LICENCE TO McMASTER UNIVERSITY

This Thesis has been written
[Thesis, Project Report, etc.]

by Jarold William Hibbert for
[Full Name(s)]
Undergraduate course number Geol 4K6 at McMaster University under the supervision/direction of Dr. C. H. Eyles.

In the interest of furthering teaching and research, I/we hereby grant to McMaster University:

1. The ownership of 2 copy(ies) of this work;
2. A non-exclusive licence to make copies of this work, (or any part thereof) the copyright of which is vested in me/us, for the full term of the copyright, or for so long as may be legally permitted. Such copies shall only be made in response to a written request from the Library or any University or similar institution.

I/we further acknowledge that this work (or a surrogate copy thereof) may be consulted without restriction by any interested person.

Dave Hooper
Signature of Witness,
Supervisor

C. H. Eyles

Jarold Hibbert
Signature of Student

May 15 1990
date

(This Licence to be bound with the work)

THE HALTON "DEFORMATION" TILL: AN APPLICATION OF G.I.S. BASIN ANALYSIS ACCOMPANIED BY A SEDIMENTOLOGICAL EXAMINATION OF THE HALTON BASAL CONTACT

by

JAROLD WILLIAM HIBBERT

A Thesis

Submitted to the Department of Geology

in Partial Fulfillment of the Requirements

for the Degree

Honours Bachelor of Art

McMaster University

April, 1990

Honours Bachelor of Arts
(Geography/Geology)

McMaster University
Hamilton, Ontario

TITLE: The Halton "Deformation" Till: An Application of G.I.S. Basin Analysis Accompanied by a Sedimentological Examination of the Halton Basal Contact

AUTHOR: Jarold William Hibbert

SUPERVISOR: Dr. C. H. Eyles

NUMBER OF PAGES: x, 159

ABSTRACT

The combined use of powerful computers and Geographic Information System (G.I.S.) technology has only recently been utilized as a geological tool in the study of unconsolidated sediments. G.I.S. is applied in mapping the bedrock topography and the geometry of the Halton Till in the Toronto region identifying the technology as an essential component of any basin-wide investigation.

The bedrock surface exhibits a strong control over the distribution of the Late Wisconsin aged Halton Till. The wide, deep Laurentian channel contains thick sequences of Mid Wisconsin sediments and is capped by a thin veneer of Halton Till. The highland areas on the flanks of the Laurentian channel contain many small bedrock channels oriented in a NW/SE trend parallel to ice flow in the Late Wisconsin. These smaller bedrock channels are often the sites of thick deposits of Halton Till.

A sedimentological investigation of the Halton Till basal contact in outcrop reveals strong evidence of incorporation of underlying sediments into the Halton Till. Sediment rafts, deformed basal zones in the Halton Till and sheared underlying sediments suggest that the traditional classification of the Halton TIll as a lodgement complex is incorrect.

A grainsize investigation of the lower 10 meters of the Halton Till supports the outcrop evidence of the incorporation of underlying sediments into the lower Halton Till. The lithology of the underlying unconsolidated sediments have a strong control on the grainsize distribution of the lower 4 meters of the Halton

Till.

The geometry of the Halton Till, its sedimentology, grainsize distribution and glacitectonic deformation of underlying units all provide evidence for the deposition of the Halton Till as a 'deformation till'. Present investigations of the Halton Till as a potential unit for the location of waste disposal sites should take into consideration the geometry and sedimentology of the till.

G.I.S. is a rapidly expanding field and it will play an important role in the study of Quaternary sediments (particulary aquifers) and the location of future hazardous waste disposal sites in Southern Ontario.

Acknowledgements

The author wishes to sincerely thank The Royal Canadian Geographic Society for providing funding for research expenses incurred in the preparation of this research. Thanks also to Dr. Carolyn Eyles who acted as supervisor, hired me and sent me off to the Scarborough Bluffs on one of the hottest summers in recent history. Special thanks to Jack Whorwood for advice on photograph presentation and McMaster University Computer Information Services (C.I.S.) for solving a computer tape crisis. The author would also like to thank all those government agencies who provided access to well data files for generous use of their office space. I would also like to thank my friends in both the Geology and Geography departments for helping me cling to a bit of sanity as the year whirled by.

Lastly, I would like to thank the R.O.M. paleontology exhibit for visiting a certain grade 7 class in the not so far north and inspiring this author to begin this long journey in the earth sciences.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF PLATES

CHAPTER 1

INTRODUCTION

1.1 Overview

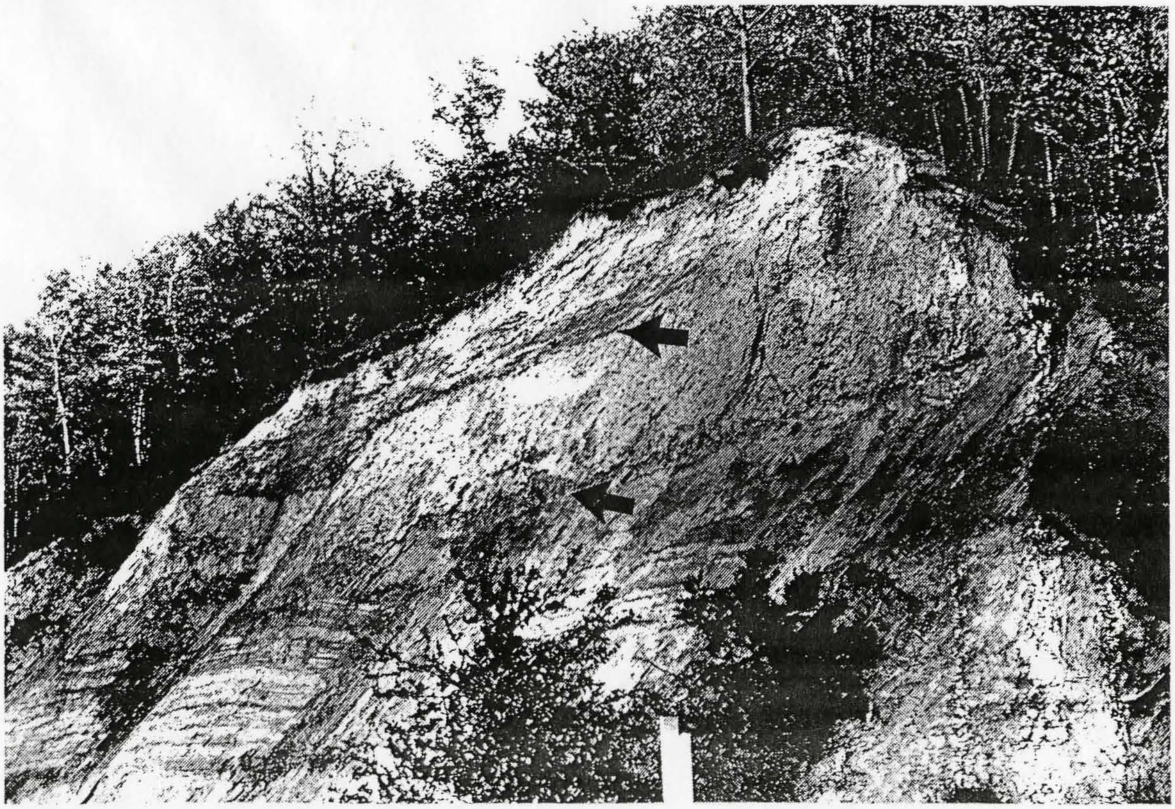
The wave cut scarps of the Scarborough Bluffs expose one of the most continious and complete records of Quaternary sediments deposited during the Wisconsin glaciation in eastern North America **(plate 1)**. These excellent exposures which open a window into the past are world renouned for their importance in determining the glaciological history of not only the Toronto area but also of most of southern Ontario.

While the exposures have been the attention of several studies since the late 19th century there still continues to be serious debate over the exact depositional history of the site and its subsequent importance in the glacial history of Ontario.

The bedrock low in the Toronto area is infilled by a wide range of glacial sediments ranging from Illinoian to Wisconsin in age **(plate 2)**. Interglacial deposits of Sangamon age are preserved between these glacial successions. The Illinoian sediments (York Till) are preserved as a diamicton which has been interpreted as a lodgement till glacial complex (Eyles et al 1985). Lacustrine sediments (Don Fm.) mark the Sangamon interglacial. The Wisconsin stratigraphy is represented by a series of interbedded clays, silts, sands (Scarborough and Thorncliffe Fm.'s) and diamicts (Sunnybrook, Seminary and Meadowcliffe assemblages). These sediments are interpreted as being the preserved remains of a delta

PLATE 1: Upper Wisconsin Stratigraphy exposed along the eastern end of the Scarborough Bluffs. The people in the lower left are for scale.

PLATE 2: Vertical exposure 1.1 km inland from S3 showing the Halton Till overlying the Scarborough Fm. sands and clays. The sequence is capped by postglacial Lake Iroquois sands. The upper and lower contacts of the Halton Till (which is approximately 7 meters thick at this location) are denoted by black arrows.



prograding into a alternating proglacial and periglacial lake occupying the Lake Ontario basin (Eyles and Eyles 1983). This sequence is capped by the Halton lodgement till complex representing the final Wisconsin advance sequence in the Toronto area **(figure 1)**.

The surfical sediments of Southern Ontario including the Toronto area consist primarily of a glacial diamict termed the Halton Till. This glacial unit covers an area of approximately 4,500 square kilometers extending from the Niagara escarpment to Port Hope. The poorly defined eastern limit of the Halton Till may have a great effect on this conservative estimate of the areal distribution of the Halton Till **(figure 2)**. The till has name equivalents and time equivalents to the west as the Wentworth Till and to the east as the Leaside till. The Leaside Till is now a discarded term previously used in early government reports to describe the Halton Till in the Toronto area (eg. Karrow, 1967; Karrow, 1972) **(figure 3)**.

Much of the recent work on the methods by which glaciers deposit sediments has come from experimental work beneath the base of glacier margins (eg. Boulton 1975; Boulton 1979; Boulton 1987; Boulton and Jones 1979; Boulton and Hindmarsh 1987). Since the work is still in its infancy the exact sedimentary processes which act beneath and at the glacier base are still not fully understood. The Halton Till has been interpreted as a subglacial till deposited by lodgment processes (Dreimanis and Terasmae 1958; Karrow 1967; Babaris 1973; Eyles and Eyles 1983; Eyles 1986). This classification of the Halton may in fact be premature due to the

FIGURE 1: A summary of the Scarborough Bluffs stratigraphy accompanied by published radiocarbon and thermoluminescence dates (y.b.p) The Halton Till rests on underlying sediments with a marked erosional contact accompanied by glacitectonic structures (from Eyles, 1986).

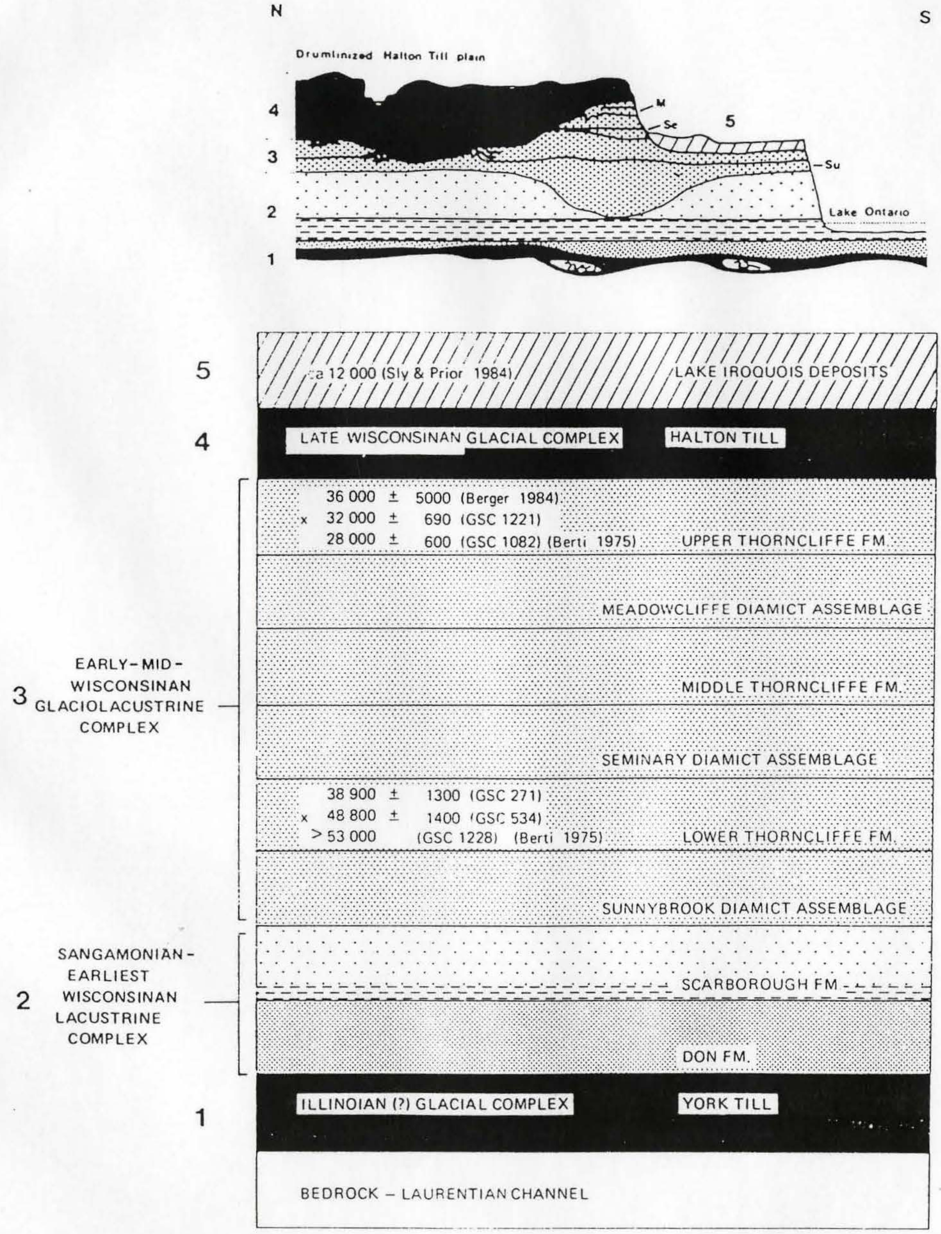
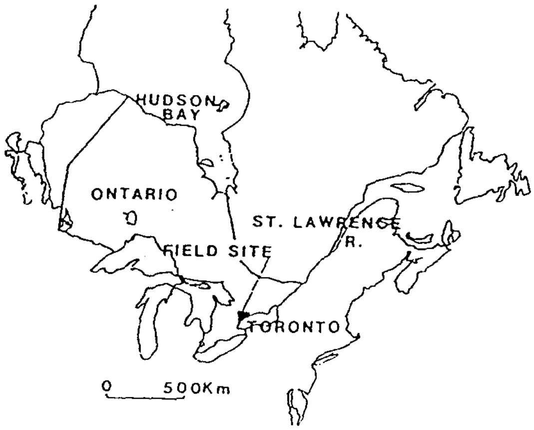
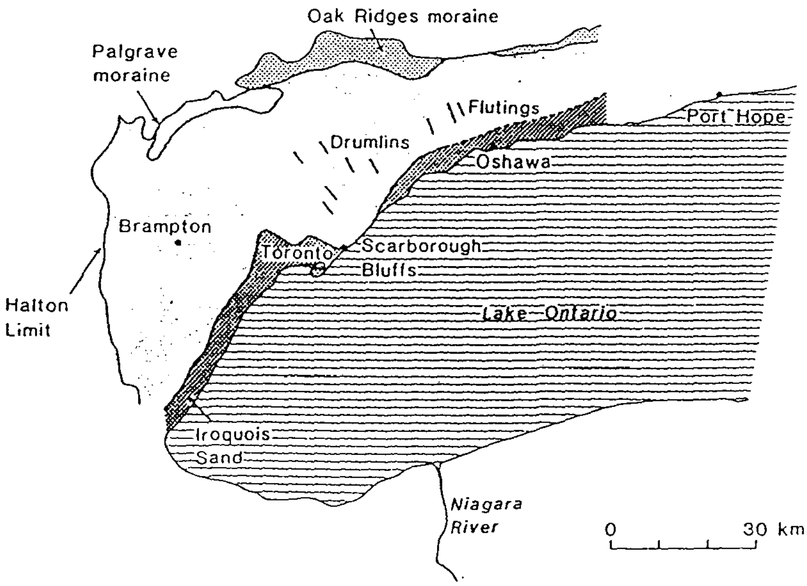

N
S
Drumlinized Halton Till plain
4
3
2
1
M
Sc
5
Su
Lake Ontario
5
ca 12 000 (Sly & Prior 1984)
LAKE IROQUOIS DEPOSITS
4
LATE WISCONSINAN GLACIAL COMPLEX
HALTON TILL
36 000 ± 5000 (Berger 1984)
x 32 000 ± 690 (GSC 1221)
28 000 ± 600 (GSC 1082) (Berti 1975)
UPPER THORNCLIFFE FM.
MEADOWCLIFFE DIAMICT ASSEMBLAGE
3 EARLY-MID-WISCONSINAN GLACIOLACUSTRINE COMPLEX
MIDDLE THORNCLIFFE FM.
SEMINARY DIAMICT ASSEMBLAGE
38 900 ± 1300 (GSC 271)
x 48 800 ± 1400 (GSC 534)
> 53 000 (GSC 1228) (Berti 1975)
LOWER THORNCLIFFE FM.
SUNNYBROOK DIAMICT ASSEMBLAGE
2 SANGAMONIAN-EARLIEST WISCONSINAN LACUSTRINE COMPLEX
SCARBOROUGH FM.
DON FM.
1
ILLINOIAN (?) GLACIAL COMPLEX
YORK TILL
BEDROCK – LAURENTIAN CHANNEL

FIGURE 2: Surficial distribution of the Halton Till along the western end of Lake Ontario. The western 'Halton limit' borders on the edge of the Niagara escarpment and the eastern limit remains undefined (from Sharpe, 1988).



HUDSON BAY
ONTARIO
ST. LAWRENCE R.
FIELD SITE
TORONTO
0 500Km



Oak Ridges moraine
Palgrave moraine
Flutings
Port Hope
Drumlins
Oshawa
Brampton
Toronto
Scarborough Bluffs
Halton Limit
Lake Ontario
Iroquois Sand
Niagara River
0 30 km

FIGURE 3: Correlation of the Leaside Till in the Scarborough area with those tills to the west near Hamilton. The name 'Leaside Till' has been replaced by the term 'Halton Till' and the upper and lower distinctions are now rarely used (from Karrow, 1967).

Suggested Correlation Chart

			HAMILTON-GALT	SCARBOROUGH
WISCONSINAN	LATE	Mankato	Halton Till	Leaside Till (upper)
			Wentworth Till	Leaside Till (lower)
		Cary	Port Stanley Till	
		Tazewell	Catfish Creek Till	
				Meadowcliffe Till
				Seminary Till
	EARLY		Canning Till (?)	Sunnybrook Till
ILLINOIAN				York Till

lack of understanding of subglacial processes and the conditions under which deposition occurs.

