lodgement tills (modified from Eyles et al., 1982). Cross-sectional view with ice flow out of page.

As two ice streams carrying different coloured basal debris (A & B) displace one another laterally, lodgement tills of different colours (plain and shaded tills) are superimposed.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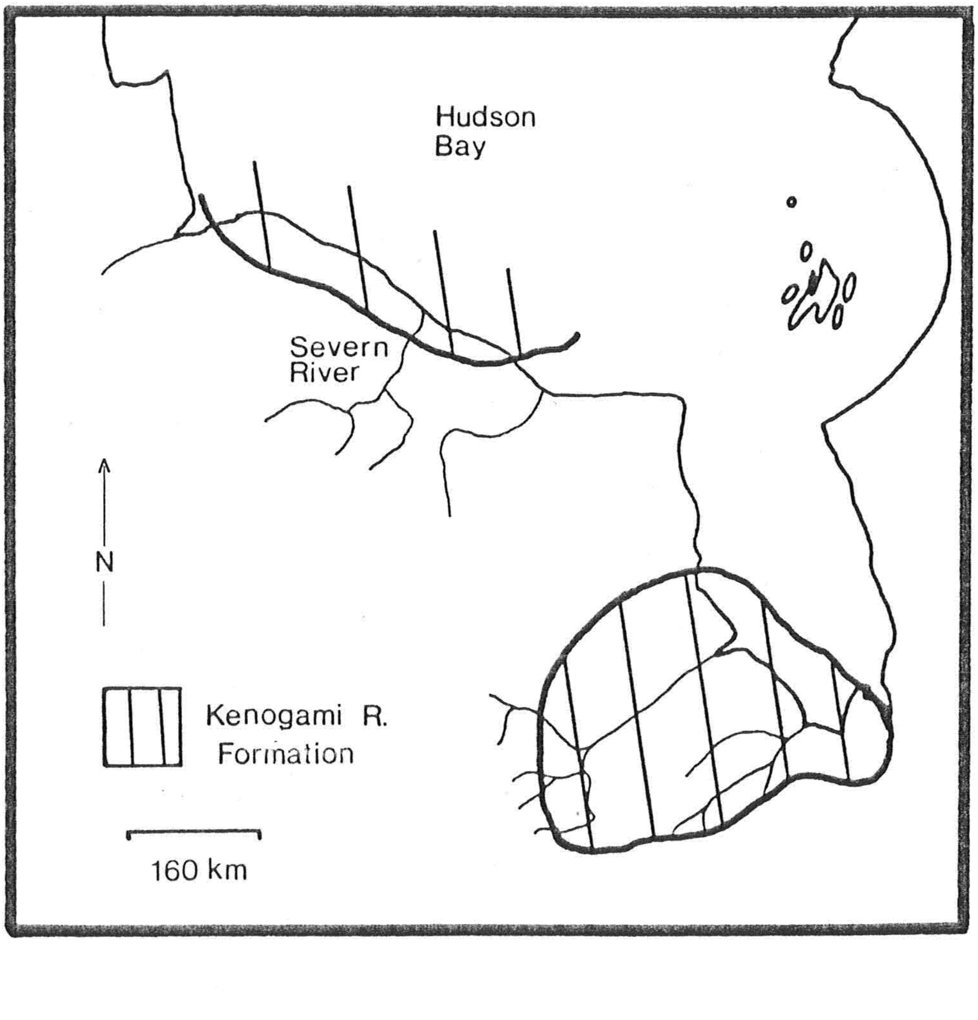
Deposition of brownish-red lodgement tills could be explained by the temporary predominance of a flow unit within the ice masses flowing from the New Quebec or James Bay ice domes, which was flowing over and eroding rocks of the Kenogami River Formation. The fact that both New Quebec and James Bay ice seem to have deposited brownish-red sediments, while Patrician ice did not, can be explained by the distribution of Kenogami River Formation rocks (fig. 16); this may also explain the fact that New Quebec ice seems to have deposited much more brownish-red sediment than James Bay ice, since the outcrop of the redbeds is much more extensive at the mouth of the Severn River, which lies in the path of the New Quebec ice.

Several workers (Meneley, 1964, Christiansen, 1971) have called on progressive unroofing of a single source area rather than competition between different flow units to explain vertical compositional variations in sediments in Saskatchewan. However, given the low estimates for the amount of glacial erosion of bedrock by the Laurentide ice sheet (Laine, 1980), this hypothesis seems unlikely.

FIGURE 16: Distribution of the Kenogami River Formation in the Hudson Bay Lowlands, from Norris and Sanford (1968).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Bay
Severn
River
N
Kenogami R.
Formation
160 km

6.8.1 Summary of ice flow changes

The presence of the three lodgement till complexes appears to indicate that ice flows or streams from three major ice domes "jostled" in the Severn River area at some point during the last glaciation. This "jostling" likely produced the three distinct flow orientations recorded in the diamict clast fabrics and striated bedrock and boulder pavements, as well as the variations in diamict matrix colour and foraminiferal abundances between the three lodgement complexes. The lack of any characteristic interglacial or interstadial deposits between these lodgement complexes suggests that this "jostling" occured during a single major advance of the Laurentide ice sheet, of which these ice flows or streams were components.

In addition, the presence of colour stratification within the individual lodgement till complexes seems to indicate that there were also competing smaller scale flow units within each of these larger ice flows. This inter-complex colour stratification can best be explained by an unconformable facies superimposition model (Eyles et al., 1982).

CHAPTER 7

CONCLUSIONS

7.1 Conclusions

Quaternary sediments exposed in the Severn River area of the Hudson Bay Lowlands are interpreted as components of four distinct types of depositional complexes, namely a lodgement till complex, a glacio-lacustrine complex, a glacio-marine complex and a marine complex.

Lodgement till complexes are dominated by massive diamict facies, which often contain associated boulder pavements. Massive diamicts are deposited as lodgement tills by frictional retardation and pressure melt-out of material from the basal layer of the ice sheet.

Channelized, laterally discontinuous fluvial sediments within the massive diamicts represent deposition by subglacial meltwater streams. Blockage of these stream channels results in subglacial meltwater ponding and deposition of laminated fine-grained sediments from suspension or from density underflows. Dropstones and diamict clots are eroded or melted out of the subglacial cavity walls or ceilings, and are dropped into these subglacial fluvial and laminated sediments.

Three distinct lodgement till complexes have been identified in the Severn River area (see below).

A glacio-lacustrine and a glacio-marine complex overlie the lodgement till complexes, and represent deposition in an ice marginal water body. Deposits of glacio-lacustrine origin show a total lack of foraminifera which differentiates them from glacio-marine deposits. Both complexes contain rhythmically laminated fine-grained sediments deposited from suspension or from density underflows of sediment-laden meltwater inputs. Dropstones and diamict clots in these fine-grained units are melted-out of debris-bearing icebergs, calving from the glacier margin into the water body.

The thin massive diamict, and stratified diamict components of the glacio-marine and glacio-lacustrine complexes represent sediments redeposited by subaqueous gravity flows. These flows are caused by the spontaneous failure of unstable, rapidly deposited silts and clays or adjacent diamict units.

The uppermost depositional complex along the Severn River is the marine complex. This represents sedimentation in the isostatically depressed Hudson Bay basin, which was occupied by the Tyrrell Sea. Components include fossiliferous beach gravels and bioturbated estuarine sands, which coarsen upwards due to regression of the shoreline caused by post-glacial isostatic rebound.

The relatively low volume of glacio-lacustrine and glacio-marine sediment, and the absence of a supraglacial complex implies a clean Laurentide ice sheet containing little or no englacial or supraglacial debris.

Ice flow orientations obtained from diamict clast fabric analysis and striated boulder pavements and bedrock surfaces support a multi-domed configuration for the Laurentide ice sheet. Three successive lodgement till complexes were deposited by ice flowing from three separate ice domes. This is supported by data on diamict foraminifera abundances, erratic clast lithologies and diamict matrix colours.

The oldest lodgement till complex outcropping in the Severn River area was deposited by ice flowing northwestward from the Patrician ice dome. This dome was located to the north of Lake Nipigon. The middle lodgement complex represents deposition by ice flowing westward from a James Bay ice dome, located on the east coast of James Bay. The youngest lodgement complex was deposited by ice flowing southwest from the New Quebec ice dome, located east of Hudson Bay.

Diamict colour stratification in the lodgement till complexes is due to unconformable facies superimposition, resulting from competition between various ice flow units within the ice masses flowing from each dome. This caused the successive deposition of debris derived from different coloured source rocks.

Interglacial or interstadial deposits are not represented in the Severn River area. Therefore, it is assumed that the sediments in the area all post-date the interglacial

Missinabi Formation. This would place the age of the Severn River deposits at less than approximately 106,000 years b.p..

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APPENDIX A

FORAMINIFERA EXTRACTION

PROCEDURE

APPENDIX A

FORAMINIFERA EXTRACTION PROCEDURE

(modified after Then and Dougherty, 1983)

The following technique was developed by combining information from several sources, as well as a great deal of trial, error and profanity. The result is a very fast method of extracting foraminiferal tests from unconsolidated sediment samples. The technique will probably work quite well on consolidated material as well, although this has not been tested.

1. Crush the sample until the debris will pass through a -1.0 phi sieve. Do not crush any smaller or you will risk destroying some of the smaller tests.

2. Place 100 g of the sample in a 2 litre beaker. Do not use a smaller beaker or you will lose some sample to boil over.

3. Put on some rubber gloves and goggles, then pour in just enough hydrogen peroxide to cover the sample. Stir with a glass rod and immediately pop the beaker in a fumehood.

4. The mixture should react fairly quickly and vigorously,

and then die down. Leave it in the fumehood for about 1 hour.

5. Remove the beaker, fill it with water and flush the sample through a 4.0 phi sieve. Wet sieve thoroughly to remove as much of the fine material as possible.

6. Transfer the >4.0 phi residue to a 600 ml beaker and add 200 ml of sodium hydroxide solution (made by dissolving 1 tablespoon of NaOH tablets in 1 litre of water), and 100 ml of household bleach.