There has traditionally been little attention given to the Halton till by geologists and as a result there is a noticeable lack of literature in scientific papers and government reports. Most of the information on the till is in the form of geotechnical reports held by private consulting companies and government offices concerned with road and bridge construction (eg. Ministry of Transpotation and Communication; Toronto Transit Commission).

Recently there has been several projects started by consulting companies in locating sites for hazardous waste landfills. Increasing demand for environmentally safe landfills has resulted in the Halton Till being reccommended for many of these potential sites. Increasing construction in the form of roads, subways, residential and commerical development are all located on the Halton Till. For safe, economical construction practices it is important to understand the lithological chatacteristics, geometries and depositional environment of the Halton Till.

While most European governments have consolidated well log and construction bore hole data into a central geological data base those in Ontario remain scattered among various non-government agencies which control access to these reports.

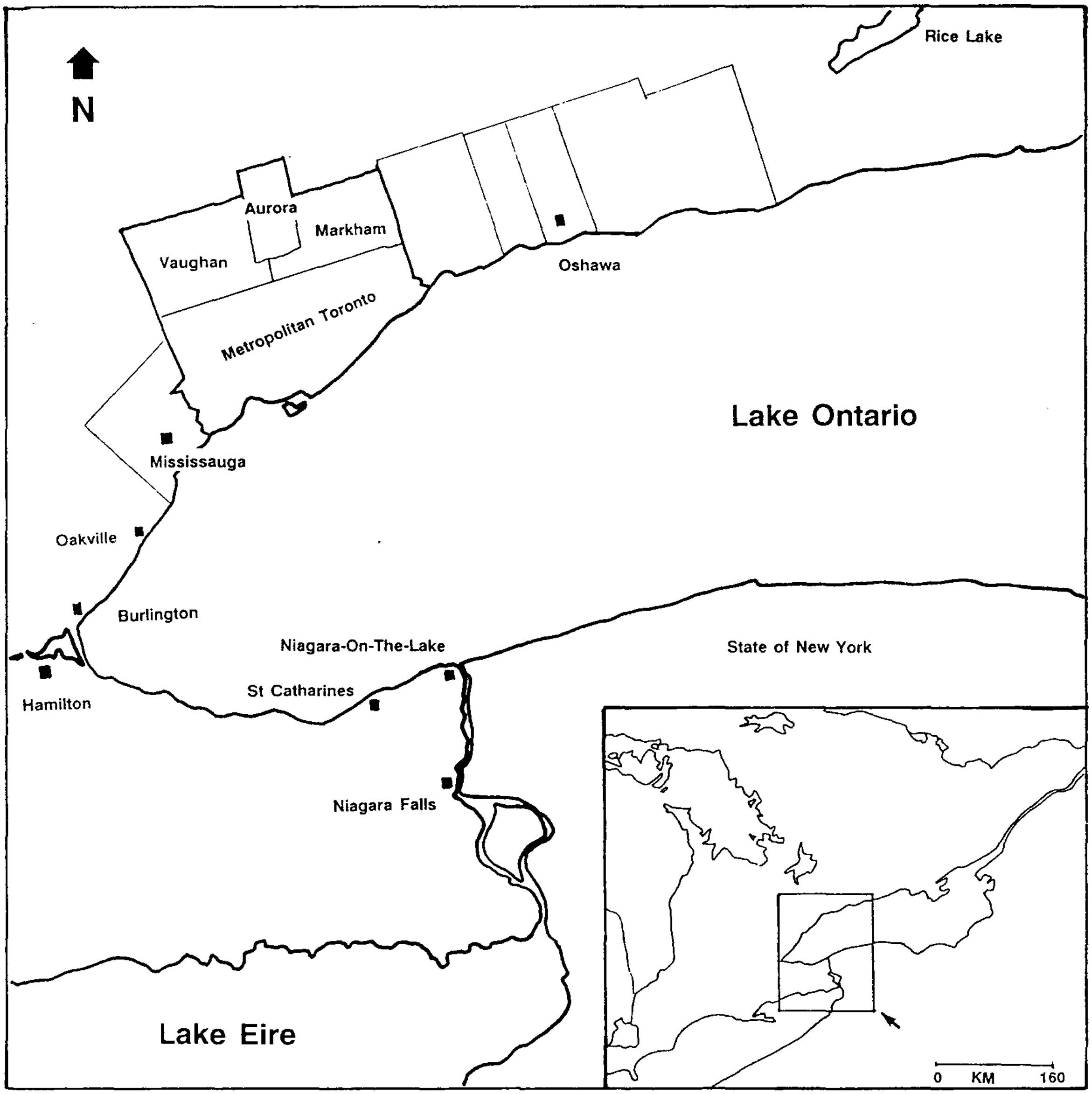
1.2 Objectives

Little is understood about the three dimensional geometry of the Halton Till in the Toronto area. There is poor inland surface exposure of the Halton Till with most outcrops occurring along bluff gullies or rivers which empty into Lake Ontario. These lakeshore areas are limited and vary widely in the thickness of sediments exposed at each site. The correlation of subsurface well logs with these surface exposures will provide access to previously unobtainable information on the distribution and geometry of the Halton Till.

A geological database is needed to compile the information contained in both scattered drill hole records and lakeshore exposures. Once compiled and continiously updated the database would enable the rapid production of informative pictorial representations of the complex stratigraphies associated with the Halton Till. Information of this nature is invaluable for sedimentological and hydrological modelling and essential for landfill and constrution site evaluation.

During the summer of 1989 the author was responsible for the creation and organization of geological data base for use with the software package SURFER. The area of concentration extended from the southern limits of the Oak Ridges Moraine Complex to the shore of Lake Ontario. It would include the municipalites of Metro Toronto (Etobicke, Scarborough, North York, East York, York), Pickering, Vaughan, Markham, and Aurora **(figure 4)**.

FIGURE 4: Data base area map showing political boundaries along the lakeshore. The data base is concentrated in the municipalities of Vaughan, Richmond Hill, Markham and Metropolitan Toronto with parts of western Pickering and eastern Mississauga included.


N
Rice Lake
Aurora
Markham
Vaughan
Oshawa
Metropolitan Toronto
Lake Ontario
Mississauga
Oakville
Burlington
Niagara-On-The-Lake
State of New York
Hamilton
St Catharines
Niagara Falls
Lake Eire
0 KM 160

The main emphasis of the data base would be two-fold:

1) to present regional maps showing bedrock elevation for the area in an effort to define preceisely the extent of bedrock channels which are thought to extend beneath the field area,

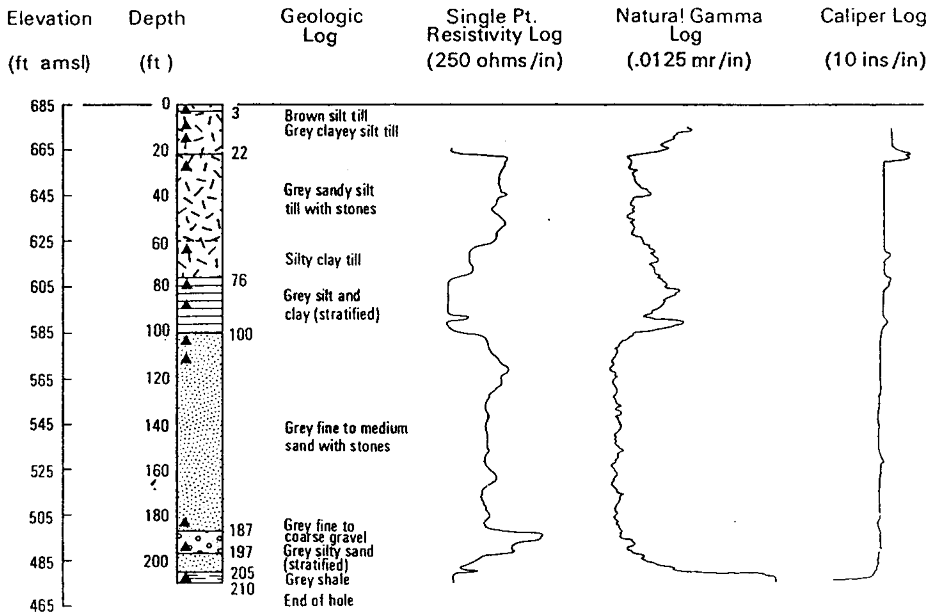
2) to produce isopach maps showing the regional thickness of the Halton Till in order to determine the regional geometry of the unit and to establish its relationship with variations in bedrock elevation.

This subsurface information is widely scattered (see chapter 2) among Ontario consultancy firms and various Municipal, Provincial and Federal departments (eg. McCellan Ltd.; Toronto Transit Commission; Ontario Ministry of Transportation and Communication; Ministry of the Environment). This information can be found in the form of water well records, descriptions of drill hole borings, resistivity logs, natural gamma logs and caliper logs **(figure 5)**.

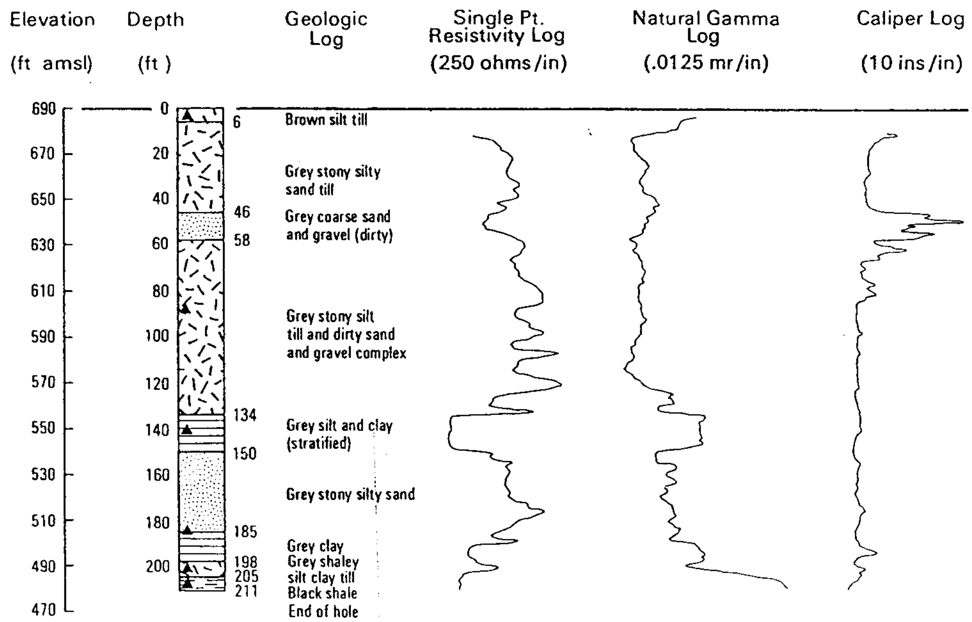
Information from these sources was collected at scattered offices and then entered into a central computer at McMaster University for further processing in which measurements were converted to metric units and U.T.M. coordinates were calculated. Published maps were digitized by the author at the University of Toronto, Department of Geography, under the guidence of Dr. S. Shulte. The equipment used was highly modified from preexisting obsolete hardware and inquires regarding the exact equipment used should be directed to Dr. S. Shulte.

FIGURE 5: A summary of a few of the various well types and logged descriptions available for mapping the subsurface stratigraphy of the Halton Till (from Sibul, 1977).

TEST HOLE 12293* DUFFINS-ROUGE BASIN



TEST HOLE 12294* DUFFINS-ROUGE BASIN



* Location shown on Map 6
▲ Split spoon sample

A second phase of the summer activity involved the field documentation of the Halton Till and and its basal contact with underlying substrates. The field sites were restricted by accessibility of exposures and limited to the areas of Guildwood on the Scarborough Bluffs and the area near Port Darlington **(figure 6)**.

The objectives of this part of the study were:

1) to obtain detailed facies descriptions of the Halton till, including information on grainsize, clast density, shape, size and lithology,

2) to produce a sedimentological classification scheme similar to those used by facies modelers,

3) to establish the nature of deposition of the Halton till and possibly its geological history,

4) to comment on the implications of this study for,

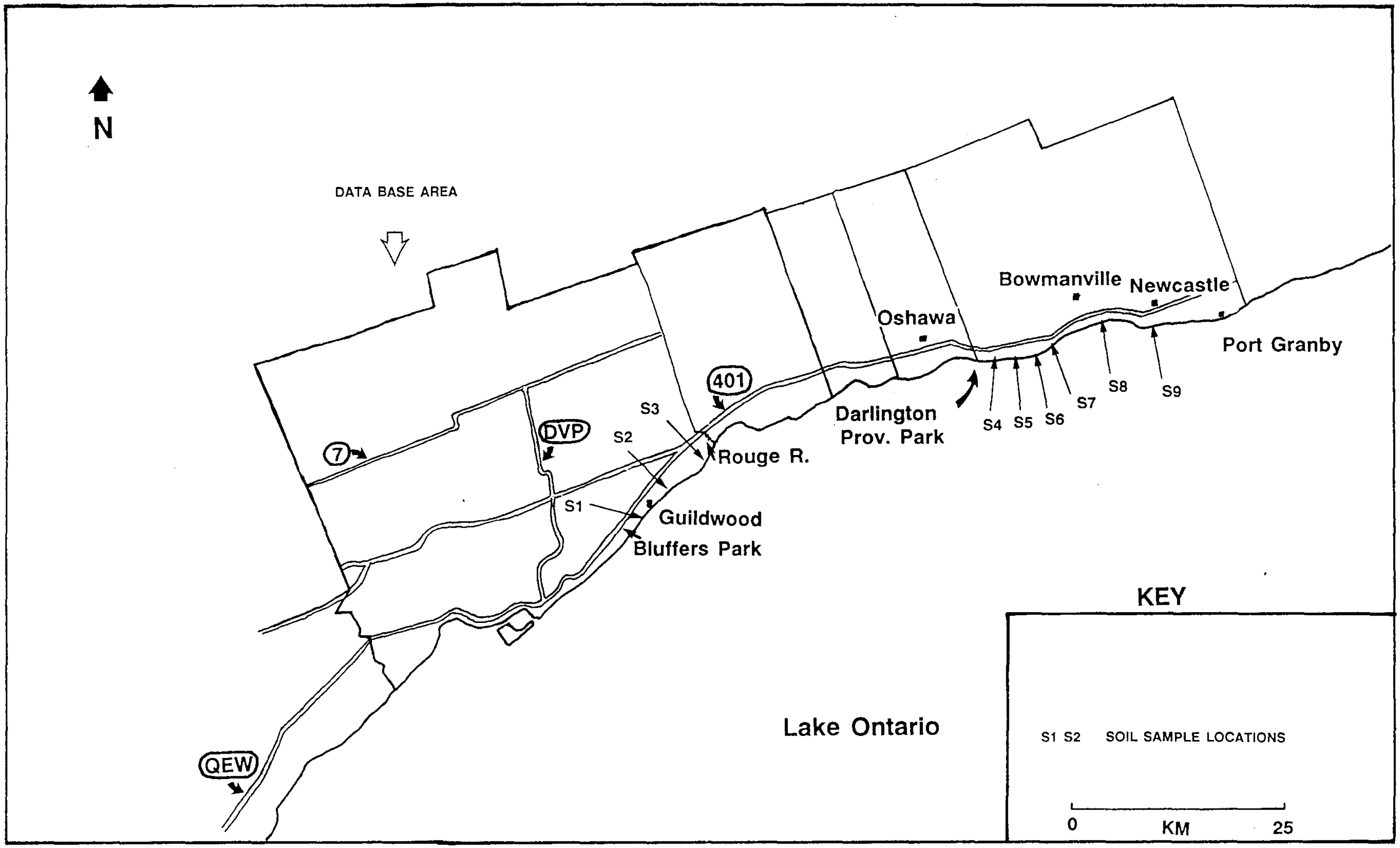
(a) the application of large scale computer assisted basin wide analysis of Quaternary sediments combined with local outcrop description and,

(b) evaluation of the Southern Ontario region as a documented field site where Boulton and Hindmarsh's (1987) deformation till theory can be tested.

1.3 Previous Halton Till Work and Stratigraphy

Most of the information collected on this till sheet has been in the form of isolated site studies by private commercial consulting companies or government departments which deal with road

FIGURE 6: Locations of field sites used in the documentation of the basal contact of the Halton Till. Soil samples from a the vertical exposure were also collected at each of these sites.


N
DATA BASE AREA
7
DVP
401
QEW
S1
S2
S3
Rouge R.
Guildwood
Bluffers Park
Oshawa
Darlington
Prov. Park
Bowmanville
Newcastle
Port Granby
S4
S5
S6
S7
S8
S9
Lake Ontario
KEY
S1 S2 SOIL SAMPLE LOCATIONS
0
KM
25

or bridge construction. Most of these construction reports are primarily concerned with geotechnical data and there is little description of the individual lithological units encountered in the exposures.

Previous studies (Karrow, 1967; Karrow, 1972) have presented only a general overview of the areal extent of the Halton till and some site specific information on till thickness. Aside from several maps which show the general surficial Quaternary geology of the Toronto area and theses which are site specific in their examination of the geotechnical properties associated with the tills there is little published data on the Halton till.

Studies on the stratigraphy of the Leaside till (which is considered to be equivalent to the Halton till in this report) by Dreimanis and Terasmae (1958) divided the till into an upper and lower Leaside seperated by a short retreat phase marked by a 'kamy sand and gravel seam'. Differences in grainsize were also ecountered between the upper and lower tills as were pebble concentrations. This seperation of the Leaside into two differnt till sheets was never clearly accepted because "As a general rule, the tills are similar, but the lower one is sometimes coarser and stonier than the upper, **although the reverse has been seen too.**" (Karrow, 1967, p. 48.).

Karrow (1967) suggested that the sand seam identified by Dreimanis and Terasmae (1958) was present in some locations but the till itself exhibited no lithological differences which warrented its seperation into two distinct tills. Karrow (1972) has gone further to say that since there is no clear break betwen the two tills, (on both a local and regional scale) the lower Leaside may regionally correlate to the Wentworth till in the Hamilton area and the upper till may correlate to the Halton till in the Halton area.

Fabric analysis by Ostry (1962) and Dreimanis and Terasmae (1958) show confilicting directions of ice flow. Ostry's (1962) results showed consistent northwest trends for clast alignment in both the upper and lower till while work by Dreimanis and Terasmae (1958) showed varying directions for clast alignment in the lower unit. Clast orientations done by Karrow (1967) (who ignored the till division) suggest a northwest trend parallel to flute markings and the trend of the long axis of drumlins.

Karrow (1972) also noted that grainsize variation did exist in the Leaside till in the central part of the Scarborough Bluffs where varved clay underlies the till. Elsewhere in the till there was no apparent variation in sand/silt/clay ratios. Carbonate ratios in his report are highest in those areas of the east where outcrops of limestone exist in the Oshawa and Whitby area.

The lack of datable material in the Halton till has resulted in its age being determined from relative dating techniques. Postglacial lake deposits and underlying Thorncliffe Fm. dates have identified the Halton Till as the last ice advance in Southern Ontario. This advance occurred during the Late Wisconsin depositing the Halton Till probably between roughly 20,000 and 18,000 years before present (y.b.p.).