7. Stir the contents and place the beaker in an ultrasonic bath or on a rotating hot plate for about 1 hour.

8. Repeat step 6 for wet sieving.

9. Transfer the sample to a pyrex beaker, and place on a hot plate at about 120 C until the sample is completely dry.

10. Before wet sieving the next sample, stain any residual particles in the 4.0 phi sieve to detect contamination of the following material. This is accomplished by soaking the sieve briefly in a toluidine blue solution make by dissolving sufficient toluidine crystals in water to turn it a dark blue.

11. Using a stack containing a 0.5 phi and a 2.5 phi sieve, dry sieve the sample for 5 minutes on a sieve shaker. Transfer the residue on the 2.5 phi screen into a 500 ml separatory funnel. This funnel must have a stopcock with an opening of at least -1.5 phi, in order to allow sand grains to pass through it. The rest of the sample can be dumped.

IMPORTANT: The following steps use carbon tetrachloride, which is extremely toxic, carcinogenic and generally bad for you. Therefore, it must be used only under a fumehood with the cover almost completely closed. Gloves must be worn, and extreme care must be taken to avoid inhaling any fumes. Rinse the funnel with acetone and then wash it with soap and water inside the fumehood between each use, before removing it from the fumehood.

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12. Add about 200 ml of carbon tetrachloride to the separatory funnel, and put the stopper in. Shake. Some sediment will stick to the sides; washing it off with a squirt bottle filled with carbon tetrachloride may help.

13. Let the sand grains settle to the bottom of the funnel. The lighter, air-filled forams should float, but don't worry if nothing seems to be floating. Open the stopcock, let the sand grains drain out into a beaker, and then close it again.

14. Rinse the sides of the funnel with a squirt bottle filled with acetone, and drain the remaining liquid into a another beaker. Keep rinsing with acetone and draining into the beaker until all the sediment is out of the funnel.

15. Place this beaker on a hot plate inside the fumehood at about 100 C, and let all the liquid boil off. Leave the beaker on the hot plate for at least 2 hours, to ensure that all the carbon tetrachloride has evaporated.

16. Transfer the dried residue to a foram picking tray, and remove and mount any dead things of interest.

APPENDIX B

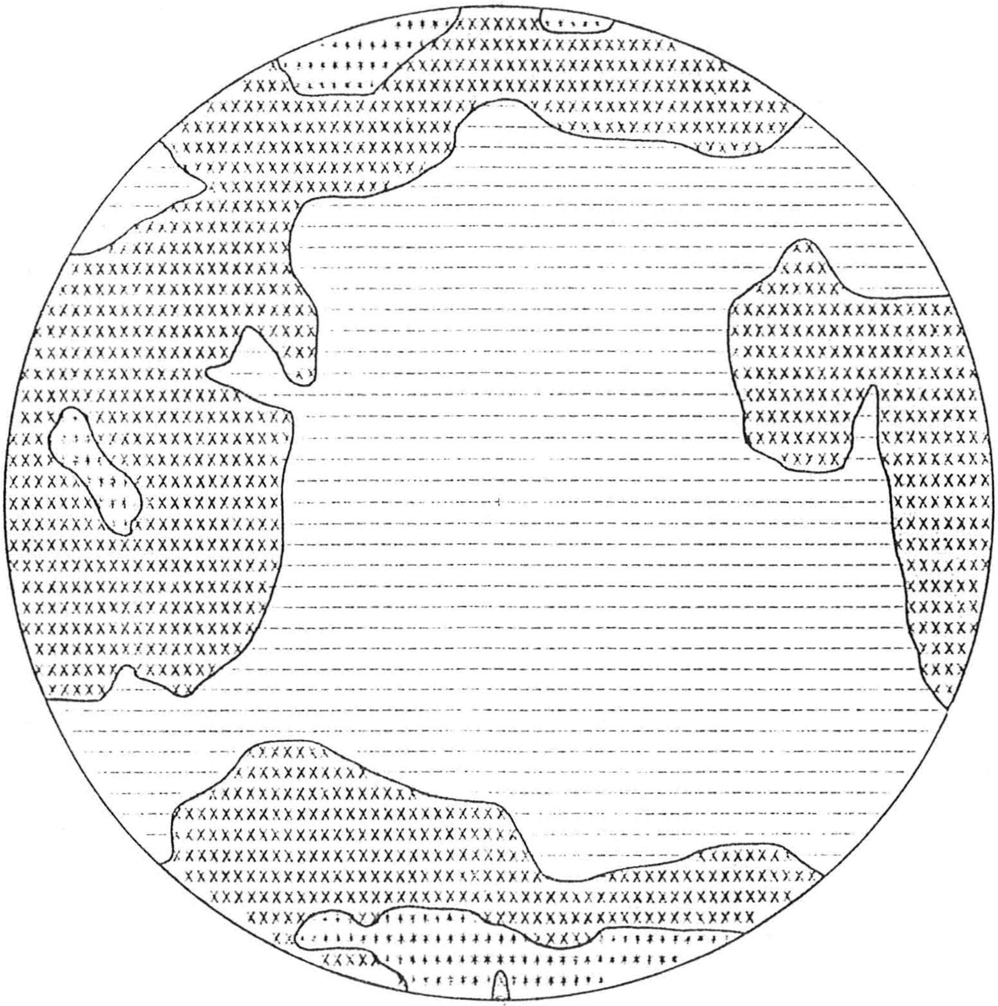
CONTOURED LOWER HEMISPHERE PROJECTIONS OF DIAMICT CLAST FABRIC ANALYSIS DATA

(TABS ON STEREONETS INDICATE ICE FLOW DIRECTION)

RANDOM FABRIC ORIENTATIONS

50 POINTS FS
COUNTING AREA = 0.074
EXPECTED NUMBER = 3.70
STANDARD DEVIATION (SIGMA) = 1.85 = (EXPECTED NUMBER) / 2.0

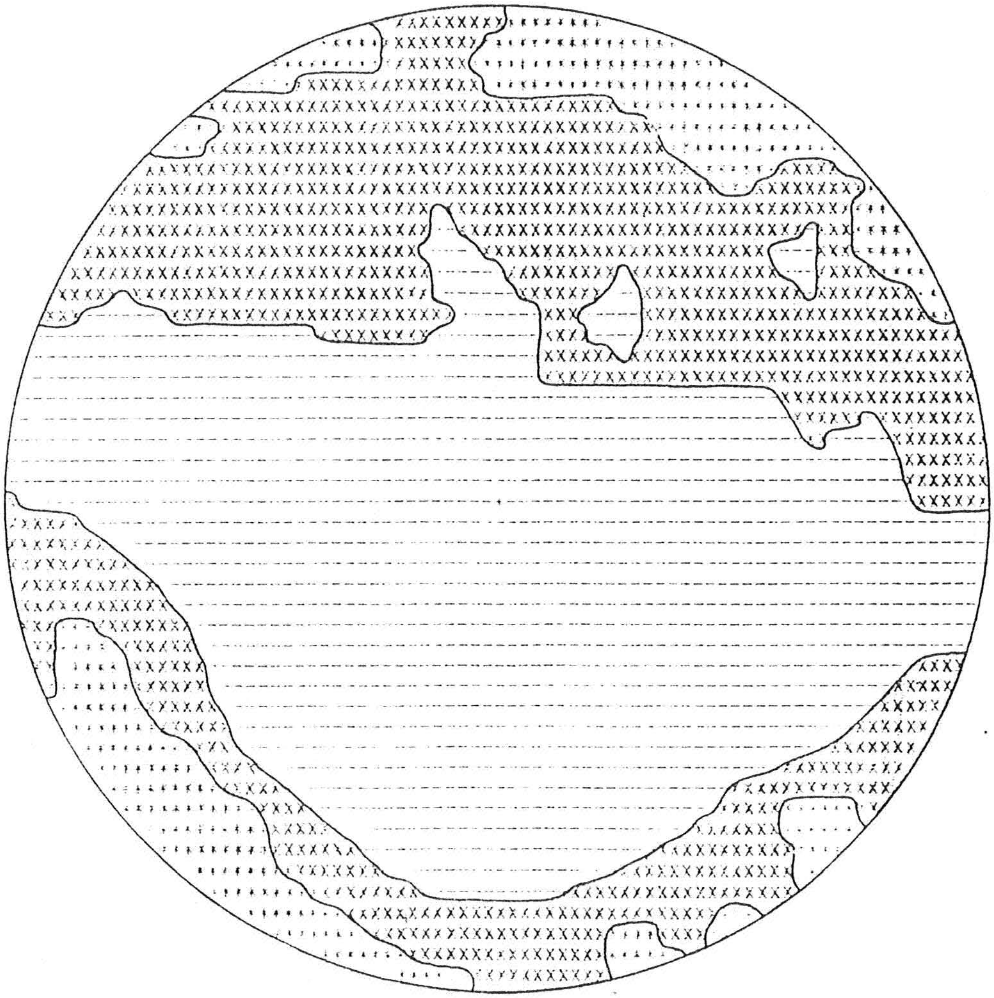
ORDER OF SYMBOLS IS -, X, +, O, /, -, ... WITH CONTOUR INTERVAL = 2.0 SIGMA =
EXPECTED NUMBER =1X RANDOM