Previous work by Dreimanis and Terasmae (1958) had suggested that the Halton till may be the last of a succession of glacial advances out of the Lake Ontario basin. These advances deposited a series of 'basal' tills which included the Sunnybrook, Seminary, Meadowcliffe and Halton tills. Babaris (1975) went further and assigned correlations between tills in the east near Bowmanville to those of the Scarborough succession. These included the Sunnybrook, Meadowcliffe and Halton tills in the Scarborough Bluffs corresponding to a 'Lower', 'Middle' and 'Upper' basal till in the east. The corresponding changes in clay content from the Sunnybrook to the Halton till were suggested to be the result of a decreasing clay volume in the lake basin due to continual ice advances scouring the lake bottom.

More recent work by Eyles et al. (1985) and, Eyles and Eyles (1983) reports a total lack of evidence for grounded ice in the sedimentary record of the Sunnybrook, Seminary and Maedowcliffe tills. Contacts between all elements of the stratigraphy of the Scarborough Bluffs were found to be transitional or interbeded except the Halton which was erosive. The Scarborough sequence is thought to be the preserved bottom stratigraphy of a large lake which occupied part of the Ontario basin (Eyles and Eyles, 1983; Eyles et al., 1985). The different facies preserved in the sequence suggest repeated basinward progradation of a wide sandy delta body over glaciolacustrine diamicts deposited below floating ice derived from the glacier (most probably in the form of bergs).

The Halton till is assumed by Eyles et al. (1985) to be a coarse-grained lodgment till deposited by a grounded ice sheet.

1.4 Previous Work on Glacial Tills

There has traditionally been two differing schools of thought of glacial deposition each with differing techniques of relating glacial processes and the sediments produced by those processes. Those schools of thought centered around the study of ancient Pleistocene deposits and the study of modern glaciers and the deposits being presently produced. Each of these schools traditionally inferred their own processes without coordinating their findings with those of the other school.

As a result several hypothetical models of glacial deposition have been erringly produced (Goodchild, 1875; Carruthers, 1947). Landmark papers on sediment emplacement beneath the glacier base (Lamplugh, 1911), the establishment of the relationship of glacier activity to sedimentation (Tarr and Martin, 1914), and the production of glacitectonic structures from glacier activity (Grip, 1929) were produced by those scientists who combined theoretical experimentation with field work from both recent and ancient diamicts. By combining previously seperate fields of study (recent verses ancient diamicts) constructive advances in glaciology were slow at first.

Fortunately the disintigration of the differing schools has rapidly increased since the late 1960's allowing more co-operative efforts between process oriented studies and those documenting the characteristics of Pleistocene glacial sediments. A notable example of these combined efforts involve the theoretical processes whereby subglacial debris could be entrained within a polar glacier

glacier which were proposed by Weertman (1961) and subsequently identified by Kamb and LaChapelle (1964).

Due to the inaccessibility of the modern subglacial environment the exact processes that operate and the sedimentary deposits produced continue to be poorly understood. The 'lodgement' till concept was concieved by Chamberlain (1894) where he suggested this till would be produced due to the frictional interaction of the glacier base and the underlying substrate. This concept was more recently expanded upon by Boulton (1975). The related features of 'flutings' associated with subglacial activities have benn described by Hoppe and Schytt (1953).

The glacier front has also attracted attention with the recent identification of tills developed from the down-wasting and stagnation of the glacier front. Lawson (1979) provides a good review of the 'melt-out till' till first described by Boulton (1972) and the 'flow till' described by Hartshorn (1958).

The production of a 'deformation till' by the shear deformation of subglacial sediment was proposed by Elson (1961). A recent process developed experimentally by Boulton and Hindmarsh (1987) expands on this concept and applies it to areas where thick deposits of deformable substrate are overridden by advancing glacier ice and partly incorporated into the subglacial debris layer. This may have considerable impact on those areas of North America which experienced multiple occupations by glacier ice or which have thick interglacial deposits of unlithified sediments. Shear deformation of <u>subglacial</u> sediments has been documented by Boulton (1979) but this is the first theoretical model where advancing ice does not push unconsolidated sediments before it in an end moraine arrangement.

The Halton Till is characteristically a widespread diamict containing a generally sandy texture (though highly variable) and variable concentrations of bullet shaped clasts. The basal contact is erosive with strong glacitectonic deformation structures (eg. undulating contact and shearing in sediments underlying the Halton Till) and evidence of incorporation of sediments which have been overridden. The Halton Till has a surfical expression often in the form of flutes and drumlins which have been used as strong evidence for the subglacial lodgement origin of the till (Dreimanis and Terasmae, 1958; Karrow, 1967; Karrow, 1972; Eyles and Eyles, 1983).

The origin of drumlins and flutes as a product of subglacial deformation has been popular (Smalley and Unwin, 1968) though not unchallenged (Shaw, 1983). Boulton and Hindmarsh (1987) report recent evidence that suggests the deformation of sedimentary sequences (eg. outwash) may lead to the formation of drumlinoid features as a result of sediment strain response **(figure 7)**. It is the interaction of high water pressures in subglacial sediments (produced from melting at the glacier base) with underlying stratigraphies that is the focus of deformation till investigations (Boulton and Jones, 1979; Boulton and Hindmarsh, 1987). If the effective water pressures in these sediments are sufficiently low to make them softer than ice, a complex interaction with glacier dynamics may result **(figure 8)**. This interaction between the glacier base and underlying sediments will dramatically affect the structural characteristics, sediment distribution and landforms

FIGURE 7: Hypothetical representation of the response of material with differing permeability to subglacial shear forces. (a) Proglacial outwash on a fine grained surface. (b-c) Progressive drumlin development from the coarse grained sediments. Originally transverse lines in the outwash demonstrate the deformation of the sediment mass (from Boulton and Hindmarsh, 1987).

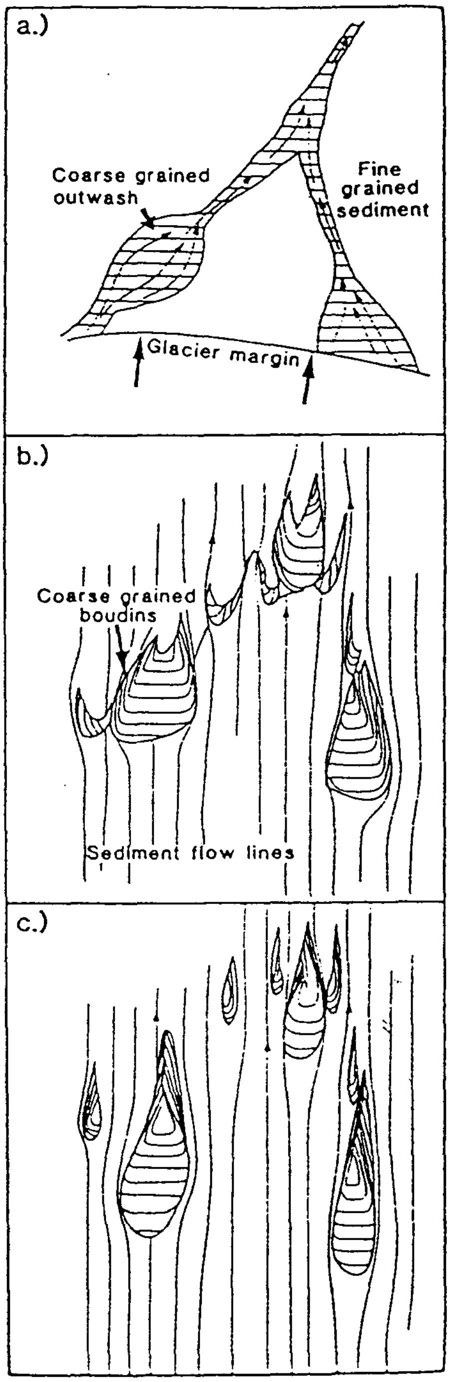
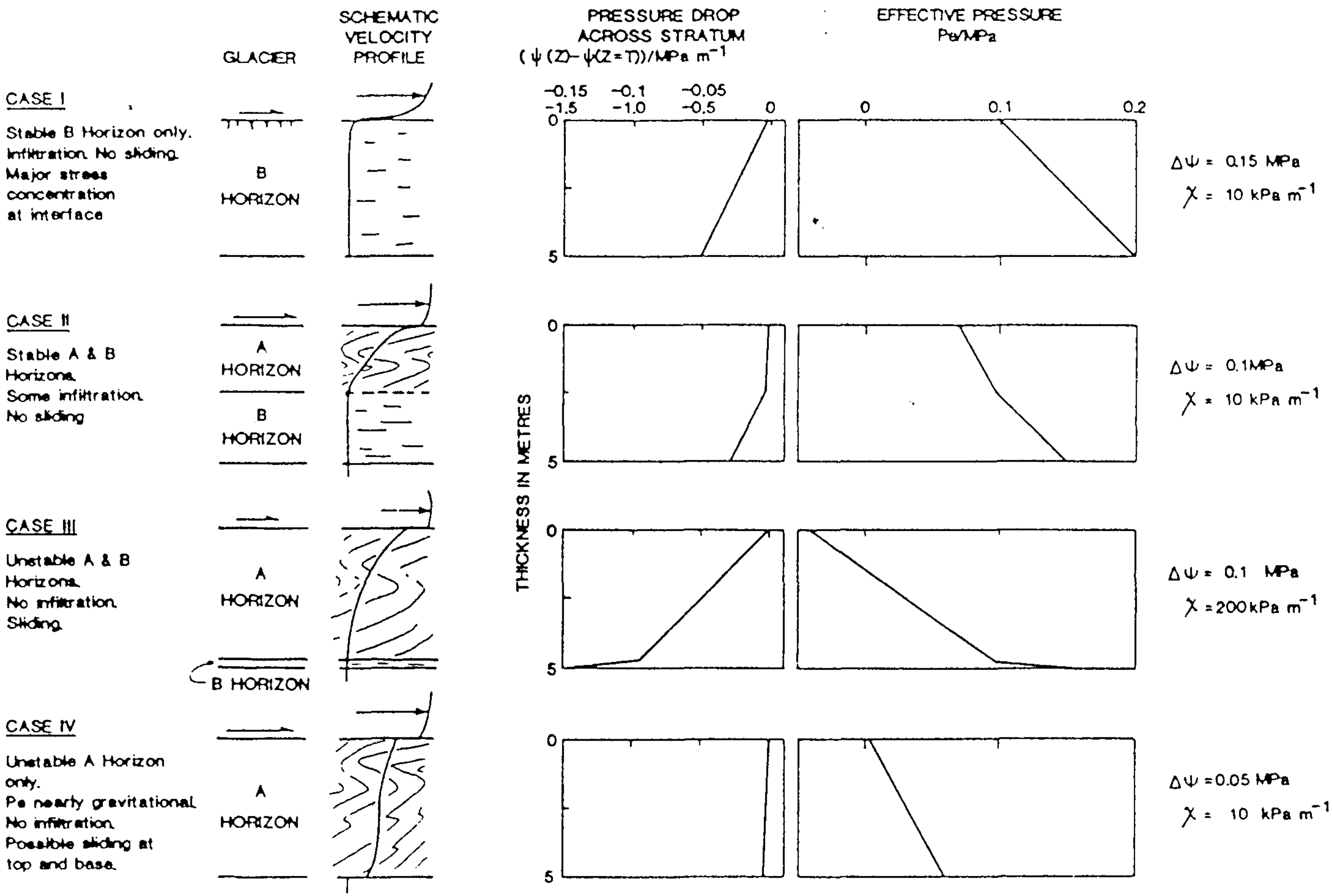

a.)
Coarse grained outwash
Fine grained sediment
Glacier margin
b.)
Coarse grained boudins
Sediment flow lines
c.)

FIGURE 8: Four different modes of deformation of subglacial beds related to changes in potential across the stratum $\Delta\Psi$ and potential gradient in the undeformed sediment $X = \mu m / K_B$ with constant shear stress (from Boulton and Hindmarsh, 1987).



In all cases $K = \frac{I - C}{\eta} = 0.1$ MPa, $G = (1-n)(P_s - P_w) = 10$ kPa m^{-1}

produced by the glacier (Boulton and Hindmarsh, 1987).

The Halton Till exhibits abundant evidence for a subglacial zone of deformation accompanied by the infiltration of large volumes of basal meltwater which softened underlying sediments producing channel-like slurry flow features within the Halton Till. These characteristics are stressed in Boulton and Hindmarsh (1987) as criteria for the identification of deformation tills. The deformation till model is touched upon by Boulton (1979), Boulton and Jones (1979), Boulton and Hindmarsh (1987) and it is the aim of this paper to examine the Halton till as a deformable substrate --a deformation till.

Those characteristics of the Halton Till which provide evidence of a deformation till will be explored in this paper by examining the three dimensional geometry of the Halton Till and it's relationship to bedrock topography (chapters 2 and 5). Further evidence will be provided by the field documentation of sedimentary structures, the basal contact (chapter 3) and grain size distribution (chapter 4).

CHAPTER 2

FIELD AND LABORATORY TECHNIQUES

2.1 Field Logging and Section Description

The field sections were examined in detail over a period of two weeks approximately 72 hours after rain events. The first week of logging concentrated east of Port Darlington and was performed with the Geology Department Zodiac to gain access to exposed faces which were inaccessible by road. The second week of logging was carried out in the Scarborough-Metro Toronto area where outcrop exposure was more easily accessible **(figure 6)**.

The sections were selected on the nature of the exposure. Only those sites where the Halton Till's basal contact was seen was described. It was attempted to sample as wide a variety as possible of contacts and the different sediment types which immediately underlie the Halton Till. Ravine exposures and those faces which were being undercut by wave action along the Lake Ontario shoreline proved to be most useful. It was attempted to space the sample sites equally along the lakeshore but poor outcrop and restricted access to some areas made this impossible.

The sections were first cleaned of slope wash and weathered material then measured and logged using the lithofacies code developed by Eyles and Eyles (1983). This non-genetic lithofacies code was used to allow the rapid logging of field sections. Other significant sedimentary structures were also noted as were bed thicknesses, geometry and the nature of the contacts **(figures 9 and**

FIGURE 9: Logged sections which accompany the sites noted in figure 6. Site numbers are in the upper right of the drawn section (eg. S1). Soil sample location sites are along the left side of the drawn section (eg. 1). Lithofacies codes along the right edge of the sections follow those described in Eyles and Eyles (1983).

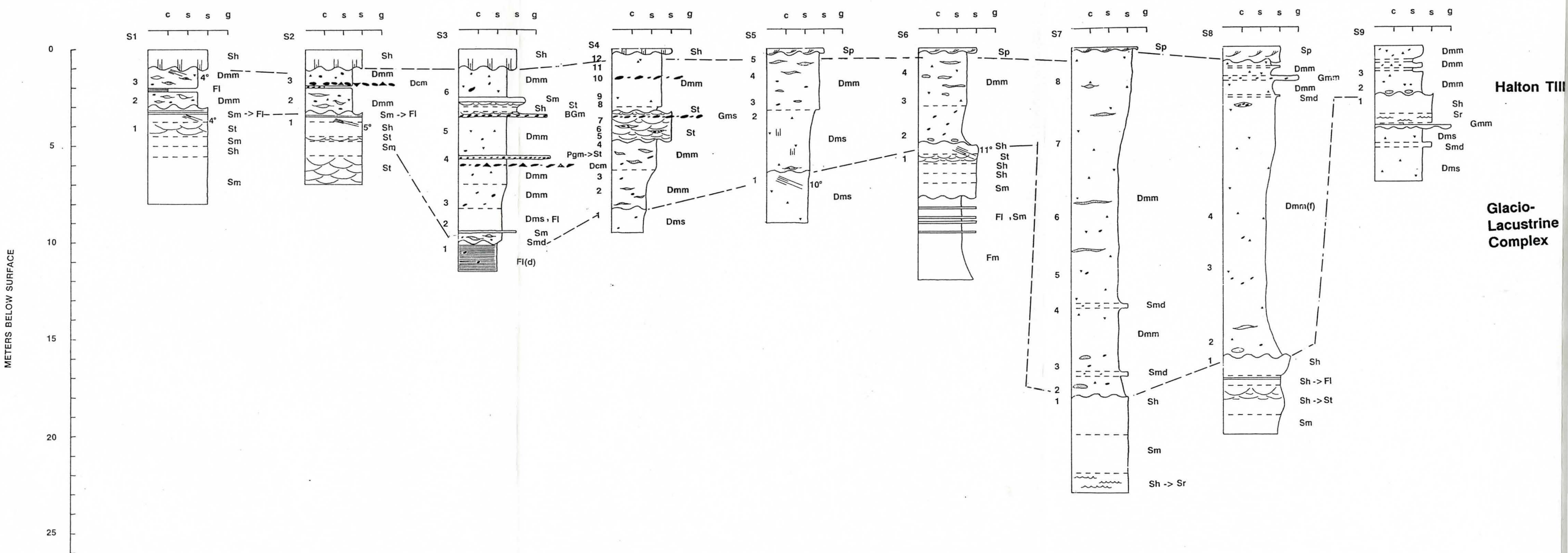
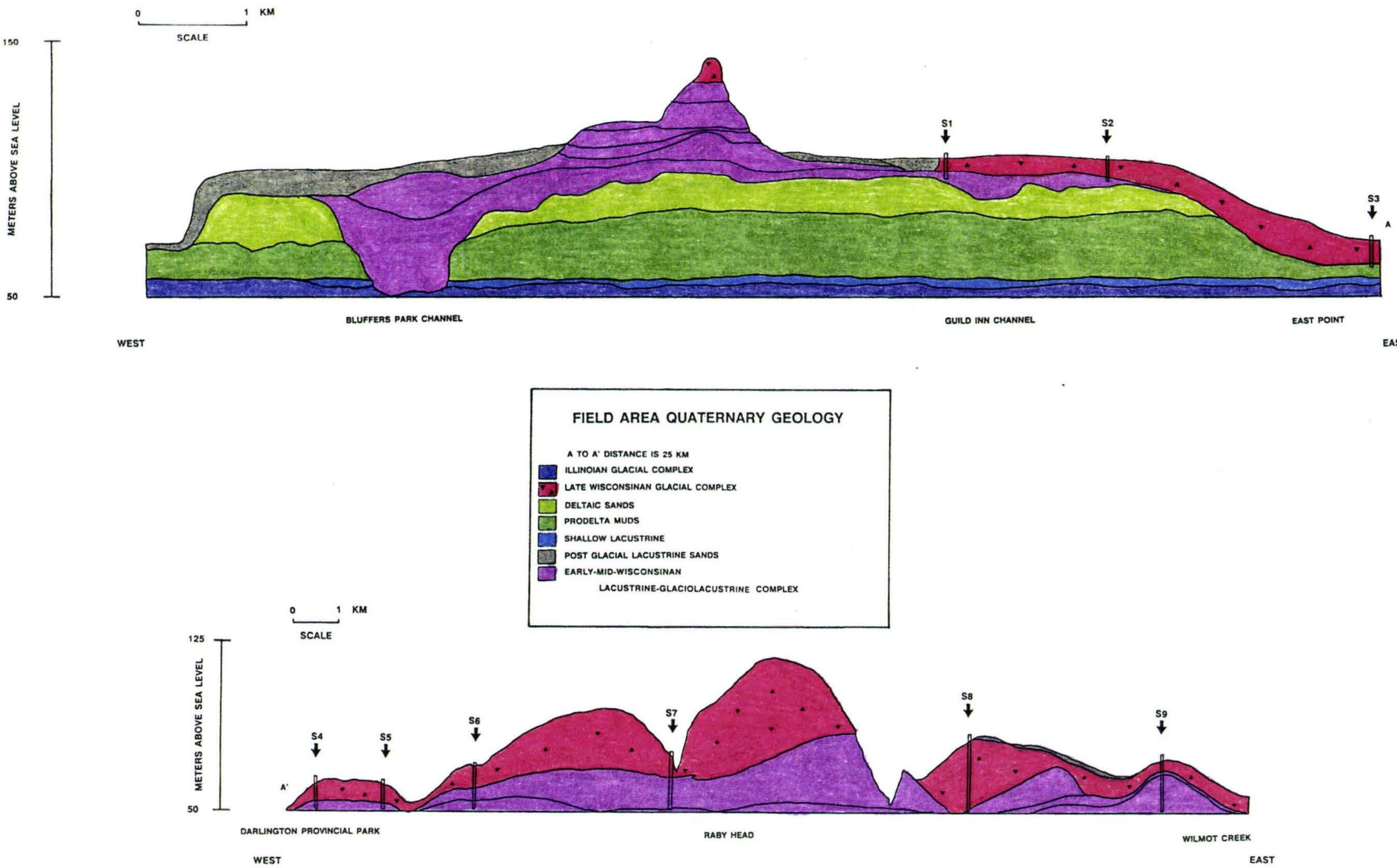

METERS BELOW SURFACE
0
5
10
15
20
25
c s s g
S1
S2
S3
S4
S5
S6
S7
S8
S9
Sh
Dmm
Fl
Sm -> Fl
St
Sm
Dcm
Sm -> Fl
BGm
Pgm->St
Dms, Fl
Smd
Fl(d)
Gms
Dms
Sp
Fl, Sm
Fm
Smd
Sh -> Sr
Gmm
Dmm(f)
Sh -> St
Sr
Halton Till
Glacio-
Lacustrine
Complex

FIGURE 10: Geometry of the Halton Till and underlying sediments. Logged sections are marked on the figure (eg. S1). Note the changes in both vertical and lateral scales for the upper and lower diagrams. Compiled from Eyles and Eyles (1983) and field work.


0 1 KM
SCALE
150
50
METERS ABOVE SEA LEVEL
S1
S2
S3
A
BLUFFERS PARK CHANNEL
GUILD INN CHANNEL
EAST POINT
WEST
EAST
FIELD AREA QUATERNARY GEOLOGY
A TO A' DISTANCE IS 25 KM
ILLINOIAN GLACIAL COMPLEX
LATE WISCONSINAN GLACIAL COMPLEX
DELTAIC SANDS
PRODELTA MUDS
SHALLOW LACUSTRINE
POST GLACIAL LACUSTRINE SANDS
EARLY-MID-WISCONSINAN
LACUSTRINE-GLACIOLACUSTRINE COMPLEX
0 1 KM
SCALE
125
50
METERS ABOVE SEA LEVEL
A'
S4
S5
S6
S7
S8
S9
DARLINGTON PROVINCIAL PARK
RABY HEAD
WILMOT CREEK
WEST
EAST

10).

2.2 Grain Size Sampling

Sediment samples were taken at approximately one meter vertical intervals from the exposed outcrop face while the field sections were being logged. This spacing was highly dependent on the complexity of the internal structure of the till exposure (ie. multiple channels, rapid changes in clast concentrations). The sediment samples chosen were representative of the till at that height and 'abnormal' variations in the till such as fluvial gravel pods were avoided.

The samples were taken by driving a tube shaped sediment sampler into the freshly exposed till face. Approximately 1.5 kg of sample was taken at each individual height in the section and the location of the sample relative to the stratigraphic column drawn at each location was noted. The unit type immediately beneath the Halton Till was also logged and a sample was taken approximately one meter beneath the contact. Where the contact was gradational and not distinct, samples were taken at 0.5 to 1.0 meter intervals, depending on the total vertical height over which the change in facies occurred. The number of samples taken at each location varied from three to thirteen depending on the complexity and the thickness of the exposed till section.

The equipment used in gathering the sediment samples is listed in Appendix I.

2.2.1 Laboratory Analysis of Sediment Samples

The mechanical analysis of the sand sized particles was carried out at Mc Master University in the laboratory of Dr. B. T. Bunting. Each sample obtained from the field work was crushed into pieces smaller than one cm cubes. The sample was then divided further into two sub-samples approximately equal in weight. Both of these 'sub-samples' were then dried in a soil oven for 24 hours at 105 degrees Centigrade, weighed and then processed separately using the procedure below to determine the variation within each sample.

Each sample was first allowed to soak in a solution of distilled water and 5% Calgon (by weight) for three days to allow clay particles to separate from clasts and nodules. The samples were agitated during this period for approximately five minutes every six hours. The samples were then wet sieved using distilled water and standard wet sieving pans set in a column at 0.5 phi intervals. The column of pans ranged in phi size from -2.00 to +4.00. A large bucket was placed beneath the pans to catch the water and fine grained sediment passing through the lower +4.00 phi pan.

Each phi size was then collected and dried in a separate crucible in a soil oven for 24 hours at 105 degrees Celsius. The dried soil was then weighed and the phi size noted. The suspension of silt and clay which was collected in the bucket was then reduced by evaporation to a 1.250 litre sample. This was then cooled and then agitated in a manner which suspended both clay and silt particles. A representative sample 250 ml in size was then taken for fine grain size analysis. The remaining one litre suspension was then held in reserve to be reduced further if the 250 ml sample proved to be unacceptable for further analysis.

Mechanical analysis of the silt and clay particles was carried out at the Scarborough campus at the University of Toronto in the lab of Dr. N. Eyles. Each of the 250 ml samples was agitated using a mechanical stirring bead for five minutes at high speed to suspend the clay and silt particles. The stirring rate was reduced and the sample was passed through a sedigraph which calculated the silt to clay ratio. In order for the sample to be properly processed the concentration of the suspended sediments had to be 19 (+/-1)% by volume. If the sample proved to be too dilute the one litre sample held in reserve was reduced to the appropriate concentration. All sedigraph work was performed by myself under the supervision of Mike Kerr.

The Micromertics 500 ET Sedigraph determines the ratio of silt to clay by passing a continuous stream of the suspension through an enclosed transparent chamber. When a switch is depressed by the operator the pump forcing the suspension through the chamber is stopped and the sample enclosed in the chamber is then bombarded with X-rays. An ink pen then moves across and down a graph marked percent (0-100) verses grain size in um. It was assumed that 2um equalled 8 phi (minimum silt size). The details used to operate the sedigraph are outlined by Duncan and Lahaie (1979).

The dry soil obtained from the Mc Master laboratory was then weighed and compared to the original dry weight of the sample (before being soaked in the Calgon solution). The weight missing was assumed to represent to total weight of the silt and clay component of the till. It was also assumed that the density of silt was equal to that of clay so that the ratio obtained from the sedigraph would represent the true ratio of silt to clay in the combined silt plus clay weight of the till. The total silt and total clay weights were then indirectly calculated from the sedigraph ratios and the combined silt and clay fraction by weight of the sample.

Each of the sub-samples were then plotted on a logarithmic curve and analyzed using statistical techniques by a program called GRAINSIZE88 written in Turbo Pascal (created by F. Bursette) and later modified by this author.

The exact equipment used in the laboratory work is listed in Appendix I.

2.3 Computer Methodology

During the summer of 1989 a database was established which would be compatible with a software package from Golden Software Inc called SURFER. The hardware used in the database operation included an IBM compatible AT microcomputer with a 20 megabyte hard drive, 3 1/2" floppy drive, 5 1/4" floppy drive, colour monitor, math coproccesser and a Laserjet series laser printer. Additional hardware support was provided by the McMaster University Geology department's VAX and when laser printer memory proved to be insufficient a Roland x,y (11" by 16") multipen plotter was used for output.

Software used in the database's operation included an VP Planner worksheet, WordPerfect 5.1 and SURFER. Software used on the VAX was primarily in the form of FORTRAN programs for reading Ministry of the Environment water well data from 1/4 " tape drives and then selecting wells that reached bedrock. These were correspondingly called BEDSORT and WELLSORT (see chapter 2.3.1).

A wide variety of data sources ranging from previously published maps to recent construction drilling reports were consulted to collect information on bedrock topography and the thickness of the Halton Till. The bedrock database consisted of primarily a set of U.T.M. grid coordinates, the bedrock elevation (in meters) and the overburden thickness. The Halton Till database contained information on U.T.M. coordinates and the thickness of the till in meters and in feet.

The primary purpose of this data bank is to produce a bedrock surface topography map and an isopach map of the Halton Till. Critical to this effort is the collection of information on the bedrock elevation and till thickness. Overburden thickness was collected for future work on drift thickness variation and the till thickness was recorded in both feet and meters because original documentation used primarily Imperial measurements. Those values given in meters are approximate.

The database will store, manipulate and produce output suitable for work in Quaternary geology in the Toronto region. When the database is expanded in the future it is probable that this centralized work-station will be invaluable in mapping the relatively unexplored subsurface geology of Southern Ontario. This study concentrated on two aspects of the regional subsurface geology, the bedrock topography and the thickness and extent of the Halton Till.

2.3.1 Bedrock Data Collection

The bedrock data file contains four pieces of information on each well which was selected to be included in the mapping project; a U.T.M. easting co-ordinate, a U.T.M. northing co-ordinate, bedrock elevation in meters and overburden thickness in meters. Those wells included in the study were selected from construction drilling logs, water well logs, geologic logs, resistivity logs, natural gamma logs, caliper logs, **(fig. 5)** topographic maps with surface exposures of bedrock and previously published bedrock maps which were digitized by the author.

Not all of the wells contain information on overburden thickness because they were added to the data file from existing older bedrock maps which were digitized (see chapter 1.2) by the author (see sources 2 and 6 below). Information on depth to bedrock was collected from the areas of Metro Toronto, Richmond Hill, Vaughan, Markham and Pickering representing an area approximately 1,500 km^2. Some additional well data were collected from areas outside but close to the boundaries of those areas mentioned above.

TABLE 1:

BEDROCK MAP DATA SOURCES

Approximate number of wells	Source of the Data
1652	1) Ministry of the Environment, Water Well Records for the Regional Municipality of York.
905	2) Metropolitan Toronto Bedrock Contours, Ontario Department of Mines Preliminary Map 102. 1961.
40	3) Toronto Transit Commission Reports for the location of subway lines and their underlying Quaternary Geology (till June 1989).
600	4) Ontario Ministry of Transportation and Communication, Road and Bridge Reports for Metropolitan Toronto, Richmond Hill, Vaughan and Markham (till June 1989).
200	5) Metropolitan Toronto Works Department, Road and Bridge Reports for Metropolitan Toronto (till June 1989).
350	6) Map 2276. Boulton Bedrock Topography. Ontario Division of Mines. (undated).
300	7) Ministry of the Environment, Water Well Records for the Regional Municipality of Durham (Pickering).

Approximate Total
Number of Wells = 4047

Due to the wide variety of information sources and the equally varied mediums on which the information was stored the bedrock data were entered into the computer in a number of ways. The bedrock data on published maps were collected by a hand held computer assisted digitizer which automatically calculated the relative U.T.M. co-ordinate of the point with the elevation data the user entered into the computer. Data collected from road and bridge reports were based on the interpretation of when bedrock was reached by work crews. It was assumed that the dolomite, limestone, sandstone and shales encountered by drilling crews trying to establish foundations in bedrock represented the approximate elevation of bedrock in the vicinity.

Bedrock data from Ministry of the Environment was collected in the form of two different mediums --a hardcopy output and a 1/4" tape reel. The hardcopy information was first visually searched to select all wells which reached bedrock. This information was entered manually into the computer. Information recorded on the 1/4" tape reel was screened by a Fortran program called BEDSORT. The program read a county record (eg. York Region) and selected those wells which terminated in or passed through lithologies which were thought to represent bedrock (eg. 'sandstone', 'limestone', 'dolomite' and 'shale').

Those wells selected by the computer were verified by visual inspection and the U.T.M. co-ordinate, depth to bedrock and surface elevation was recorded. The data contained within this computer generated file was then compared to the data stored in the file created from the manually entered data. All duplicate data points were discarded. This information was then entered into a worksheet where the drift thickness and bedrock elevation were calculated by cell operations and stored. Finally the U.T.M. co-ordinates, bedrock elevation and drift thickness was imported into the data base creating a database of 4,047 data points **(Table 1)**.

2.3.2 Halton Till Data Collection

The data entered into the Halton Till data base consists of four pieces of information; a U.T.M. Easting co-ordinate, a U.T.M. Northing co-ordinate, Halton Till thickness in meters and Halton Till thickness in feet. Some wells contain information on the elevation of the base of the Halton Till but it was not possible to obtain this information for all sites. The data base contains information on the areas of Metropolitan Toronto, Richmond Hill, Vaughan, Markham and Pickering a total area of approximately 1,500 km^2.

TABLE 2:

HALTON TILL ISOPACH DATA SOURCES

Approximate Number of Wells	Sources of Information
15	1) Ministry of the Environment, Water Resources Report 8, Ground-Water Resources of the Duffins Creek-Rouge R. Drainage Basins.
30	2) Sharpe, D. R., 1980. Quaternary Geology of Toronto and Surrounding Area; O.G.S. Preliminary Map P.2204, Geological Series. Scale 1:100,000. Compiled 1980.
50	3) Toronto Transit Commission Reports on the location of subway lines and the underlying Quaternary geology (till June 1989).
115	4) Ontario Ministry of Transportation and Communications, Road and Bridge Reports for Metro Toronto, Vaughan, Richmond Hill and Markham (till June 1989).
60	5) Metropolitan Toronto Works Department, Road and Bridge Reports for Metropolitan Toronto (till June 1989).
25	6) Karrow, P.F., 1967. Pleistocene Geology of the Scarborough Area, Ontario Department of Mines, Geological Report 46, 108p.

37 7) Hibbert J.W., Field Sections Measured during summer of 1989.

Approximate Total
Number of wells = 347

Halton Till thickness data collected from published maps were hand plotted onto new U.T.M. co-ordinate maps and their positions were then recorded as well as the thickness of the Halton Till in that vicinity. Till thickness data obtained from road, bridge, T.T.C. and water resource reports were based on interpretation of split spoon drilling records, resistivity logs, natural gamma logs caliper logs and bulk density measurements. Till thicknesses recorded in the field were based on direct observation and measurement of the sediments.

It is important to note that till thickness entered into the Halton Till data base represent the absolute thickness of the Halton till at those specific sites. Only those wells which revealed a distinct basal contact for the Halton Till were considered providing a database containing 347 data points **(Table 2)**.

2.3.3 Computer and Data Manipulation

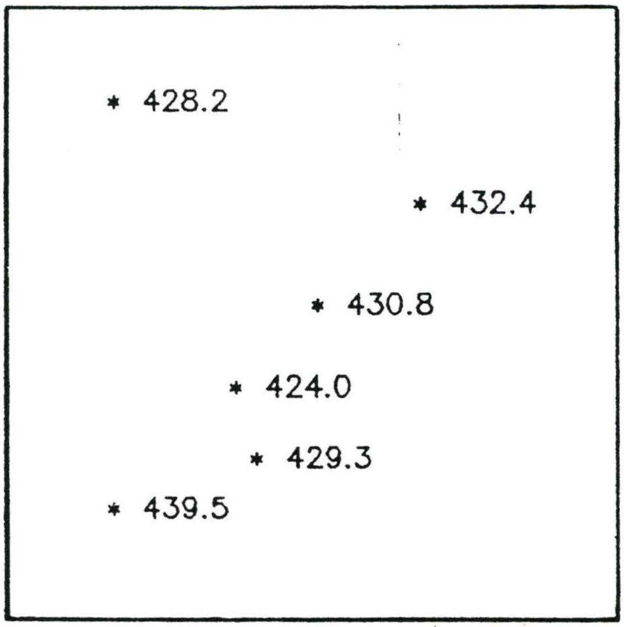
All data collected for the bedrock topographic map and the Halton Till isopach map were entered into the data storage area of the SURFER program. It was from this central xyz data file that further manipulation of the well information occurred through interactive user controlled commands.

The raw data in the data file were first structured into a usable format by the GRID command. The contour maps and three dimensional surface plots required as an end product need a regularly spaced form before they can be created. This form is called a 'grid' and the SURFER software creates this grid from the irregularly spaced data we have collected **(figure 11)**. The GRID command produces a series of vertical and horizontal lines that are closely spaced based on the maximum and minimum xy co-ordinates given by the user **(figure 12)**. The grid program then takes the xyz data stored by the user and fits it to this grid produced from x and y lines. When an xy intersection does not have an absolute value one is interpolated from the xyz values surrounding it **(figure 13)**.

The very accurate interpolation technique known as **kriging** was used in this thesis and the mathematics and manipulations involved in the process are discussed elsewhere in detail (Bancroft and Hobbs, 1986; Burgess and Webster, 1980a; Burgess and Webster, 1980b; Webster and Burgess, 1980; Burgess et al., 1981; Carr et al., 1986; Carr and Bailey, 1986; Journel, 1986a; Journel, 1986b; Puente and Bras, 1986; Solow, 1986; Warnes, 1986).

The TOPO command allows the user to create topographic maps from the regularly spaced xyz data created by the 'grid' command **(figure 14)**. The contours on the map can be easily changed by the user so that a variety of intervals can be seen. The relative position of the data points collected by the user can also be plotted on the map and labeled if desired. The outline of certain objects such as municipal boundaries can also be plotted on the

FIGURE 11: Since the distance from one well to another is not always the same, the data are considered to be irregularly spaced. The table in this figure shows the data as entered by the user into the GRID file from a map represented by the points enclosed in the box. Note the 'holes' or areas lacking data which will have values assigned to them by the gridding process (from SURFER manual).



X coord.	Y coord.	Z coord
1666.7	8332.5	428.2
6666.0	6666.0	432.4
4999.5	4999.5	430.8
3666.3	3666.3	424.0
4000.0	2500.7	429.3
1666.7	1666.7	439.5

FIGURE 12: The data from figure 11 have been gridded and values have been calculated for each intersection of a grid line from the original data. The data is now considered to be regularly spaced or 'gridded' (from SURFER manual).