EQUAL AREA PROJECTION ON LOWER HEMISP

50 POINTS F16
COUNTING AREA = 0.074
EXPECTED NUMBER = 3.70
STANDARD DEVIATION (SIGMA) = 1.25 = (EXPECTED NUMBER) / 2.0

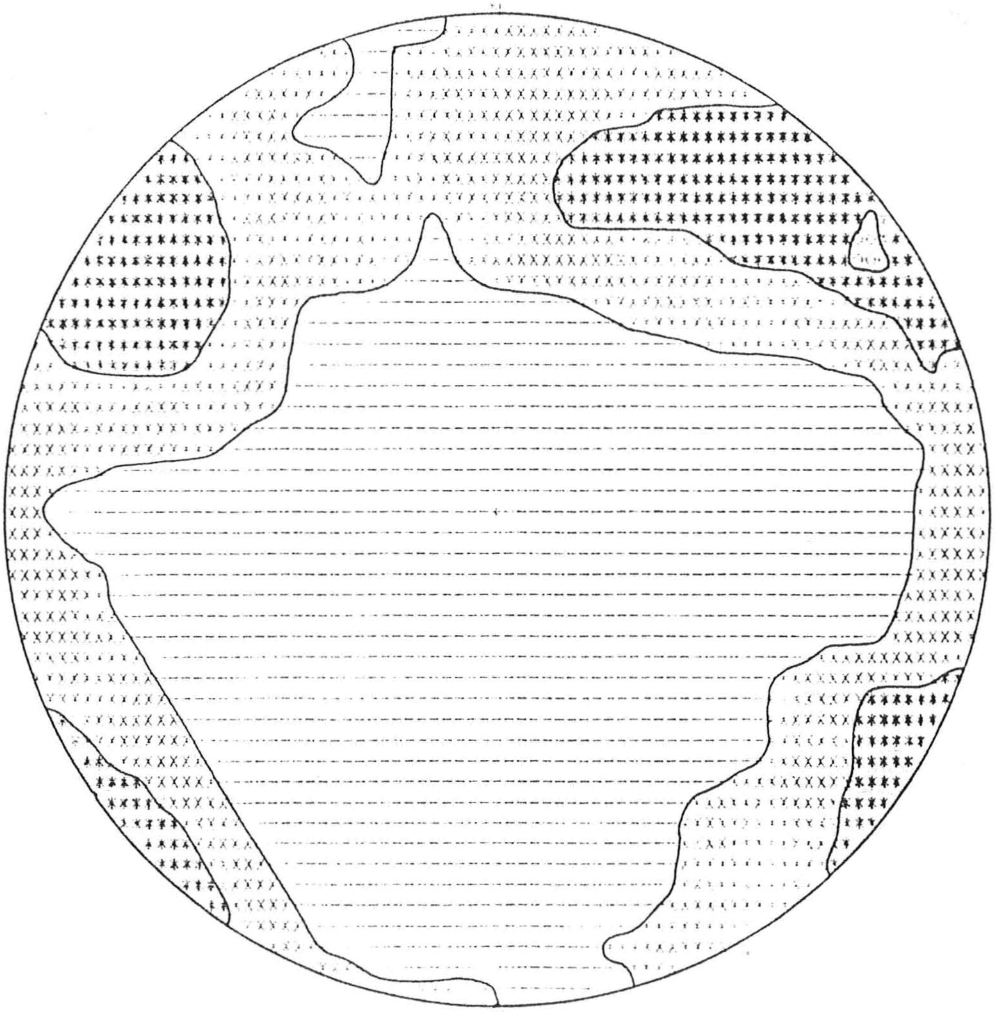
ORDER OF SYMBOLS IS -, X, +, 0, /, -, ... WITH CONTOUR INTERVAL = 2.0 SIGMA =
EXPECTED NUMBER =1X RANDOM



[illegible] PROJECTION ON [illegible]

50 POINTS F17
COUNTING AREA = 0.074
EXPECTED NUMBER = 3.70
STANDARD DEVIATION (SIGMA) = 1.05 = (EXPECTED NUMBER) / 2.0

ORDER OF SYMBOLS IS -, X, +, O, Z, -, ... WITH CONTOUR INTERVAL = 2.0 SIGMA =
EXPECTED NUMBER =1X RANDOM

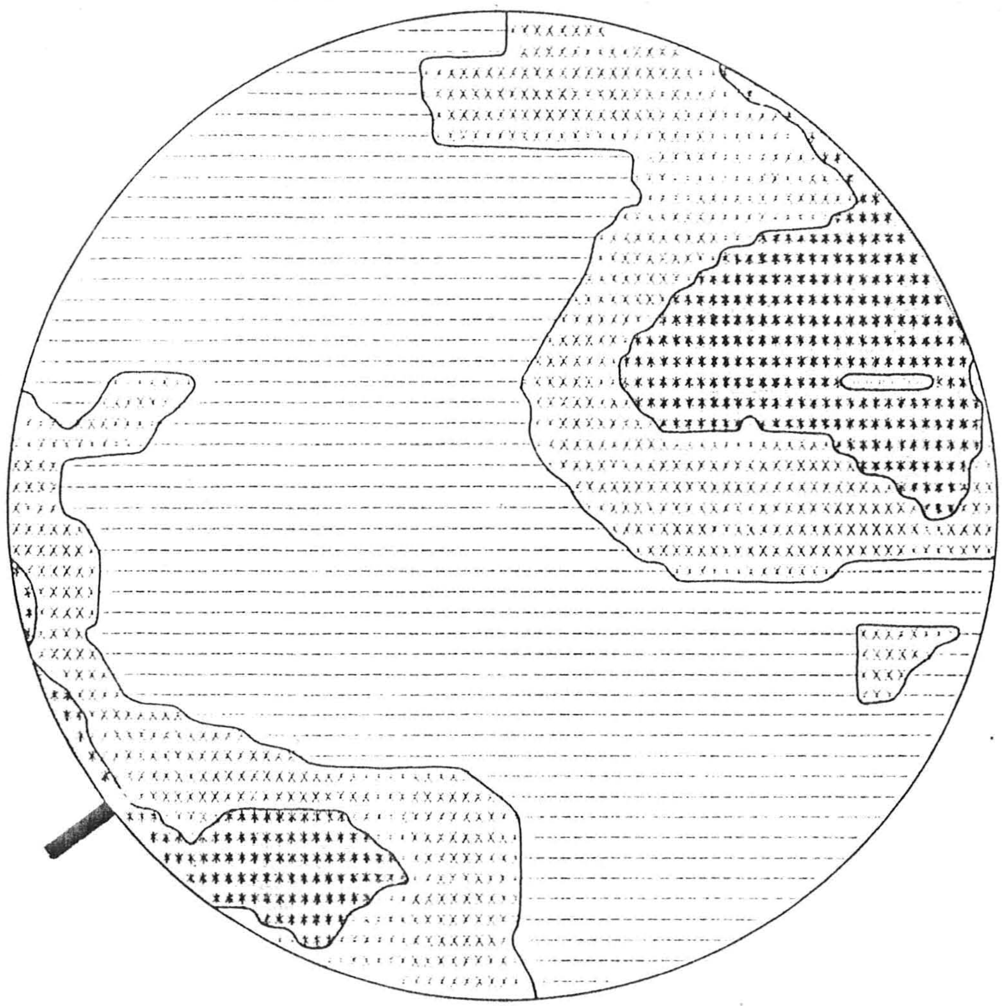


EQUAL AREA PROJECTION ON LOWER HEMISPHERE

SOUTHWESTWARD FABRIC ORIENTATIONS

50 POINTS F1
COUNTING AREA = 0.074
EXPECTED NUMBER = 3.70
STANDARD DEVIATION (SIGMA) = 1.95 = (EXPECTED NUMBER) / 2.0

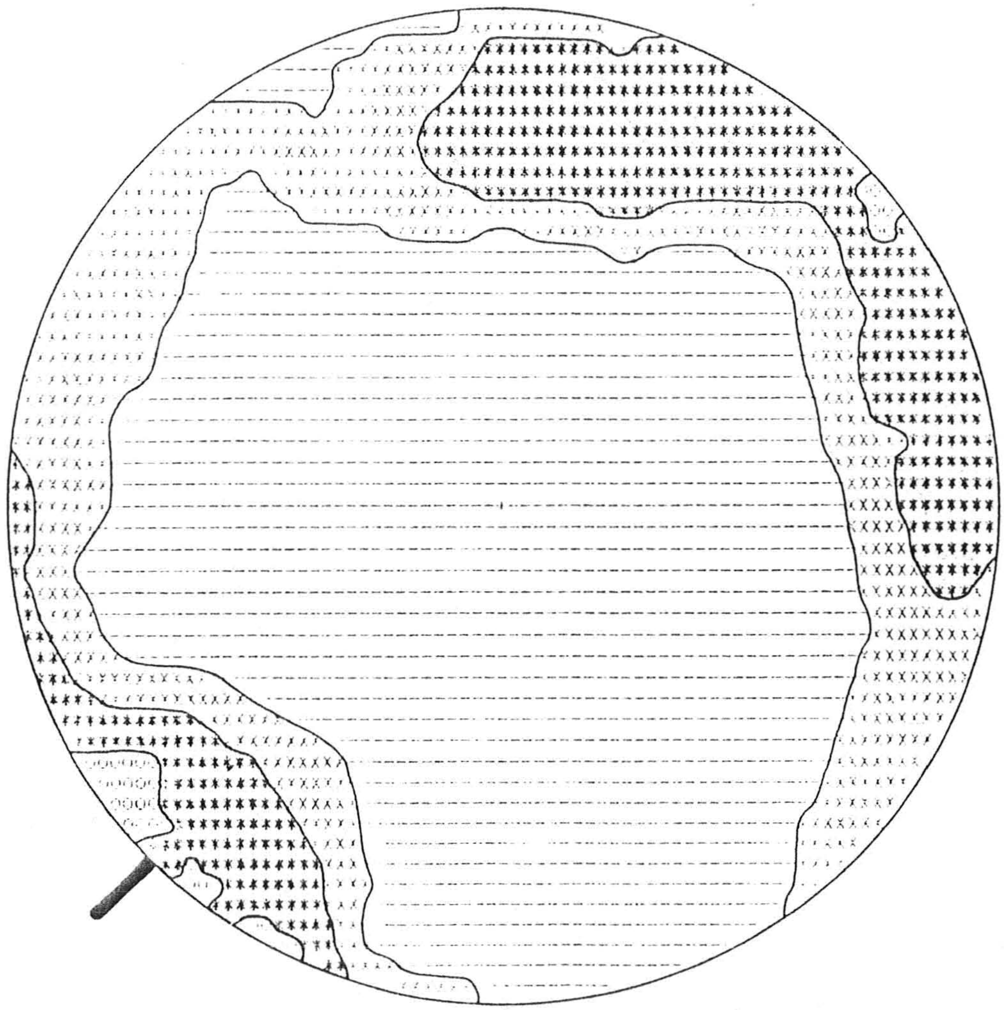
ORDER OF SYMBOLS IS -, X, *, ., /, -, ... WITH CONTOUR INTERVAL = 2.0 SIGMA =
EXPECTED NUMBER =1X RANDOM