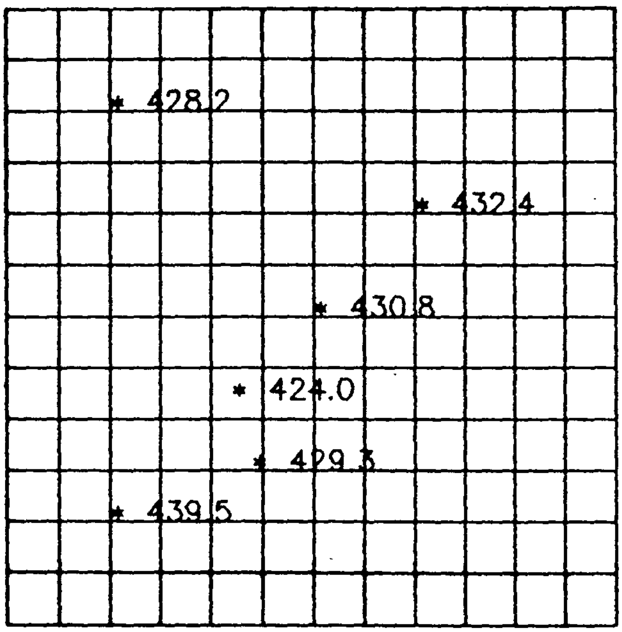
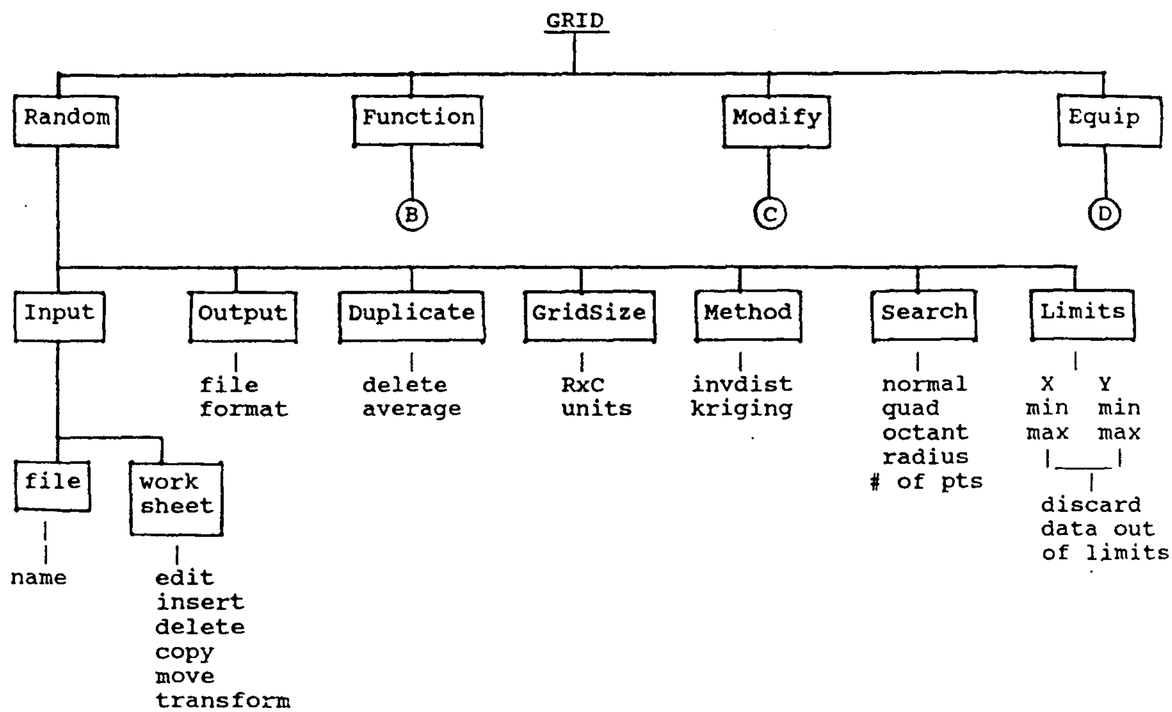
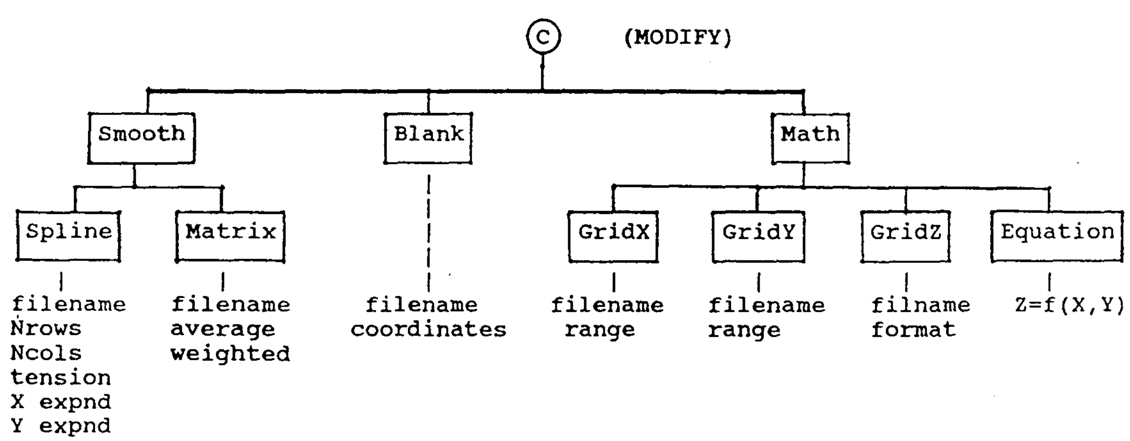
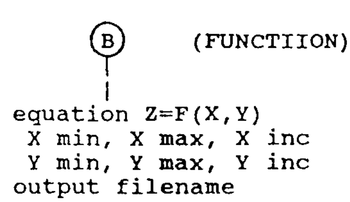

428.2
432.4
430.8
424.0
429.3
439.5

FIGURE 13: GRID's organizational chart representing the network of commands which can be executed by the user in an 'interactive' rather than 'batch' mode (from SURFER manual).


GRID
Random
Function
Modify
Equip
B
C
D
Input
Output
Duplicate
GridSize
Method
Search
Limits
file
format
delete
average
RxC
units
invdist
kriging
normal
quad
octant
radius
# of pts
X min max
Y min max
discard data out of limits
file
work sheet
name
edit
insert
delete
copy
move
transform


C (MODIFY)
Smooth
Blank
Math
Spline
Matrix
GridX
GridY
GridZ
Equation
filename
Nrows
Ncols
tension
X expnd
Y expnd
filename
average
weighted
filename
coordinates
filename
range
filename
range
filname
format
Z=f(X,Y)


B (FUNCTIION)
equation Z=F(X,Y)
X min, X max, X inc
Y min, Y max, Y inc
output filename

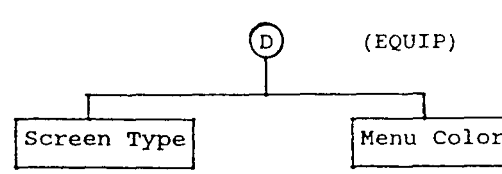
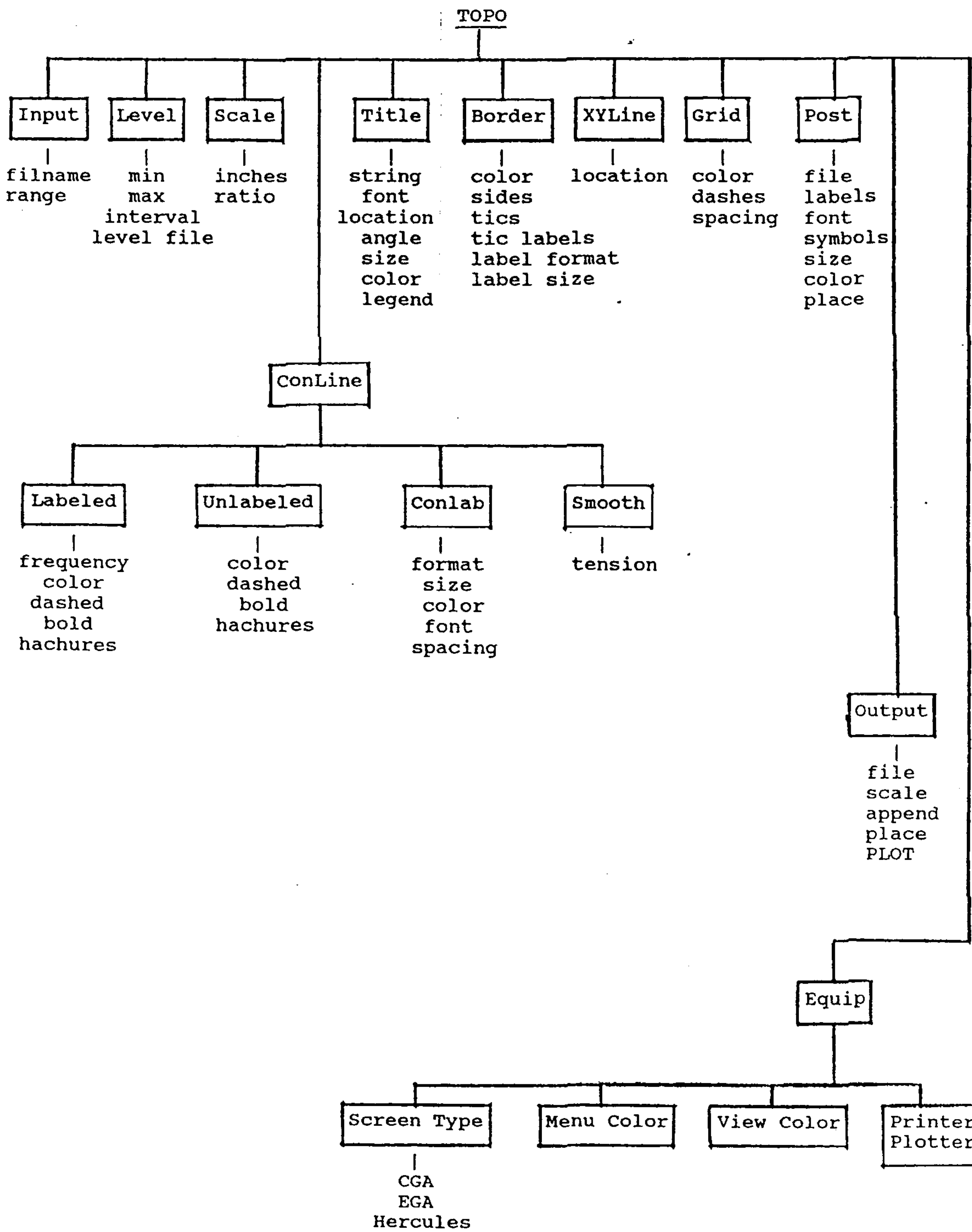

D (EQUIP)
Screen Type
Menu Color

FIGURE 14: TOPO's organizational chart illustrating the commands available to the user for the production of individual topographic maps (from SURFER manual).


TOPO
Input
filname
range
Level
min
max
interval
level file
Scale
inches
ratio
Title
string
font
location
angle
size
color
legend
Border
color
sides
tics
tic labels
label format
label size
XYLine
location
Grid
color
dashes
spacing
Post
file
labels
font
symbols
size
color
place
ConLine
Labeled
frequency
color
dashed
bold
hachures
Unlabeled
color
dashed
bold
hachures
Conlab
format
size
color
font
spacing
Smooth
tension
Output
file
scale
append
place
PLOT
Equip
Screen Type
CGA
EGA
Hercules
Menu Color
View Color
Printer
Plotter

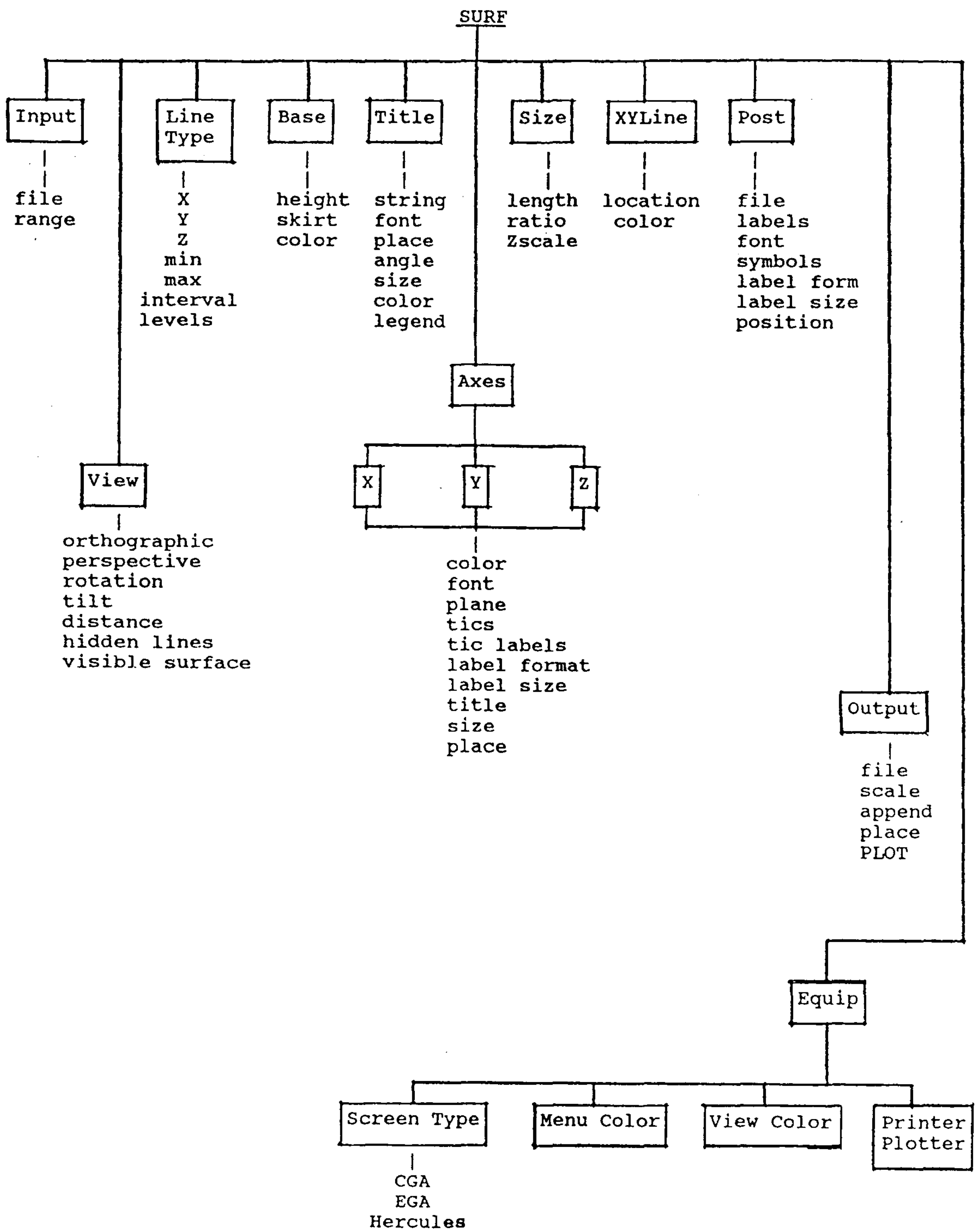
topo map for orientation purposes. Output can be directed to the screen or the plotter by the PLOT command.

The SURF command provides the user with the ability to produce a three dimensional surface representation of a topographic map produced from the data in the grid file **(figure 15)**. These 'fish net' images are block diagrams of the topographic maps seen before. The user can control the design of the image by determining what combination of x,y or z lines will be plotted. The image can be rotated along a 360 degree axis, it can be viewed from a 0 to 90 degree perspective and the image can be moved closer or further from the user upon command. Output can be directed to the screen or the plotter by the plot command (discussed later).

The PLOT command is used to generate hardcopy output to a printer connected to the computer. The command allows the user to shift the plot in the x and y direction to centre the figure on a page. The command can also be used to rescale the image you wish to plot making it larger or smaller.

The summaries of the commands described above are only brief and it is advisable that those interested in further details obtain a copy of the SURFER software and manual from Golden Software Inc. A general review of the basic interpolation techniques available for G.I.S. systems and their relative advantages and disadvantages can be found in Burgess (1987).

FIGURE 15: SURF's organizational chart demonstrating the commands necessary for the production of three dimensional block diagrams of data points which have been 'gridded' (from SURFER manual).


SURF
Input
file
range
View
orthographic
perspective
rotation
tilt
distance
hidden lines
visible surface
Line Type
X
Y
Z
min
max
interval
levels
Base
height
skirt
color
Title
string
font
place
angle
size
color
legend
Axes
X
Y
Z
color
font
plane
tics
tic labels
label format
label size
title
size
place
Size
length
ratio
Zscale
XYLine
location
color
Post
file
labels
font
symbols
label form
label size
position
Output
file
scale
append
place
PLOT
Equip
Screen Type
CGA
EGA
Hercules
Menu Color
View Color
Printer Plotter

CHAPTER 3

FACIES DESCRIPTIONS

3.1 Introduction

The facies model approach to sedimentology was first applied to the study of marine and fluvial sedimentology with only recent attention given to glacially influenced deposits (Walker, 1984). Modern sedimentological studies of glacial sediments have used the facies models approach in several successful papers (Eyles and Eyles, 1983; Eyles and Miall, 1984; Eyles et al., 1983).

Defined as group of sediments with "lithological, structural and organic aspects detectable in the field" (de Raaf et al., 1965) facies are not genetic interpretations but classifications that are merely descriptive and may be used later for interpretations. The sediments comprising the Halton Till are divided into two major facies types, both diamicts, distinguished on the basis of underlying sediment lithology, pebble content, pebble lithology and grainsize.

3.2 Diamict Facies

The Halton Till consists of a diamict which varies widely in its matrix texture, clast content, and clast size. This variation is usually linked to the sediment type directly underlying the Halton Till. The most common sediment types encountered underlying the Halton TIll are (i) sands from the Thorncliffe and Scarborough

Formations (Sm) and (ii) diamict from the Sunnybrook Diamict (Dms) **(figure 1)**. There is a strong link between the facies description of the Halton Till and these sands and diamicts which are described in this chapter.

3.3 Halton Till over Sands (Sm)

This facies consists of a generally massive, matrix supported diamict which has a coarse, sandy texture. The basal contact is sharp, undulating and erosive in nature, often accompanied by shear planes in the underlying sands **(plate 3)**. The lower sands are often massive and devoid of primary sedimentary structures.

The zone along the erosive, basal contact of the till exhibits strong sediment deformation structures **(plate 4)**. These structures include shear planes in underlying units accompanied by rafts and stringers of sediment from those lower units which have been interpreted as glacitectonic in origin **(plates 5 and 6)**. There is also distinct incorporation of the underlying sands into the basal area of the Halton Till in the form of coarse grained 'pods' and sand 'stringers' **(plate 7)**. The pods are usually massive, oblate and less than 10 cm in length **(plate 8)**. The sand stringers are massive and/or contorted generally less than 40 cm in length (though some are discontinuous for several meters).

Sand pods are relatively uncommon and are restricted to a zone within 1 to 3 meters of the basal contact of the Halton Till. Sand stringers are very common and do not appear to be restricted to any zone. There is a tendency for the stringers to be thinner and

PLATE 3: Sharp undulating basal contact of the Halton Till (marked by a black arrow) overlying Scarborough Sands. Shear structures exist within the upper portions of the sand unit indicating deformation and movement of sand. The location is S3.

PLATE 4: Deformation of a clast concentration (gravel pod ?) within the Halton Till showing an undulating wave pattern traced by the black arrows. Note the small size of the Paleozoic clasts and the areas lacking any clasts in this photo. This distribution of low concentrations of small clasts is typical of the basal area of the Halton Till where it overlies sandy units. The basal contact is denoted by the head of the ice pick. The location is 20 m east of S2.

PLATE 5: Glacitectonic deformation in the lower Halton Till overlying sands. Note the incorporated deformed sand raft directly beneath the black arrow and the dish shaped feature to the right of the arrow from which a sand raft has been preferentially eroded. Clasts are absent. The site is 1.1 km inland of S3 and the field of view is approximately 30 cm by 50 cm.

PLATE 6: Abundant shear planes in massive sands underlying the Halton Till. The basal contact of the Halton is denoted by the black arrow and is inclined to the upper left. The trowel is 20 cm long and the site is 20 m east of S8.

PLATE 7: Deformation of sands underlying the Halton Till which show a large block of sand about to be incorporated into the till. A well developed shear plane is marked by a slim black arrow along which lateral movement of approximately 1 cm has occurred. The trowel along the right side of the photo is 20 cm long. The plate is an enlargement of the area to the right of the large black arrow in plate 3.

shorter in length near the basal area. This may indicate they are partially incorporated pods or derived from smaller scale inclusion of the lower sands **(plate 9)**.

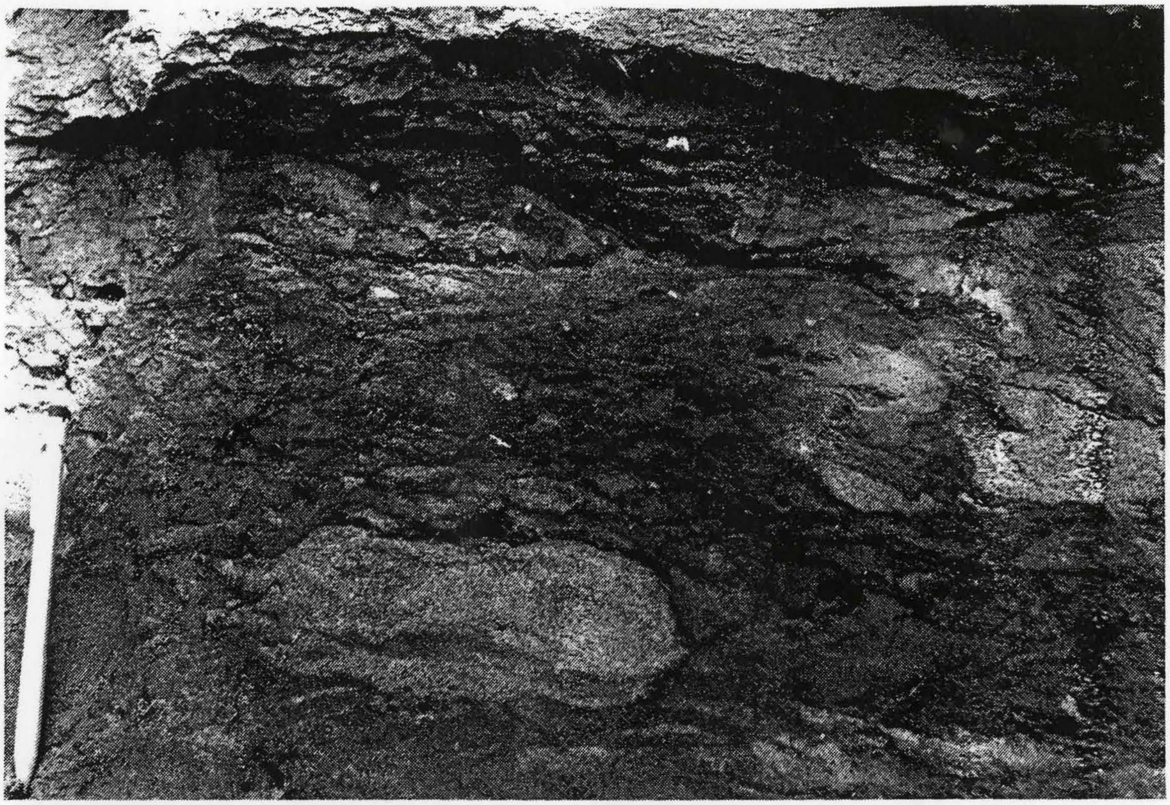
Pods of gravel with a very coarse, massive sandy-pebbly matrix are rare and occur generally in the upper portions of the till. These may represent incorporated subglacial meltwater channels since the clasts are rounded and generally less than 4 cm in length **(plates 10, 11 and 12)**.

Clasts in the basal part of the Halton Till are dominated by rounded, Paleozoic carbonates less than 3 cm in length. Clast density within the diamict is generally less than 40 per square metre near the basal contact; however, clast size and density increase upsection through the Halton Till. Scattered small Precambrian clasts are found about 4 meters from the basal contact and increase in frequency and size as the upper portions of the till are reached. Both Paleozoic and Precambrian clasts in the upper Halton tend to be 10 to 20 cm in length and exhibit faceted bullet shaped forms with striations on their upper surfaces and plucked stoss ends. Paleozoic clasts near the base of the Halton were rounded and much smaller in size showing multiple often crossing striations on both their upper and lower surfaces.

The till matrix from field tests showed no significant change in sand content throughout the till except at the basal contact where sand stringers often created a stratified deposit. The matrix near the base of the Halton was slightly less consolidated than areas in the upper parts of the till. Boulder pavements are generally poorly developed, but where present consist of rounded

PLATE 8: Light coloured oblate sand 'pods' accompanied by darker more abundant stained sand stringers. The field of view is entirely of the basal area of the Halton Till and is approximately 30 cm by 50 cm. The location is 10 m west of S2.

PLATE 9: Contorted stained sand stringers thinning to the left and becoming incorporated into the Halton Till. Field of view is approximately 30 cm by 50 cm. The location is 10 m west of S1.



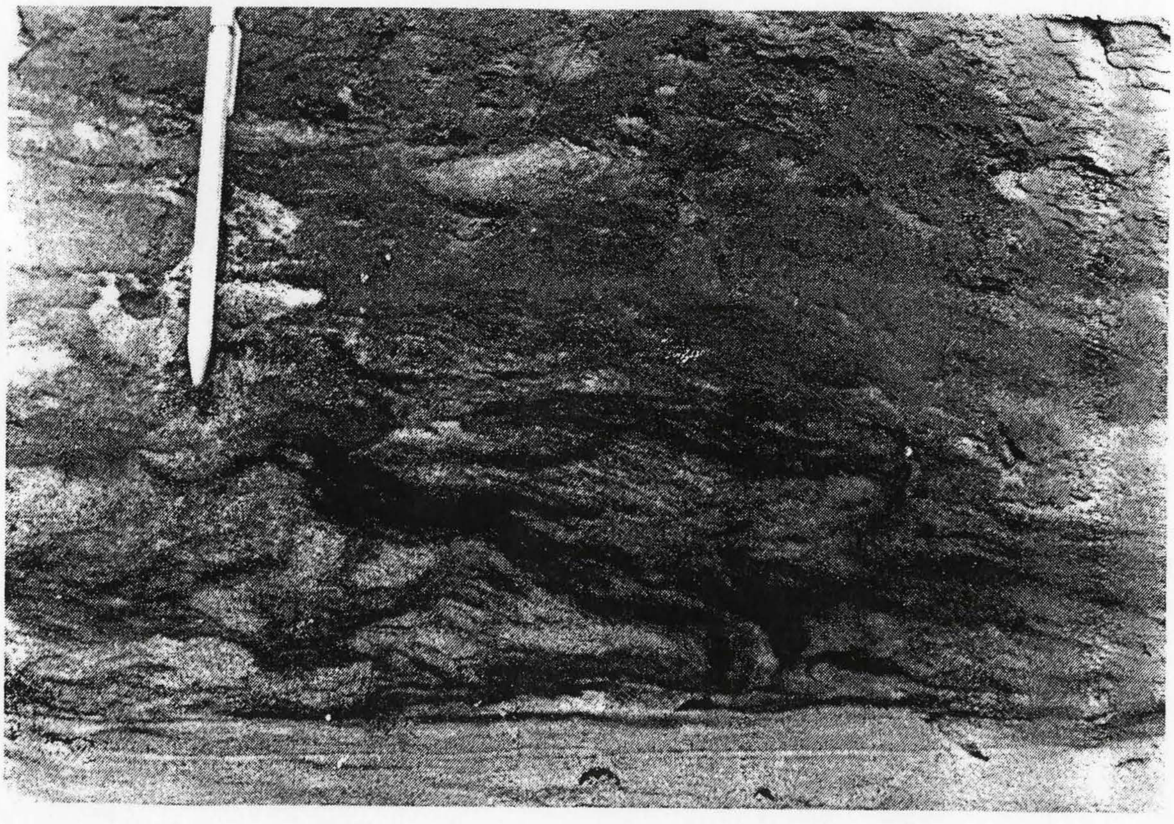
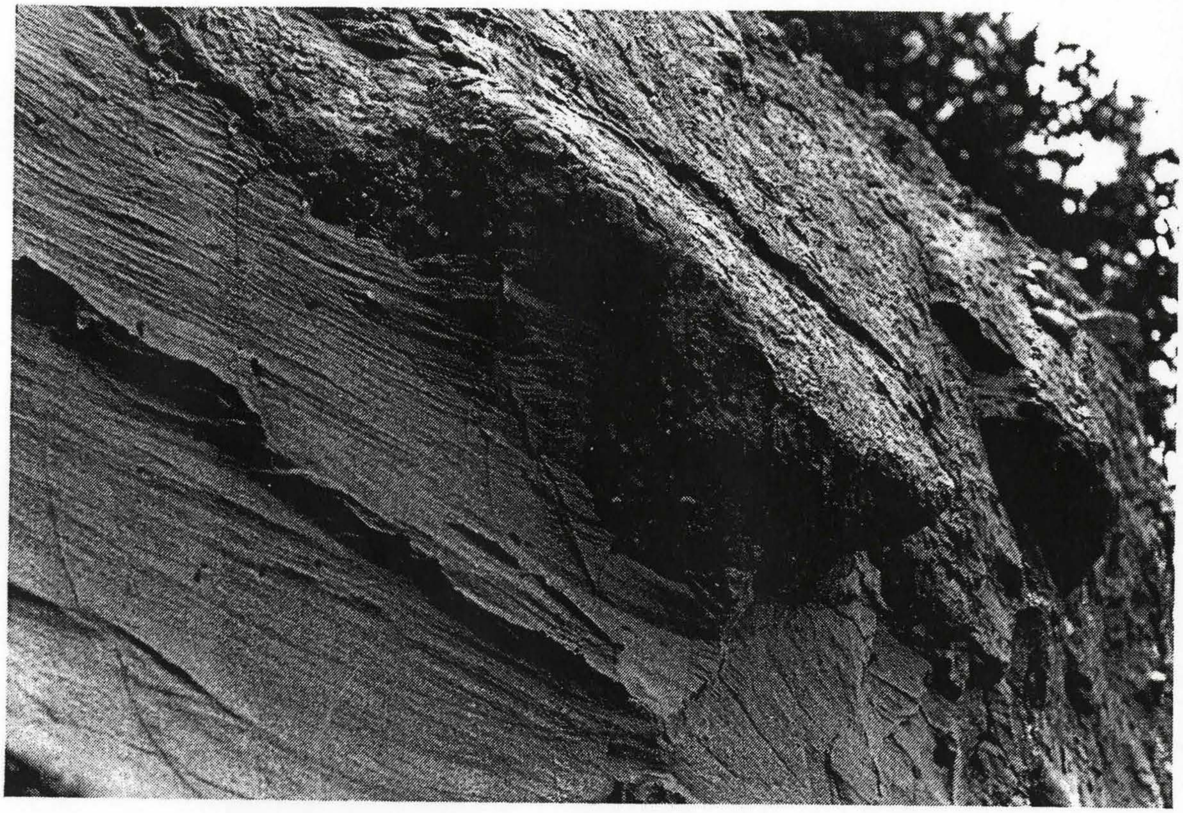


PLATE 10: In some areas where the Halton Till overlies sandy units pebble concentrations occur along the basal contact. These small rounded Paleozoic clasts may be evidence of the subglacial meltwaters which saturated the Halton Till mobilizing fines and concentrating coarser sands and gravels creating a highly permeable layer (desireable for deformation to occur). The pebble concentration is on the underside of the overhanging surface (the Halton Till basal contact). The field of view is approximately 50 cm by 100 cm. The site is 15 m east of S2.

PLATE 11: Fossilized (?) piping structures extending from the pebbly Halton Till basal contact into underlying sands. The structure is preferentially preserved by calcium carbonate cementation between sand grains which is thought to originate from subglacial meltwater dissolution of Paleozoic carbonates in the till. The structure is crudely cylindrical approximately 1 m long by 20 cm wide. The location is 10 m east of S2.



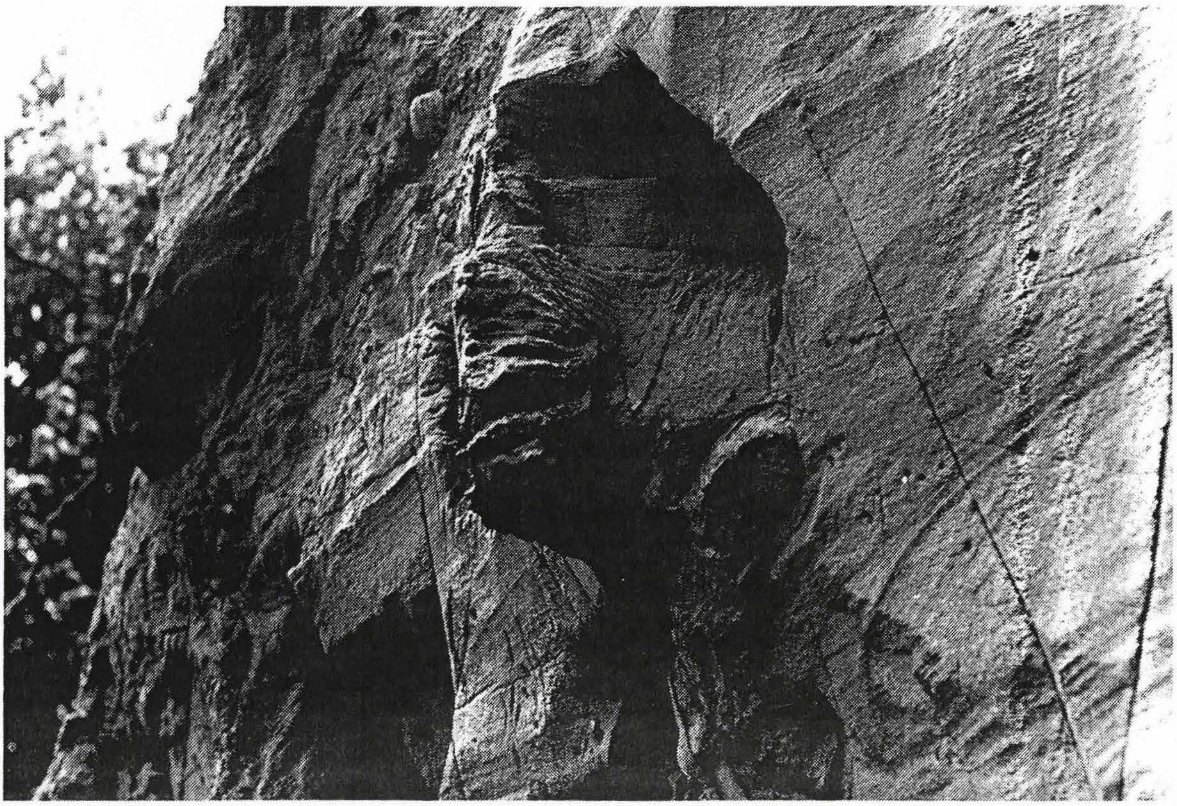
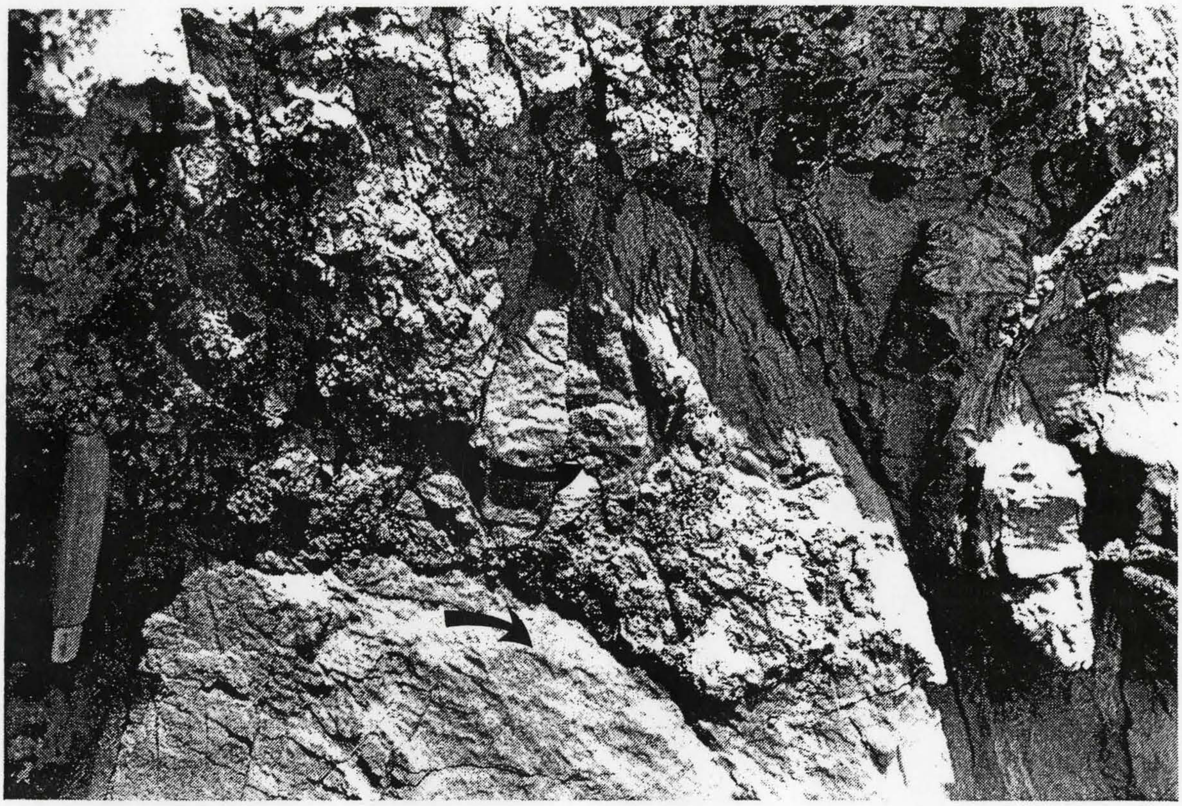


PLATE 12: These pebbly concentrations are sometimes deformed by glacitectonism resulting in their injection into underlying sands (the thrust pattern is marked by the black arrows). The location is 1 km east of S9 with a trowel 20 cm long for scale.