EQUAL AREA PROJECTION ON LOWER HEMISPHERE

50 POINTS F2
COUNTING AREA = 0.074
EXPECTED NUMBER = 3.70
STANDARD DEVIATION (SIGMA) = 1.85 = (EXPECTED NUMBER) / 2.0

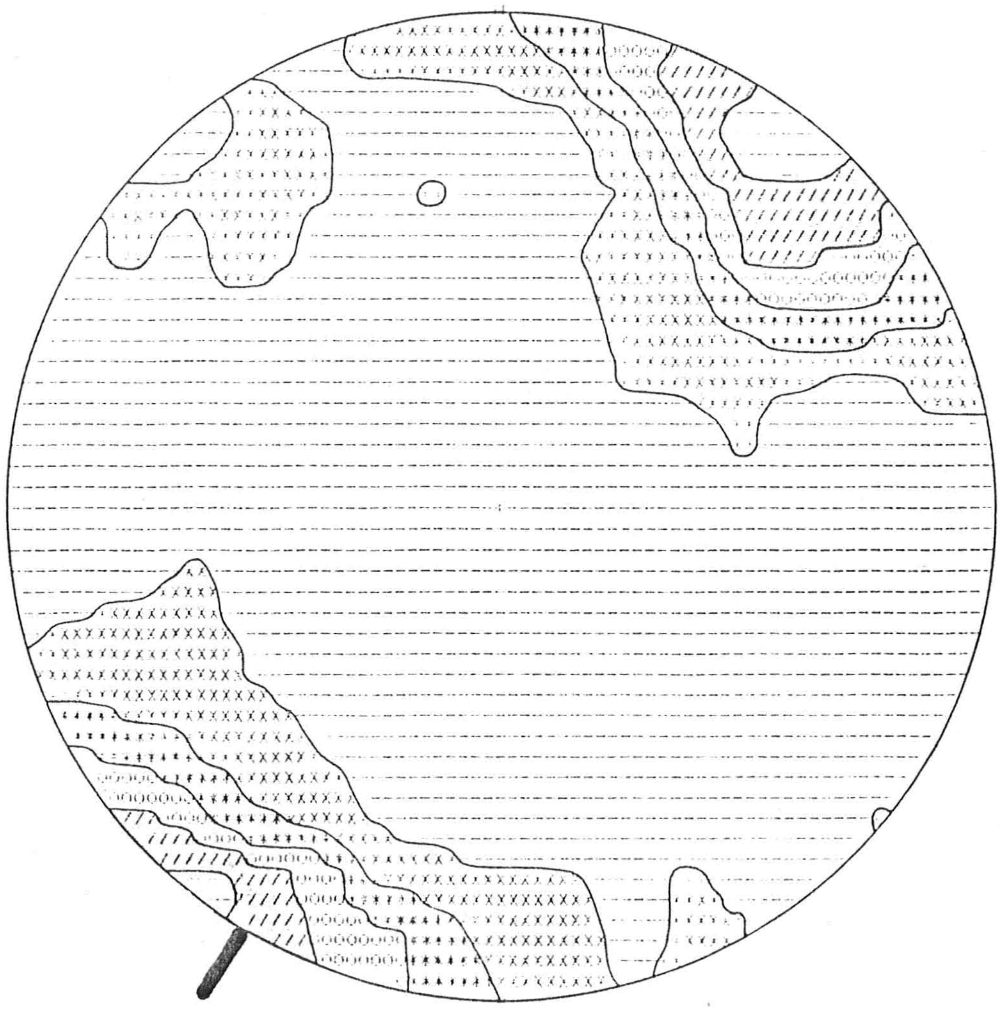
ORDER OF SYMBOLS IS -, X, #, 0, /, +, ... WITH CONTOUR INTERVAL = 2.0 SIGMA =
EXPECTED NUMBER =1X RANDOM



EQUAL AREA PROJECTION ON LOWER HEMISPHERE

50 POINTS F10
COUNTING AREA = 0.074
EXPECTED NUMBER = 3.70
STANDARD DEVIATION (SIGMA) = 1.65 = (EXPECTED NUMBER) / 2.0

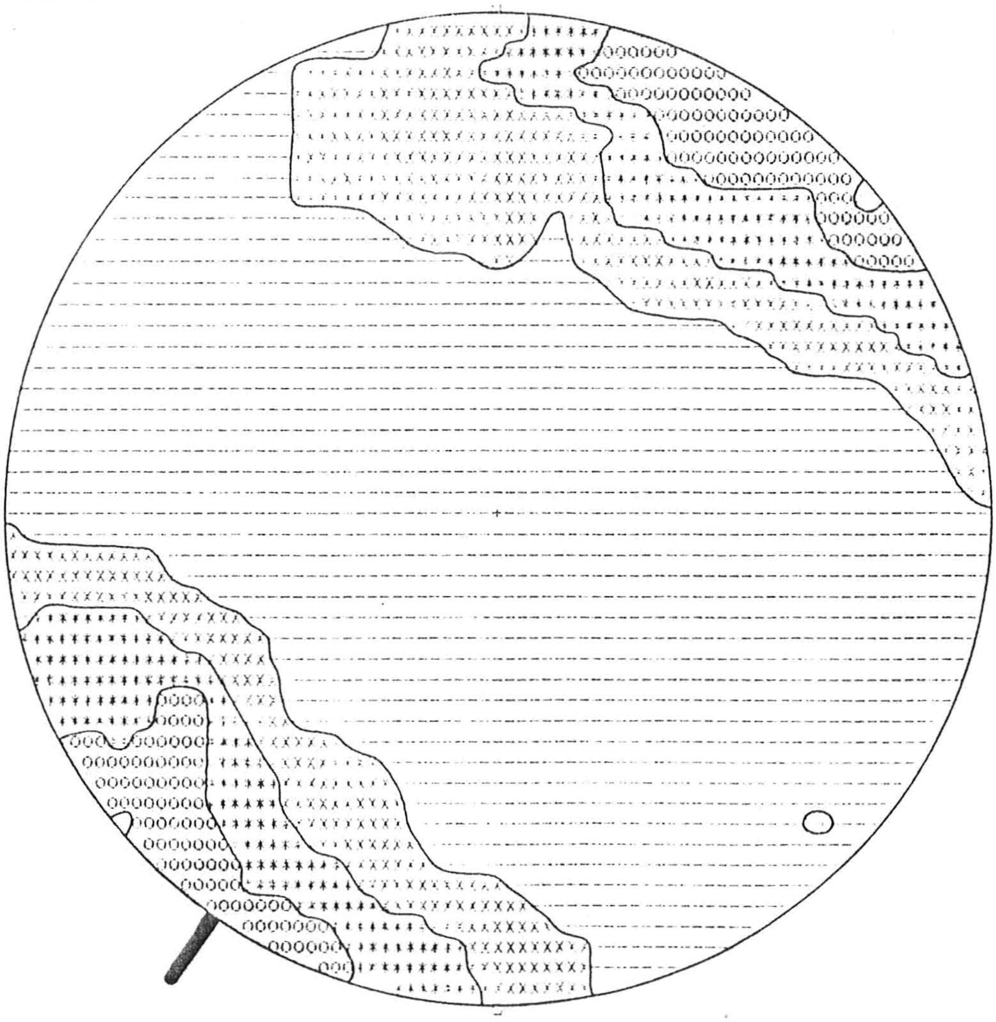
ORDER OF SYMBOLS IS -, X, *, O, /, +, ... WITH CONTOUR INTERVAL = 2.0 SIGMA =
EXPECTED NUMBER =1X RANDOM



EQUAL AREA PROJECTION ON LOWER HEMISPHERE

50 POINTS F12
COUNTING AREA = 0.074
EXPECTED NUMBER = 3.70
STANDARD DEVIATION (SIGMA) = 1.85 = (EXPECTED NUMBER) / 2.0

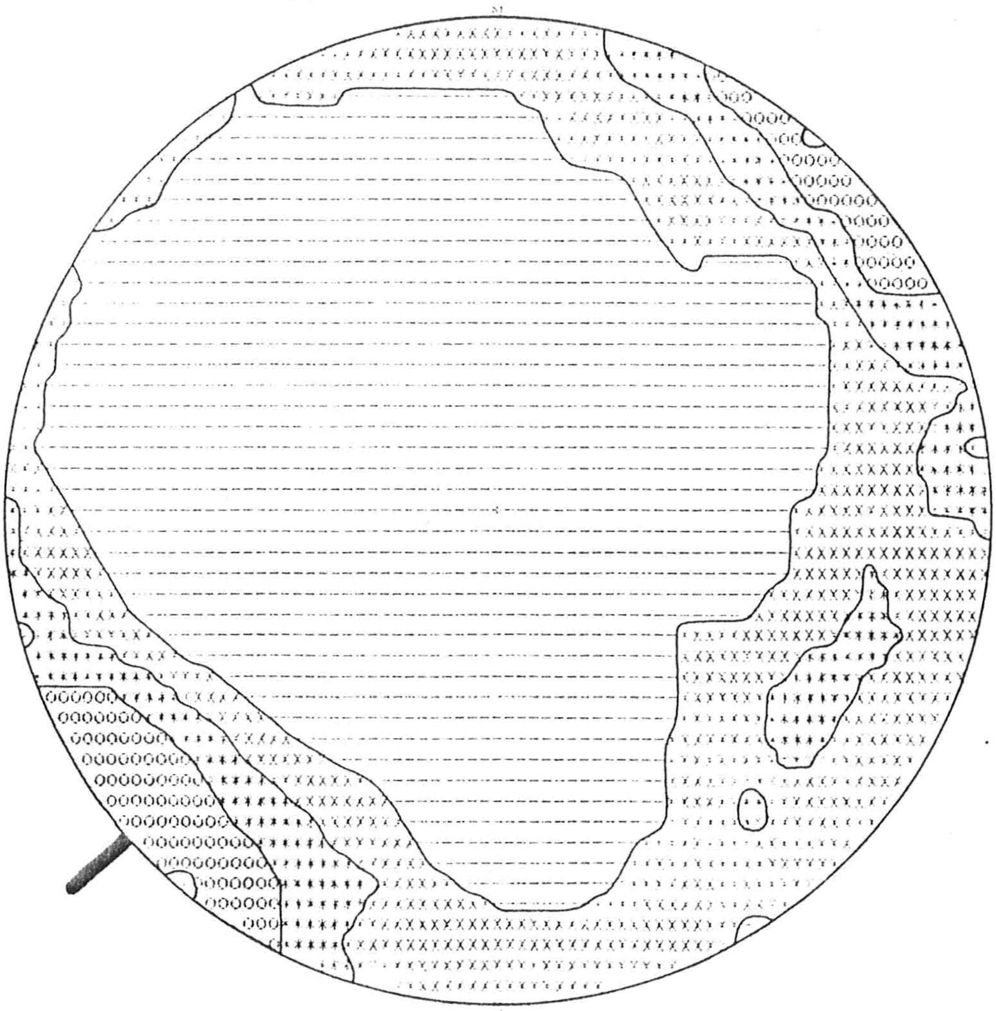
ORDER OF SYMBOLS IS -, x, +, 0, /, =, ... WITH CONTOUR INTERVAL = 2.0 SIGMA = EXPECTED NUMBER =1X RANDOM