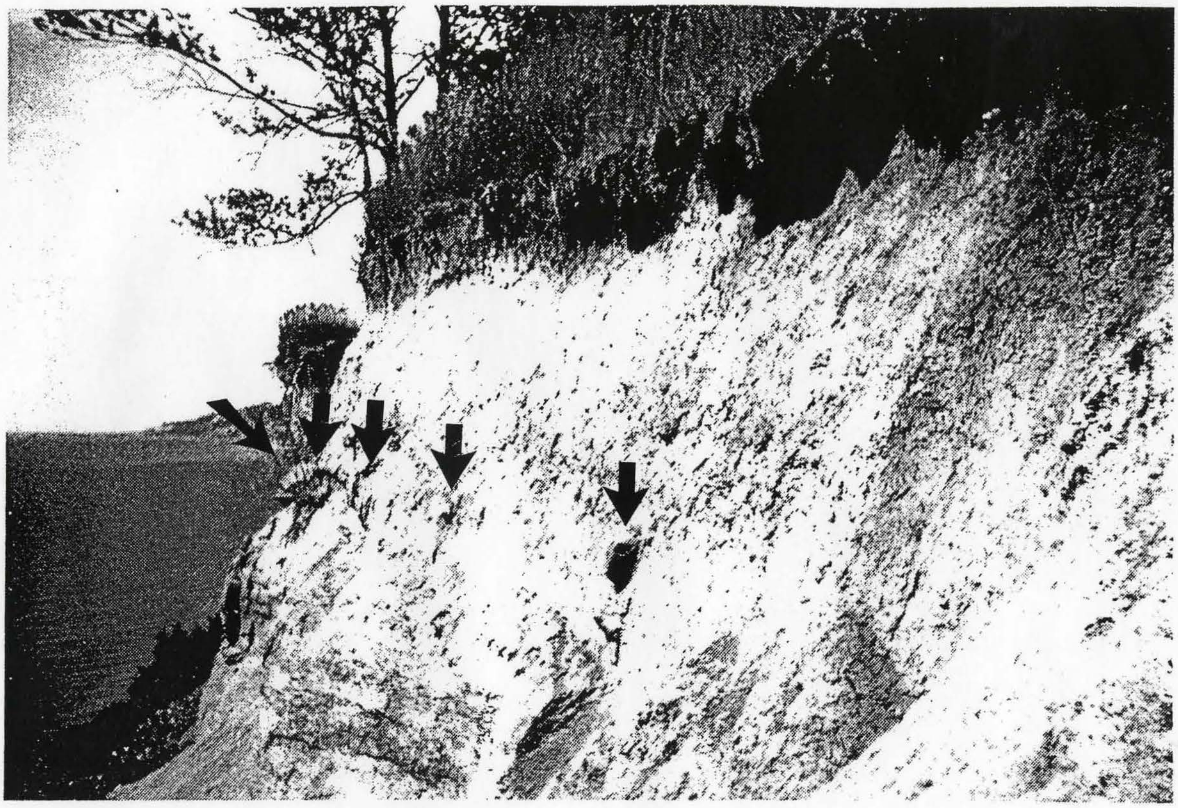


or bullet-shaped Paleozoic and Precambrian clasts with lengths in excess of 10 cm **(plate 13)**. There was a tendency for pavements to be created about three to five meters above the basal contact of the Halton Till overlying sands or where the till had overridden sand or gravel channels.

3.4 Halton Till over Diamicts (Dms)

The matrix of the Halton Till in those locations that overlie the Sunnybrook diamict (which consists of a clayey-silt matrix with some sand) is noticeably more fine grained than that experienced in areas where the till overlies sands **(plate 14)**. The basal contact between the Halton Till and the Sunnybrook diamict is poorly defined due to the fine grained nature of both units. A consistent erosive contact between the Halton Till and the Sunnybrook diamict existed at all field sites. This contact was highlighted by the presence of characteristic fine grained, rhythmic laminations in the Sunnybrook diamict. In some situations fine grained laminations (lenticular in geometry) existed above the basal contact of the Halton Till. These fine grained, poorly stratified silts and clays were interpreted to be sediments derived from glaciofluvial or subglacial ponding. These units formed only where there was a large areal contact between the Halton Till and the underlying Sunnybrook diamict. These silt and clay lenses (located above the basal contact of the Halton Till) contained only a few clasts, most being rounded Paleozoic and Precambrian clasts less than 5 cm in size. The Sunnybrook diamict beneath these

PLATE 13: A poorly defined boulder pavement consisting of small Paleozoics near the basal contact of the Halton Till located about 10 m west of S2. The field of view is approximately 8 m by 10 m. The boulder closest to the centre of the plate is 1.2 m above the Halton Till basal contact.



lenses still contained well developed stratification but was heavily contorted with strong glacitectonic deformation structures (eg. shear planes).

Structures showing the incorporation of the underlying Sunnybrook into the basal areas of the Halton were not well developed. Poorly defined contorted stringers of massive silts and clays were common near the basal contact of the Halton up to 5 m in length. The length of these stringers increased in size higher up in the Halton and decreased in frequency. The lenses often contained rounded Paleozoic carbonates less than 3 cm in length similar to those encountered in the upper parts of the Sunnybrook **(plate 15)**.

Sediment incorporation structures were generally limited to a zone less than 5 m in thickness from the base of the Halton Till. Shear structures were also present in the Sunnybrook diamict. The lower Halton was also less consolidated than the Halton higher in the stratigraphic column. The density of the till also seemed to increase where the silt and sand stringers were absent in the upper parts of the Halton.

Boulder pavements were rare in the Halton where it overlay the Sunnybrook diamict and were mainly confined to areas over sandy-pebbly channels which were overlain by the till. The density distribution of clasts varied widely within the Halton where it overlay the Sunnybrook **(plates 16 and 17)**. The basal areas were often devoid of clasts or contained only a few small rounded Paleozoics (20 clasts per square metre). The density and size of both Paleozoic and Precambrian clasts increased with height in the

PLATE 14: Halton Till containing large percentages of clays and silts derived from underlying diamicts. The lens cap has a diameter of approximately 4 cm. Location is 1 km east of S3.

PLATE 15: Note the small size of the rounded Paleozoic carbonates likely derived from the underlying Sunnybrook diamict. The clasts show multiple striations and orientations. Sediment incorporation structures in the form of silty clay stringers are hard to see in this plate. The trowel is approximately 20 cm long.

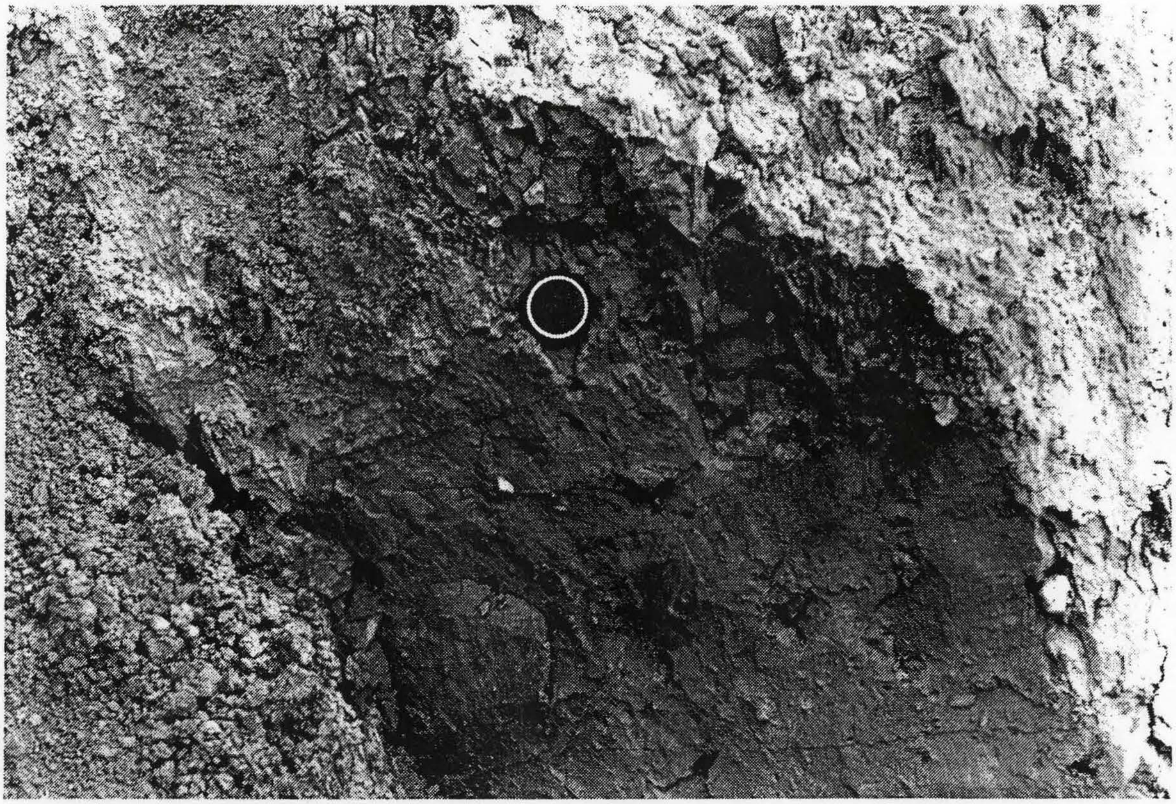
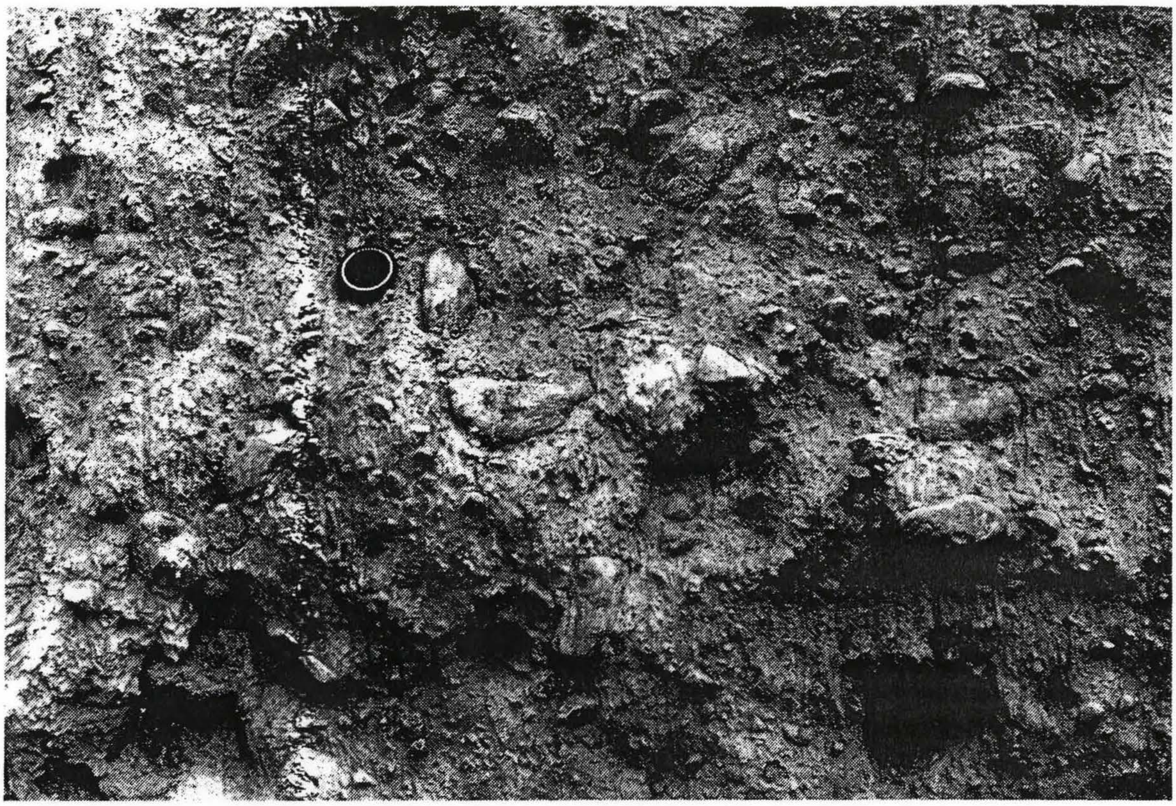


PLATE 16: Clasts located within the Halton were often located at right angles to each other suggesting that they were not emplaced by lodgement processes. The photo was taken 2.5 m above the basal contact of the Halton Till. The lens cap is approximately 4 cm in diameter. Located 2 km east of S9 in a drumlinoid form.

PLATE 17: A pair of rounded flat iron clasts showing multiple crossing striations sitting on end (position of deposition). The photo was taken 3 m above the Halton Till basal contact in a drumlinoid form 1.5 km east of S9. The central clast is 20 cm in length.



Halton till. The number of bullet shaped boulders also increased in a similar pattern.

CHAPTER 4

GRAINSIZE ANALYSIS

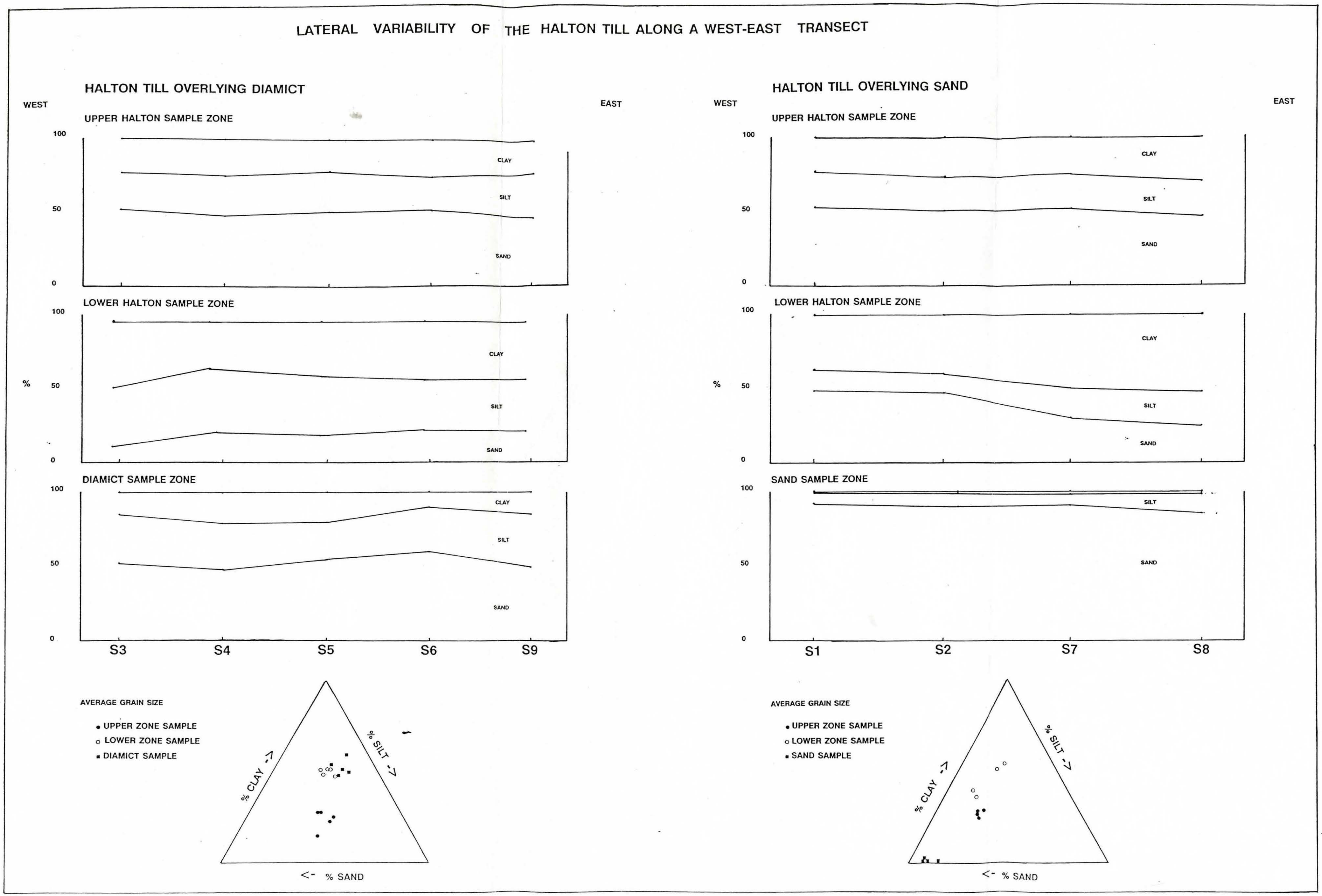
4.1 Lateral Variability of the Halton Till overlying Sands (Sm)

Due to the wide variability in the height of the exposures that were logged only the lower two meters (Halton basal contact to +2.0 m) and the upper two meters of section (between +7.0 and +9.0 m) were considered in the investigation. This variance in till thickness may be due in part to the original thickness but all of the exposures examined had been modified by glacial Lake Iroquois and differential erosion may have occurred.

In examining those samples which overlie glaciolacustrine sands **(figure 16)** it was discovered that the basal layer of the till (a zone defined as the area from the basal contact to a height 2 metres above this point) contained a high percentage of sand often exceeding 42.3 %. There appears to be a strong increase in the total percentage of sand present in this basal zone from the east to the west. The minimum average sand values in this basal zone occurred in the east at site S8 (24.2 % near Bowmanville) and the maximum sand values occurred to the far west at site S1 (51.2% near Guildwood)--a substantial difference of 26.0 %.

The two metre thick basal zone of the Halton Till also displays a strong trend in the distribution of silt and clay. Both silt and clay total percentages decrease steadily from the east to the west of the study area from highs of 20.2 % and 55.6 % respectively to lows of 15.3 % and 33.5 %. Total changes of 4.9 % and 22.7 % indicate that more than just random local variance may

FIGURE 16: Lateral variability of the Halton Till matrix over varying lithologies. Separated into two zones, an upper (+7 to +9 m) and lower (0 to +2 m), the Halton Till exhibits evidence from grainsize analysis that shows incorporation of underlying units into the lower zone of the Halton. The upper zone shows little evidence of direct incorporation of underlying sands and diamicts. The upper zone of the Halton Till exhibits similar characteristics whether it overlies sands or diamict.



LATERAL VARIABILITY OF THE HALTON TILL ALONG A WEST-EAST TRANSECT
HALTON TILL OVERLYING DIAMICT
WEST
EAST
UPPER HALTON SAMPLE ZONE
100
50
0
CLAY
SILT
SAND
LOWER HALTON SAMPLE ZONE
%
DIAMICT SAMPLE ZONE
S3
S4
S5
S6
S9
AVERAGE GRAIN SIZE
UPPER ZONE SAMPLE
LOWER ZONE SAMPLE
DIAMICT SAMPLE
% CLAY ->
% SILT ->
<- % SAND
HALTON TILL OVERLYING SAND
SAND SAMPLE ZONE
S1
S2
S7
S8
SAND SAMPLE

be affecting the grain size distribution in the silts and clays.

Examining the upper 2.0 meter zone (between +7m and +9m) shows only a slight increase in the total sand content of the upper Halton till from east to west **(figure 16)**. Minimum values occurred in the east again (46.7 %) and maximum values also were in the far west (51.0 %). The difference is very small at 4.3 % and may be due to local variance.