EQUAL AREA PROJECTION ON LOWER HEMISPHERE

50 POINTS   F13
COUNTING AREA = 0.074
EXPECTED NUMBER = 3.70
STANDARD DEVIATION (SIGMA) = 1.85 = (EXPECTED NUMBER) / 2.0

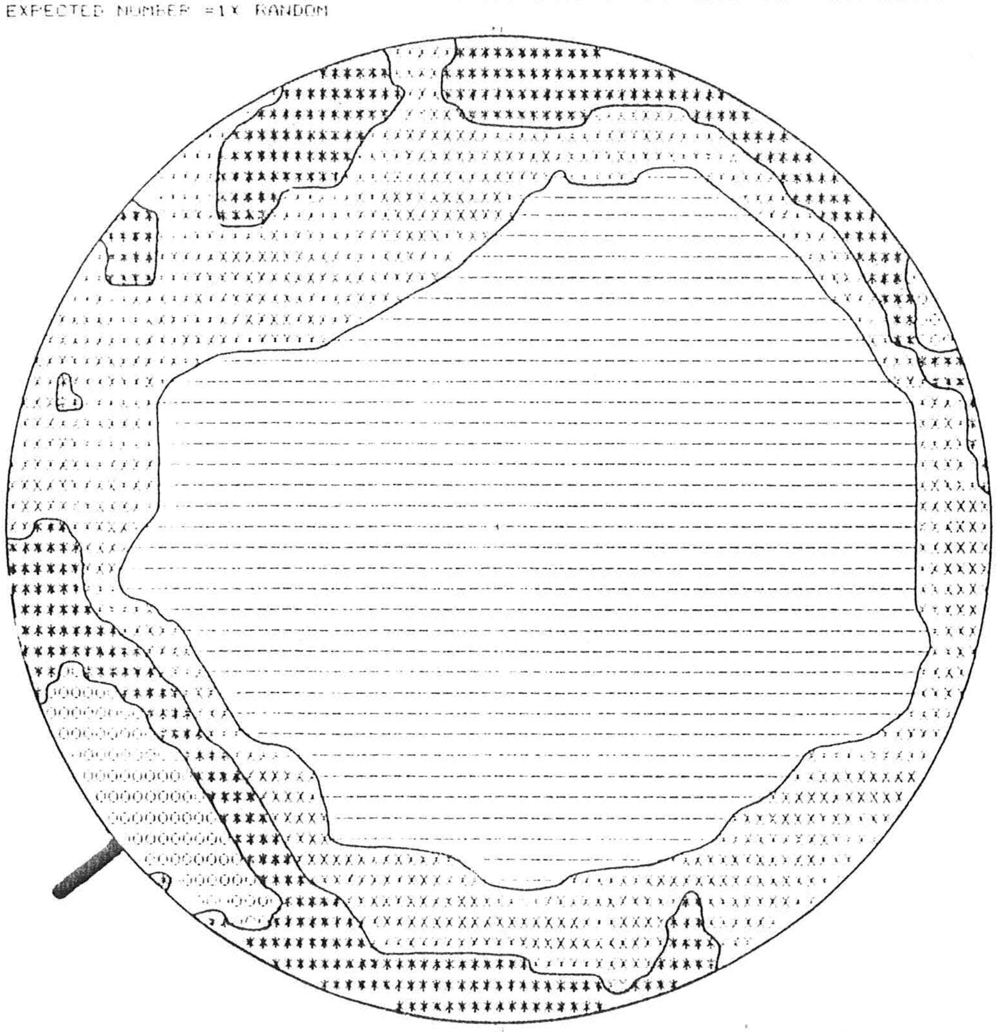
ORDER OF SYMBOLS IS -, X, *, O, /, -, ... WITH CONTOUR INTERVAL = 2.0 SIGMA =
EXPECTED NUMBER =1X RANDOM



EQUAL AREA PROJECTION ON LOWER HEMISPHERE

50 POINTS F14
COUNTING AREA = 0.074
EXPECTED NUMBER = 3.70
STANDARD DEVIATION (SIGMA) = 1.85 = (EXPECTED NUMBER) / 2.0

ORDER OF SYMBOLS IS -, X, *, O, /, =, ... WITH CONTOUR INTERVAL = 2.0 SIGMA =
EXPECTED NUMBER =1X RANDOM

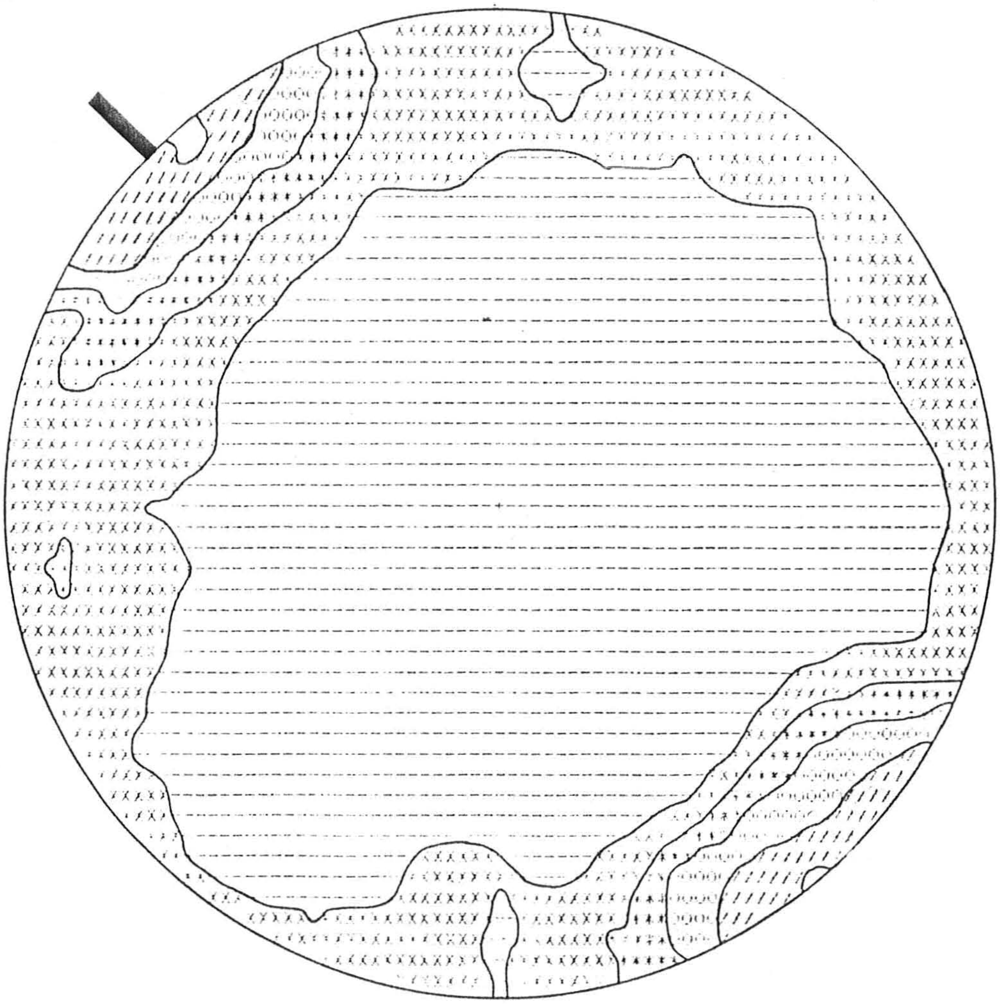


EQUAL AREA PROJECTION ON LOWER HEMISPHERE

NORTHWESTWARD FABRIC ORIENTATIONS

50 POINTS F3
COUNTING AREA = 0.074
EXPECTED NUMBER = 3.70
STANDARD DEVIATION (SIGMA) = 1.85 = (EXPECTED NUMBER) / 2.0

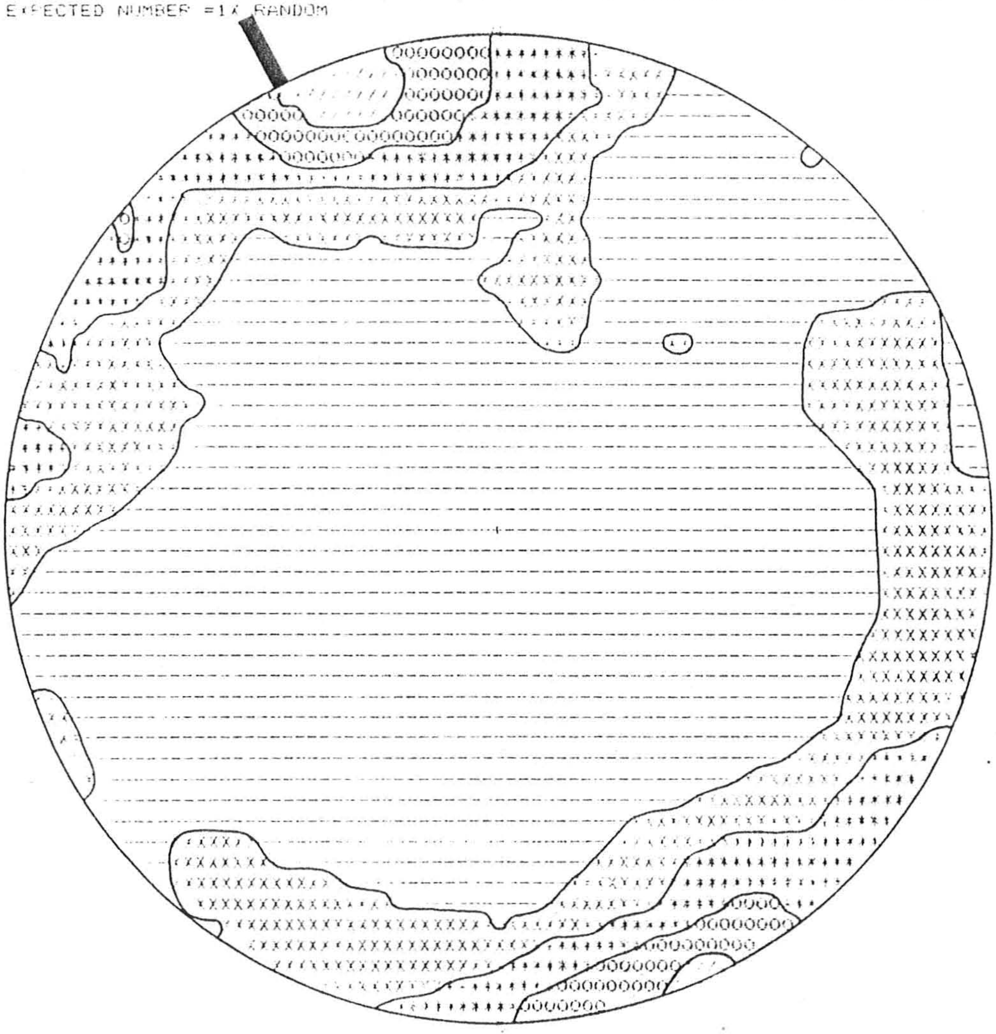
ORDER OF SYMBOLS IS -, X, *, O, /, -, ... WITH CONTOUR INTERVAL = 2.0 SIGMA =
EXPECTED NUMBER =1X RANDOM



EQUAL AREA PROJECTION ON LOWER HEMISPHERE

50 POINTS F4
COUNTING AREA = 0.074
EXPECTED NUMBER = 3.70
STANDARD DEVIATION (SIGMA) = 1.85 = (EXPECTED NUMBER) / 2.0

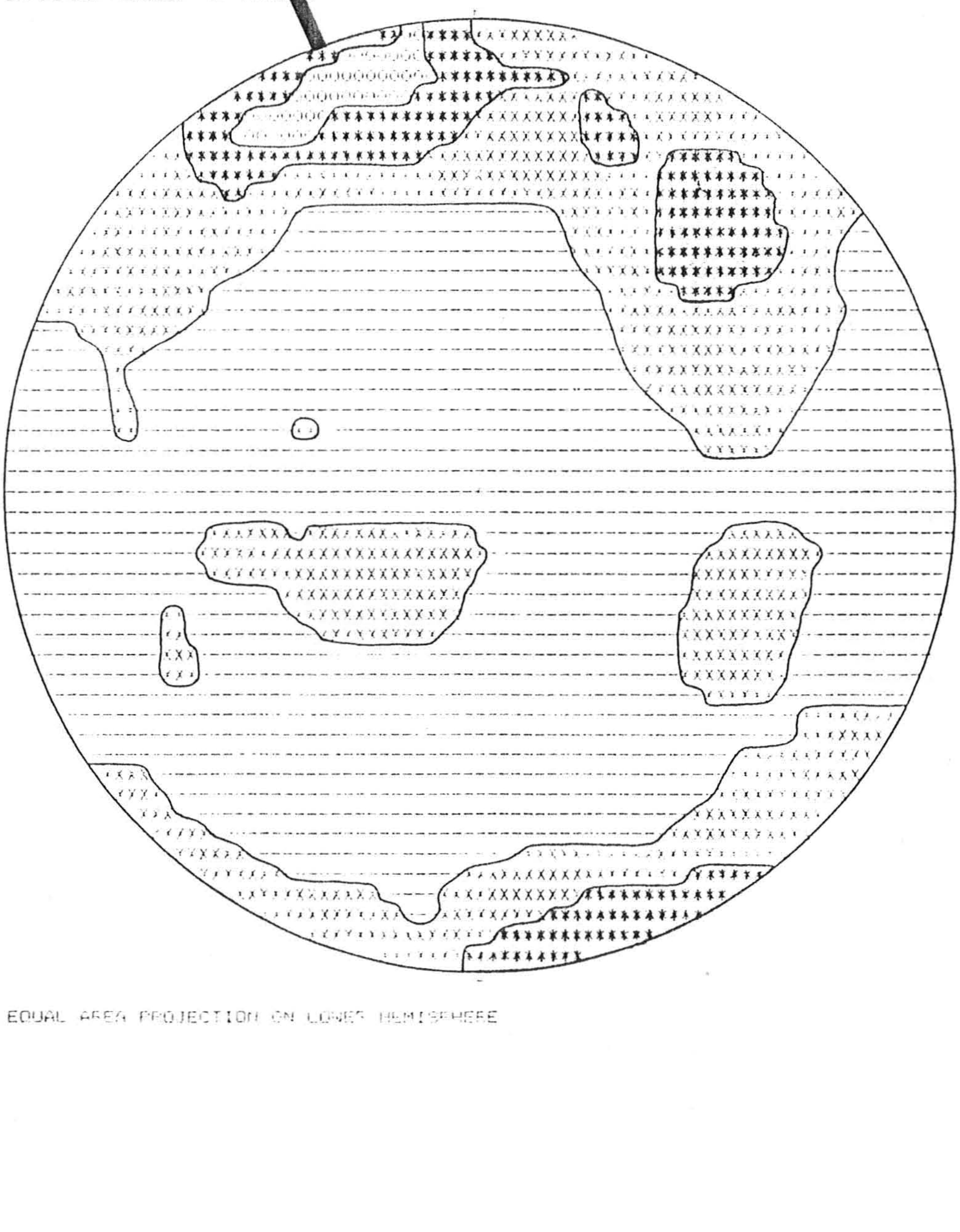
ORDER OF SYMBOLS IS -, X, *, 0, /, -, ... WITH CONTOUR INTERVAL = 2.0 SIGMA =
EXPECTED NUMBER =1X RANDOM



EQUAL AREA PROJECTION ON LOWER HEMISPHERE

50 POINTS F13
COUNTING AREA = 0.074
EXPECTED NUMBER = 3.70
STANDARD DEVIATION (SIGMA) = 1.65 = (EXPECTED NUMBER) / 2.0

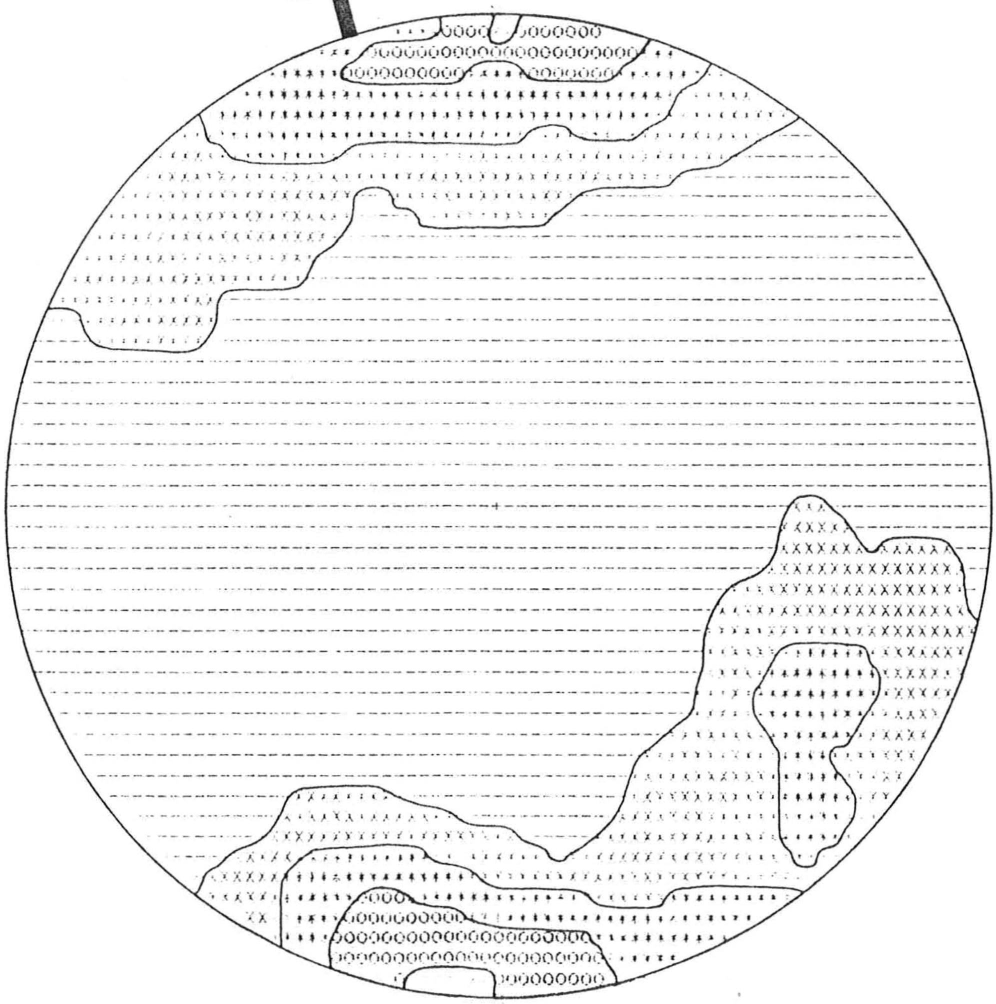
ORDER OF SYMBOLS IS -, [illegible] *, O, /, =, ... WITH CONTOUR INTERVAL = 2.0 SIGMA =
EXPECTED NUMBER =1/ RANDOM



EQUAL AREA PROJECTION ON LOWER HEMISPHERE

50 POINTS   F15
COUNTING AREA = 0.074
EXPECTED NUMBER = 3.70
STANDARD DEVIATION (SIGMA) = 1.85 = (EXPECTED NUMBER) / 2.0

ORDER OF SYMBOLS IS -, X, *, O, Z, #, ... WITH CONTOUR INTERVAL = 2.0 SIGMA =
EXPECTED NUMBER =1X RANDOM

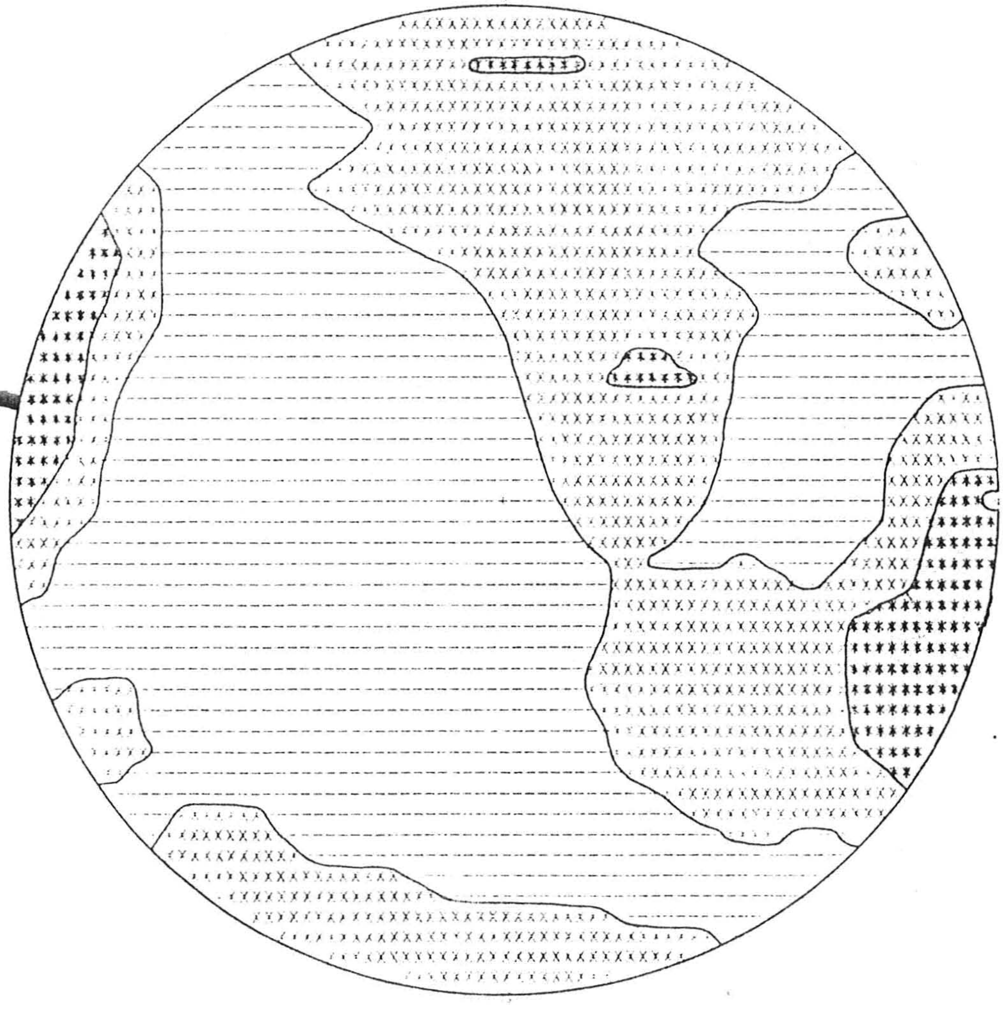


EQUAL AREA PROJECTION ON LOWER

WESTWARD FABRIC ORIENTATIONS

50 POINTS   Fo
COUNTING AREA = 0.074
EXPECTED NUMBER = 3.70
STANDARD DEVIATION (SIGMA) = 1.85 = (EXPECTED NUMBER) / 2.0

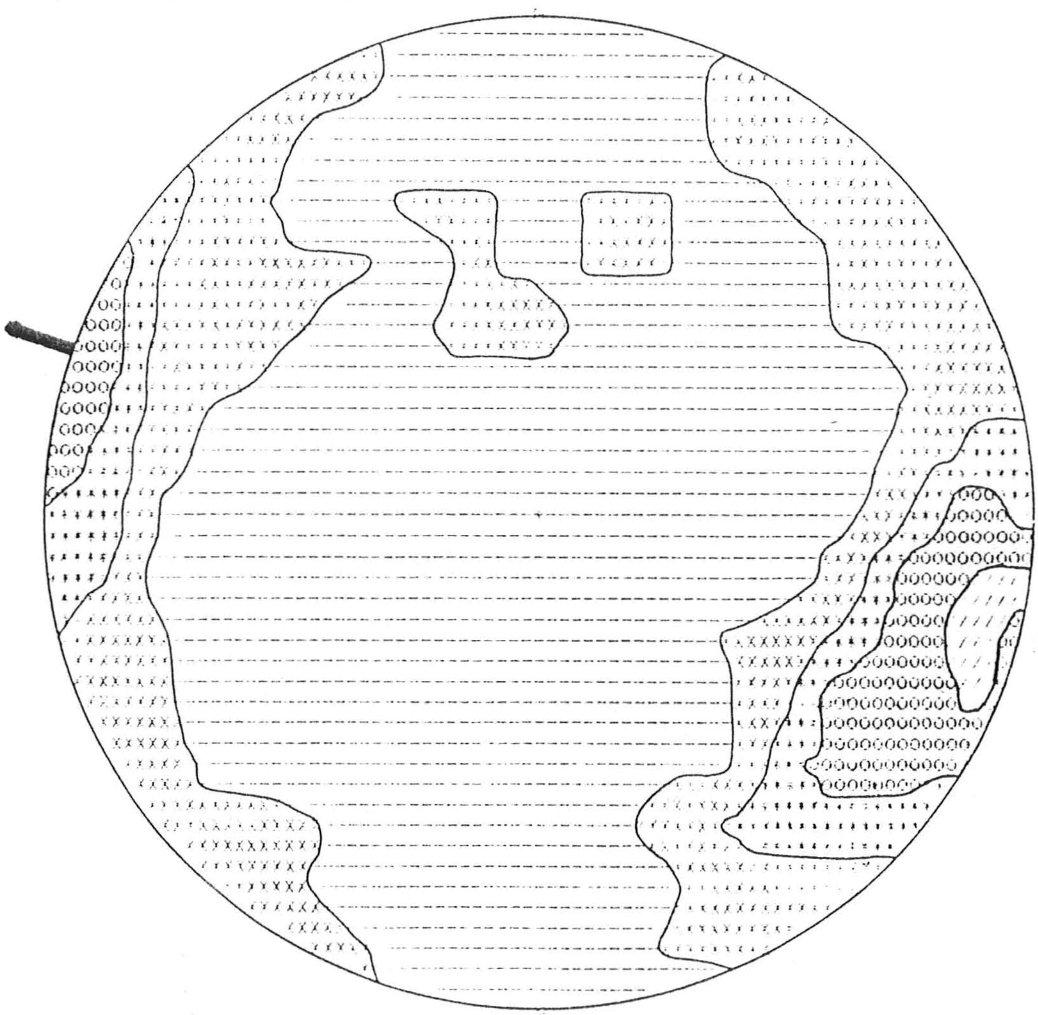
ORDER OF SYMBOLS IS -, X, *, O, /, -, ... WITH CONTOUR INTERVAL = 2.0 SIGMA = EXPECTED NUMBER =1X RANDOM



EQUAL AREA PROJECTION ON LOWER HEMISPHERE

50 POINTS F7
COUNTING AREA = 0.074
EXPECTED NUMBER = 3.70
STANDARD DEVIATION (SIGMA) = 1.85 = (EXPECTED NUMBER) / 2.0

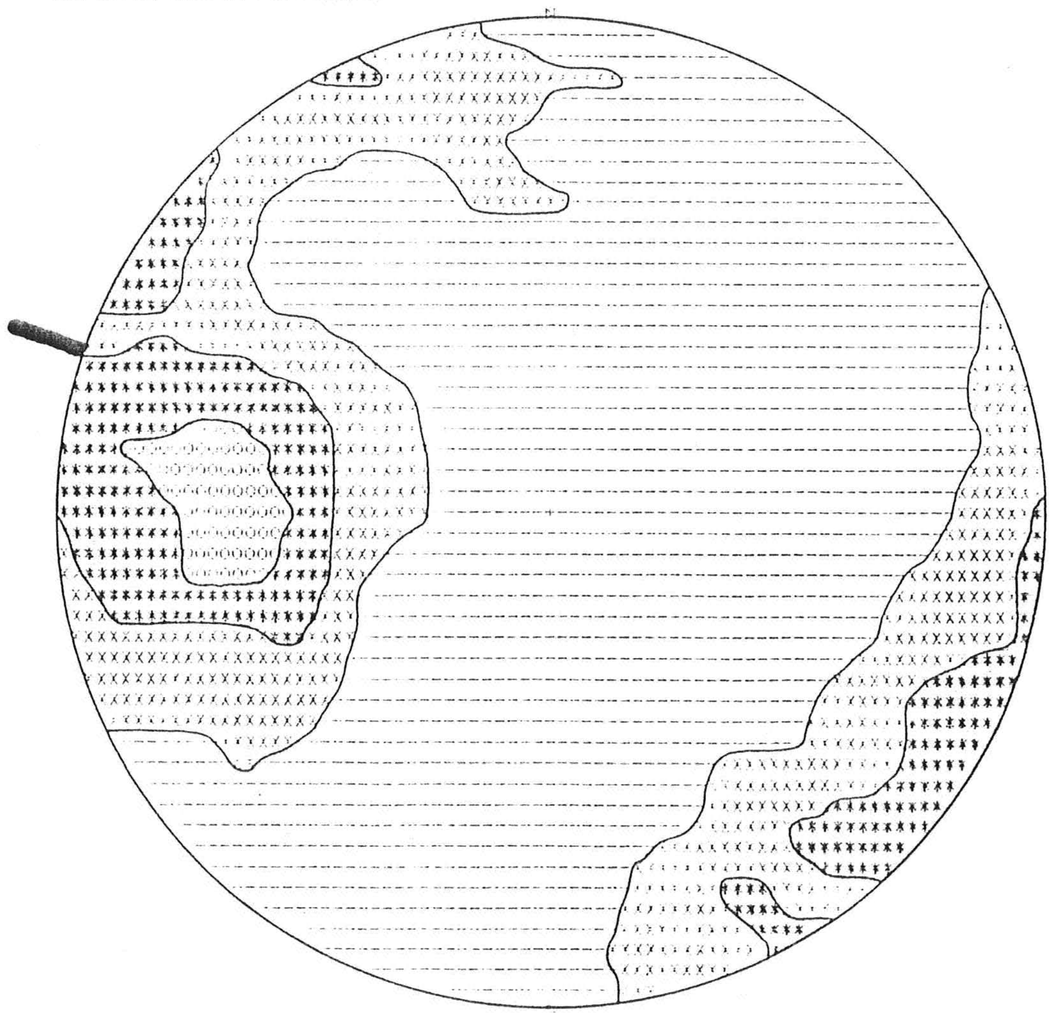
ORDER OF SYMBOLS IS -, X, +, O, /, -, ... WITH CONTOUR INTERVAL = 2.0 SIGMA = EXPECTED NUMBER =1X RANDOM



EQUAL AREA PROJECTION ON LOWER HEMISPHERE

50 POINTS FB
COUNTING AREA = 0.074
EXPECTED NUMBER = 3.70
STANDARD DEVIATION (SIGMA) = 1.85 = (EXPECTED NUMBER) / 2.0

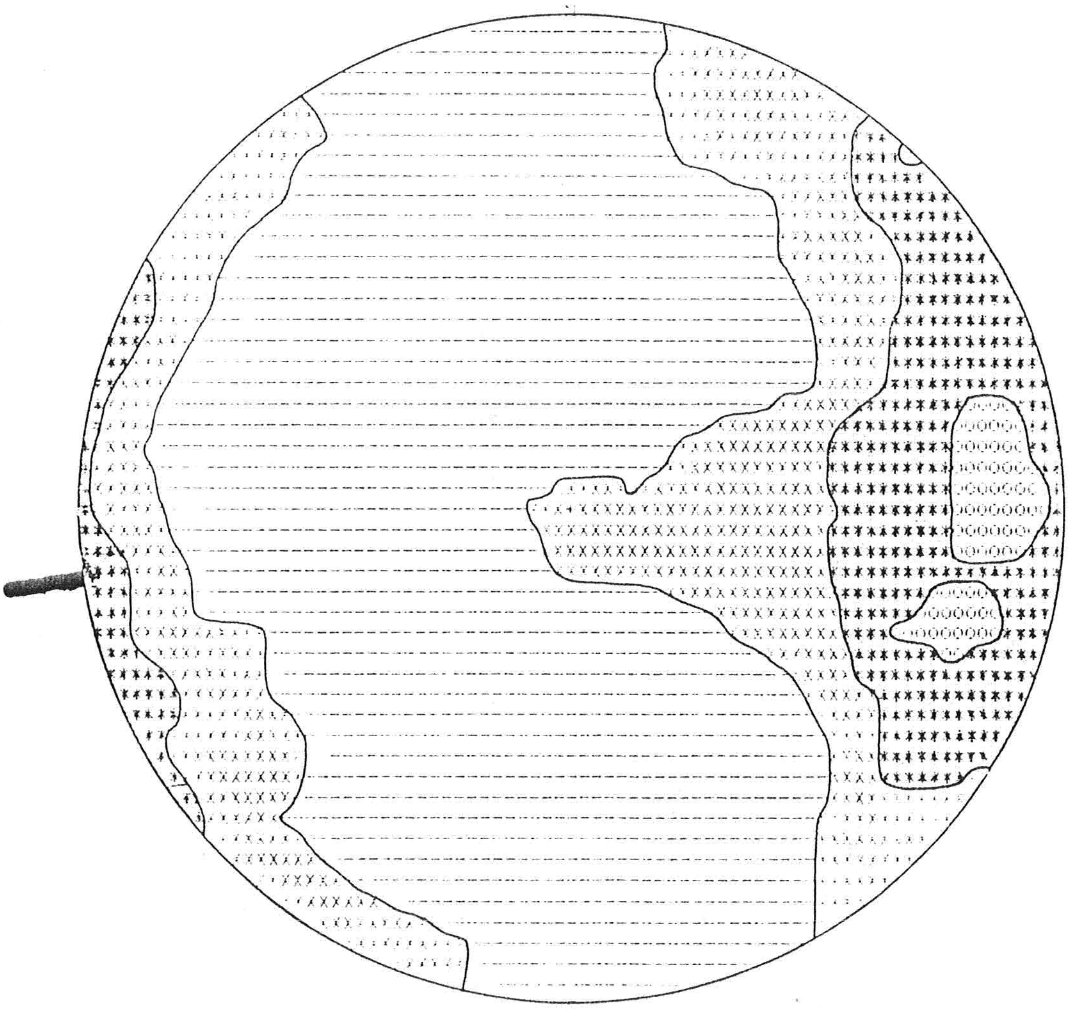
ORDER OF SYMBOLS IS -, X, *, 0, /, -, ... WITH CONTOUR INTERVAL = 2.0 SIGMA = EXPECTED NUMBER =1X RANDOM



EQUAL AREA PROJECTION ON LOWER HEMISPHERE

50 POINTS F9
COUNTING AREA = 0.074
EXPECTED NUMBER = 3.70
STANDARD DEVIATION (SIGMA) = 1.85 = (EXPECTED NUMBER) / 2.0

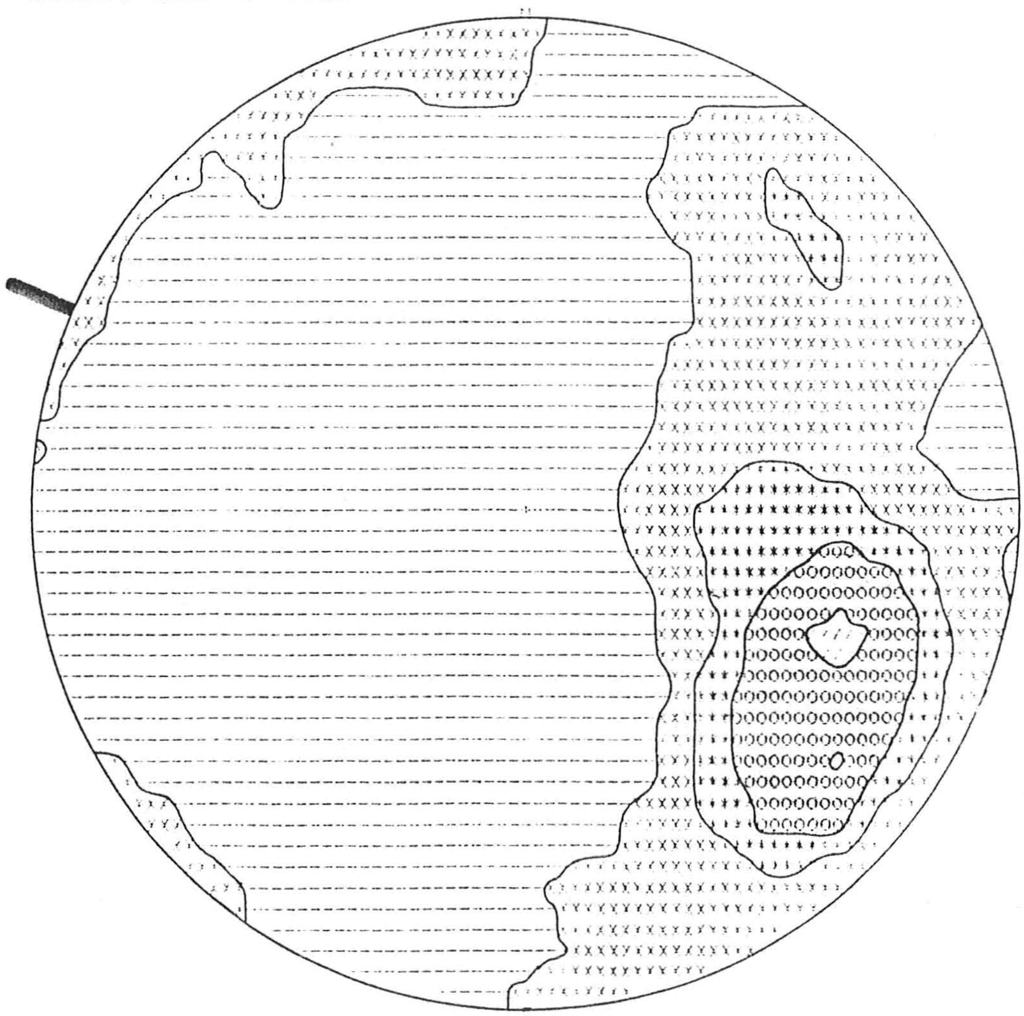
ORDER OF SYMBOLS IS -, X, *, O, Z, +, ... WITH CONTOUR INTERVAL = 2.0 SIGMA =
EXPECTED NUMBER =1X RANDOM



EQUAL AREA PROJECTION ON LOWER HEMISPHERE

50 POINTS   F11
COUNTING AREA = 0.074
EXPECTED NUMBER = 3.70
STANDARD DEVIATION (SIGMA) = 1.85 = (EXPECTED NUMBER) / 2.0

ORDER OF SYMBOLS IS -. X. *. O. /. -. ... WITH CONTOUR INTERVAL = 2.0 SIGMA =
EXPECTED NUMBER =1% RANDOM



EQUAL AREA PROJECTION ON LOWER HEMISPHERE