Silt percentages in the upper Halton Till remained relatively constant from east to west with minimum values occurring in the east near Bowmanville at S8 (22.7 %) and maximum values of 25.2 % occurring in the far west (S1 near Guildwood). A difference of only 2.5 %. Maximum values for clay occurred in the east at 30.6 % (S8) and decreased to a minimum of 26.3 % at S1. A difference of 4.3%. Both the variation in the silt and clay could be caused by local random variation.

4.2 Lateral Variability of the Halton Till overlying Diamict (Dmm)

Examining those samples from ares where the Halton till basal contact lies on massive fine grained diamict of the Sunnybrook unit shows patterns similar to those where Halton till overlies sand units.

In the lower basal zone (a band extending from the Halton Till basal contact to +2 m) the sand content averages about 21.3 % and is much lower over all than that seen where the Halton overlies sand units **(figure 16)**. The total silt and clay content of the till seems to increase in a general fashion from east to west of

the study area, from lows at site S9 of 38.6 % and 37.6 %, to highs of 47.9 % and 38.6 %. Total sand percentages decreased from east to west of the study area from a high near site S9 (23.8 %) to a low near site S3 (13.5 %).
The differences in sand, silt and clay values of 10.3, 1.0 and 9.3 percent indicate a general increase in the total proportion of fines to the west.

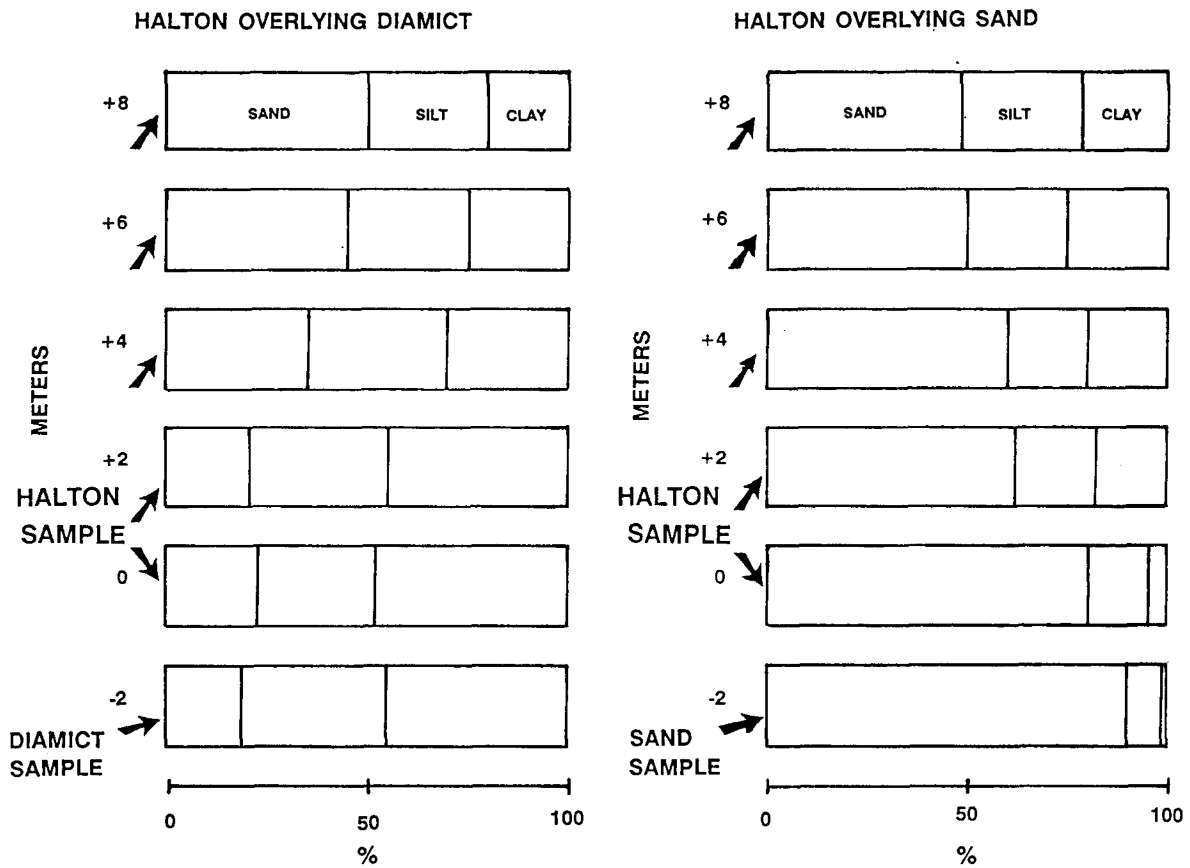
The upper zone in the Halton till (+7.0 to +9.0 m) where it overlies diamict shows a similar trend to the upper zone where the Halton sits on sand units **(figure 16)**. The total percentage of sand increases gradually to the west from a low of 47.8 % (at site S9) to maximum of 52.2 % at site S6 near the centre of the field area. Further west there is a gradual decrease in sand content to 50.2 % (at site S3). Silt and clay percentages follow a similar pattern with a gradual shift from a low of 27.2 % and 25.0 % to a high near the central field area of 28.1 % and 20.3 %. The total percentage of silt and clay then decrease to the west to 24.8 % and 25.0 % respectively.

4.3 Average Vertical Grainsize Variability of the Halton Till

Where the Halton overlies glaciolacustrine sand deposits there is a strong variation in the total percentages of sand, silt and clay with vertical position in the outcrop **(figure 17)**. Sand percentages decrease an average of 19 % from the basal contact to a point 8 m above the base (eg. a change from 70 % to 51 % in subsamples near site S7). Silt and clay both increase an average

FIGURE 17: Vertical variability of the Halton Till. The grainsize analysis for a specific height at all sites has been averaged to give a generalized distribution of the matrix components--sand, silt, and clay. Distinct trends show incorporation of underlying units into the Halton Till.

AVERAGE VERTICAL GRAINSIZE VARIABILITY OF THE HALTON TILL



19 % and 20 % from the base to the upper limit (eg. 20 % to 29 % and 10 % to 20 % for subsamples near S2).

In locations where the Halton till rests on massive fine-grained diamict there appears to be a similar strong variation in grain size from the base to the upper limit **(figure 17)**. Sand percentages increase by 30 % on average from the basal contact to the point 8 m from the top (eg. an increase from 10 % to 50 % at site S3). Silt and clay percentages show a general decrease in total percentages of 10 % and 30 % respectively from the base to the top of the till (40 % to 30 % and 50 % to 20 %).

4.4 Grainsize Discussion

The cumulative grain size distribution curves (presented in #appendix III) which have been summarised in **figures 16 and 17** show strong evidence of significant variation in grain size distribution near the basal contact of the Halton till which appears to be related to the underlying substrate.

Where the Halton has overridden sand units high percentages of sand are found in the 'basal zone' of the Halton Till. Where the till has overridden massive fine-grained diamict high percentages of silts and clays are found. This suggests that the Halton till is including some of the underlying substrate into its matrix. The presence of shear planes in the substrate also show evidence of glacitectonic deformation suggesting the inclusion of portions of underlying units into the 'basal zone' of the Halton Till. The strong erosional contact present at most sites and the presence of sand stringers (over areas where the lower unit is sandy) and diamict clots (over areas where the lower unit is massive fine-grained diamict) suggests that the Halton till may be deforming the sediments near the basal contact and incorporating the underlying units into its matrix.

The generally massive 'upper zone' (+7 to +9m) of the Halton Till shows little evidence of deformation structures (eg. shear planes and sediment rafts) whether it overlies sands or diamicts. This suggests that as the Halton Till increases in thickness the underlying units exercise less direct control on the grain size distribution of the till matrix. The presence of incorporated glaciofluvial deposits (which probably formed in advance of the glacier) does modify this grain size distribution pattern locally.

4.5 Halton Grainsize Error

By comparing the two independent grain size analyses performed on each sample the variation (ie. error) between the cumulative grain size distribution curves from each site is very small. It is important to note that all samples were not evenly spaced vertically (due to variations in outcrop accessibility) possibly resulting in some systematic error **(figure 9)**. While this systematic error may affect site specific grainsize distribution curves, the very strong east-west grainsize variation patterns (discussed in sections 4.3 and 4.4) will be only minimally effected.

Further work in this area should concentrate on the use of much more closely spaced samples (perhaps every 5 cm). This will increase accuracy in detecting grain size variation between the generally massive 'upper zone' of the Halton Till and the more highly variable 'lower zone' of the till. However, this may also result in local effects (eg. variability due to incorporated glaciofluvial deposits) having disproportionate representation in both the vertical and lateral grain size distribution of the Halton Till.

While more closely spaced vertical sampling of outcrops may aid in determining the transition between the 'lower' and 'upper' zones in the Halton Till, the time and resources necessary are proportionally greater due to the labour intensive nature of sediment analysis.

CHAPTER 5

COMPUTER DATA BASE ANALYSIS

5.1 Regional Bedrock Map

One of the computer databases assembled during the summer of 1989 contained information on the bedrock topography of the Toronto area. Compiled from several different sources (see chapter 2) this database is perhaps the most extensive collection of bedrock data for the Toronto region ever collected. Using the data, a bedrock topographic map was prepared in an attempt to reveal the form of the subsurface basement **(figure 18)**.

The area of the bedrock map was approximately 1,500 km^2 and contained over 4,000 wells, providing a density of over two wells per square km **(figure 19)**. While the location of wells were dependent on construction sites (eg. roads and bridges) the coverage given is quite good except in those areas where the overburden is thick (eg. the central area of the Laurentian channel). While scattered wells exist for these areas, better well control is desirable to improve definition of the bedrock topography particularly in areas where relatively small bedrock channels are present.

The bedrock topographic map provides an excellent tool with which to view the bedrock channels some of which are thought to represent the courses of preglacial river systems (Spencer, 1890) **(figure 20)**. These river channels may represent evidence for a direct link between Georgian Bay and Lake Ontario during the late

FIGURE 18(a): The bedrock topographic map produced from the compiled data set using the SURFER software (specifically the TOPO command). The contour interval is 10 meters with every other contour line labeled. Lines that are hatched represent depressions. THe form of the subsurface data indicates a narrow channel roughly 5 km in width enters the map area at 615000,4870000 and flows southwards along the edge of the bedrock ridge to the west. The channel looses its definition as it enters a broad basin near the northern Metropolitan Toronto boundary. At this point the channel divides into a series of distributary channels emptying into the basin now occupied by Lake Ontario. Each small tick along the map border represents one km. The six and seven digit numbers that label the ticks are U.T.M. co-ordinates. For explanations of the letters on the map refer to figures 18(b) and 18(c).

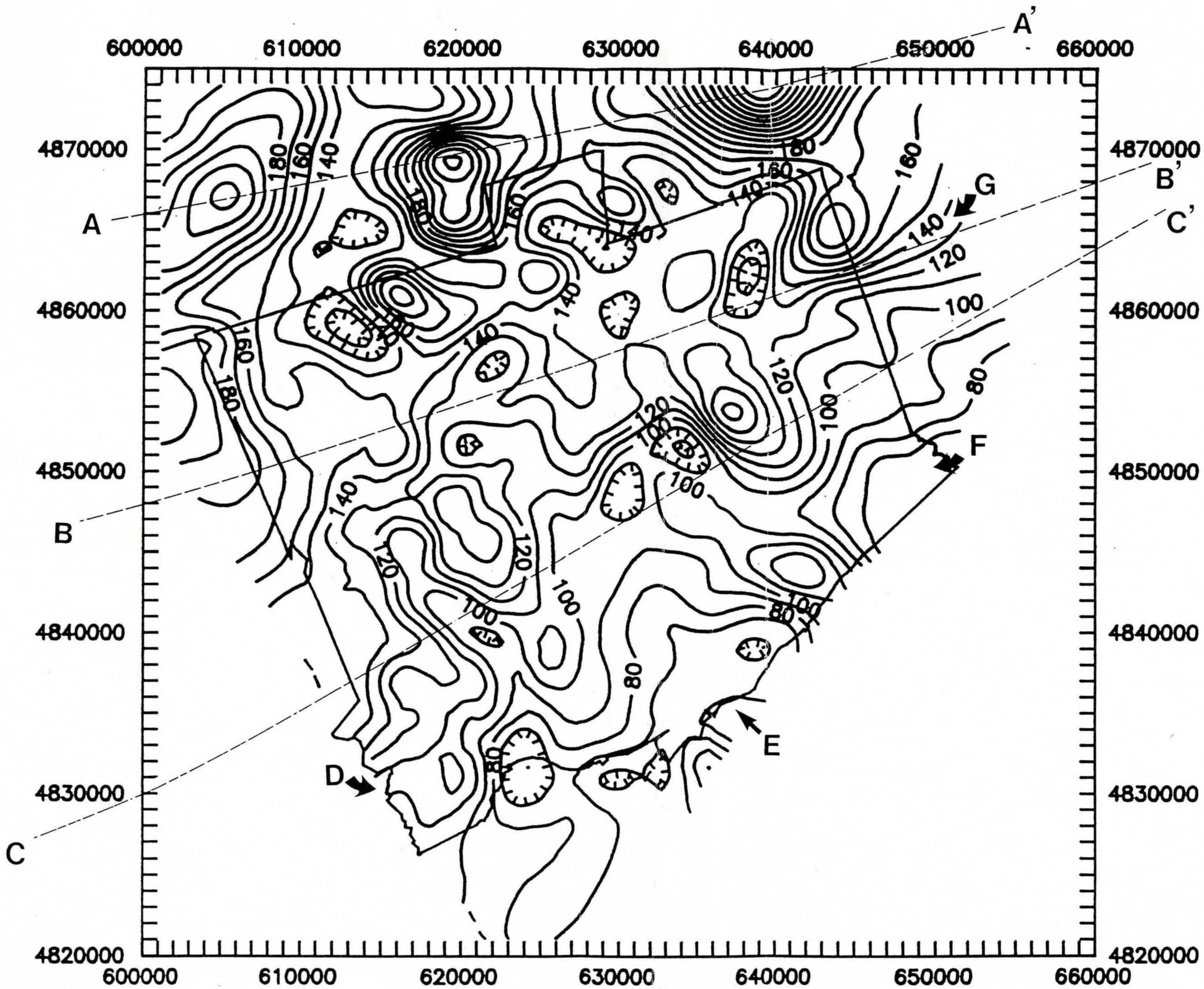

A
A'
B
B'
C
C'
D
E
F
G
600000
610000
620000
630000
640000
650000
660000
4820000
4830000
4840000
4850000
4860000
4870000
180
160
140
120
100
80

FIGURE 18(b): The cross sections shown by the lines A-A, B-B' and C-C' show the change in the geometry of the Laurentian channel from north to south. The northern bedrock profile A-A' indicates a narrow controlled channel. The profile B-B' shows a wide fairly flat large channel with some indication of many smaller channels begining to form. The most southerly profile C-C'suggests that there are several smaller well developed channels (distrubutary channels ?).

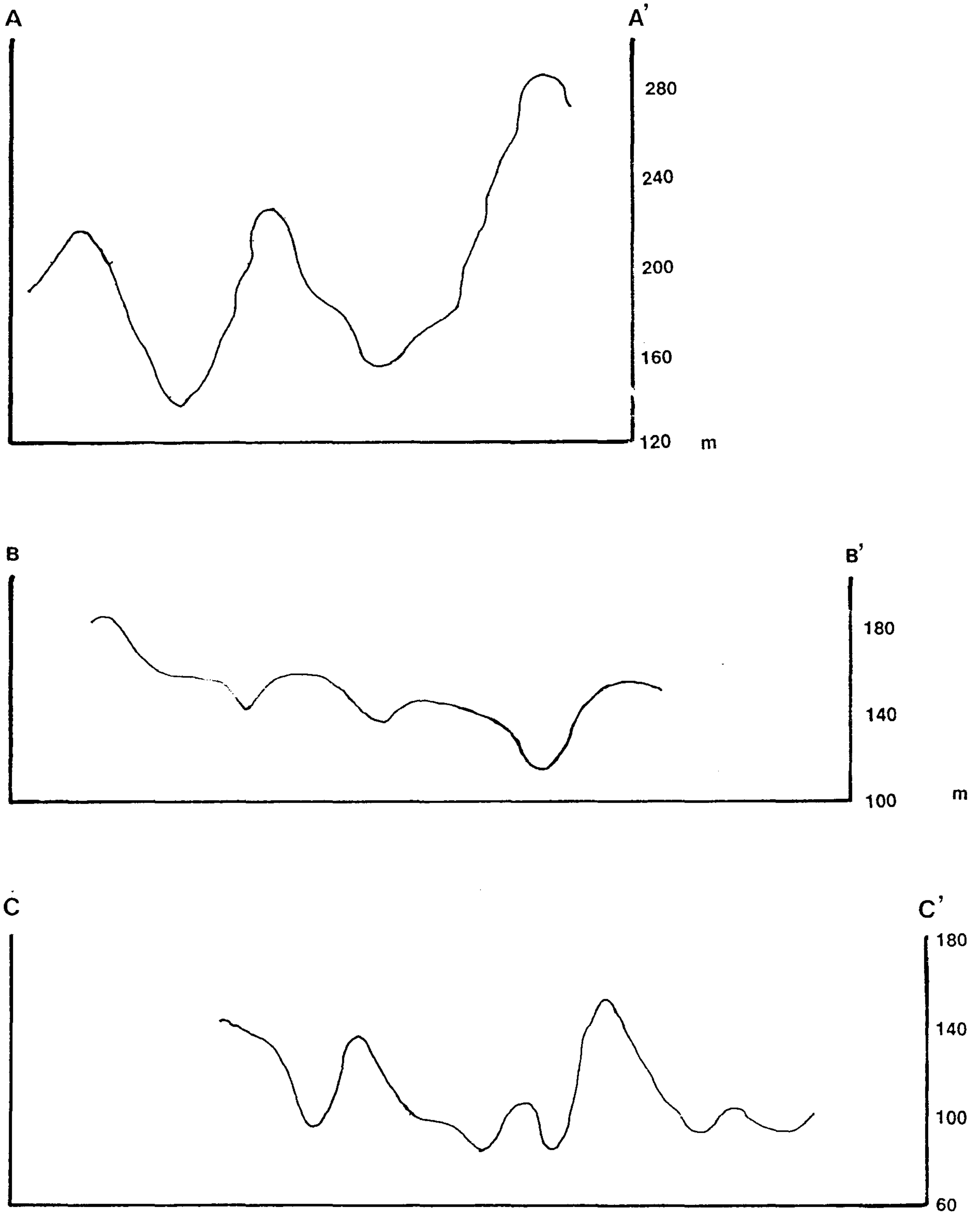

A
A'
280
240
200
160
120
m
B
B'
180
140
100
m
C
C'
180
140
100
60

FIGURE 18(c): The letters D,E,F, and G refer to points on the bedrock map for which a representative section of the drift cover has been sketched. The cross-sectional profile is oriented west to east and shows thin deposits of the Halton Till in the Laurentian channel contrasted with thicker in bedrock highs and smaller Late Wisconsin channels.

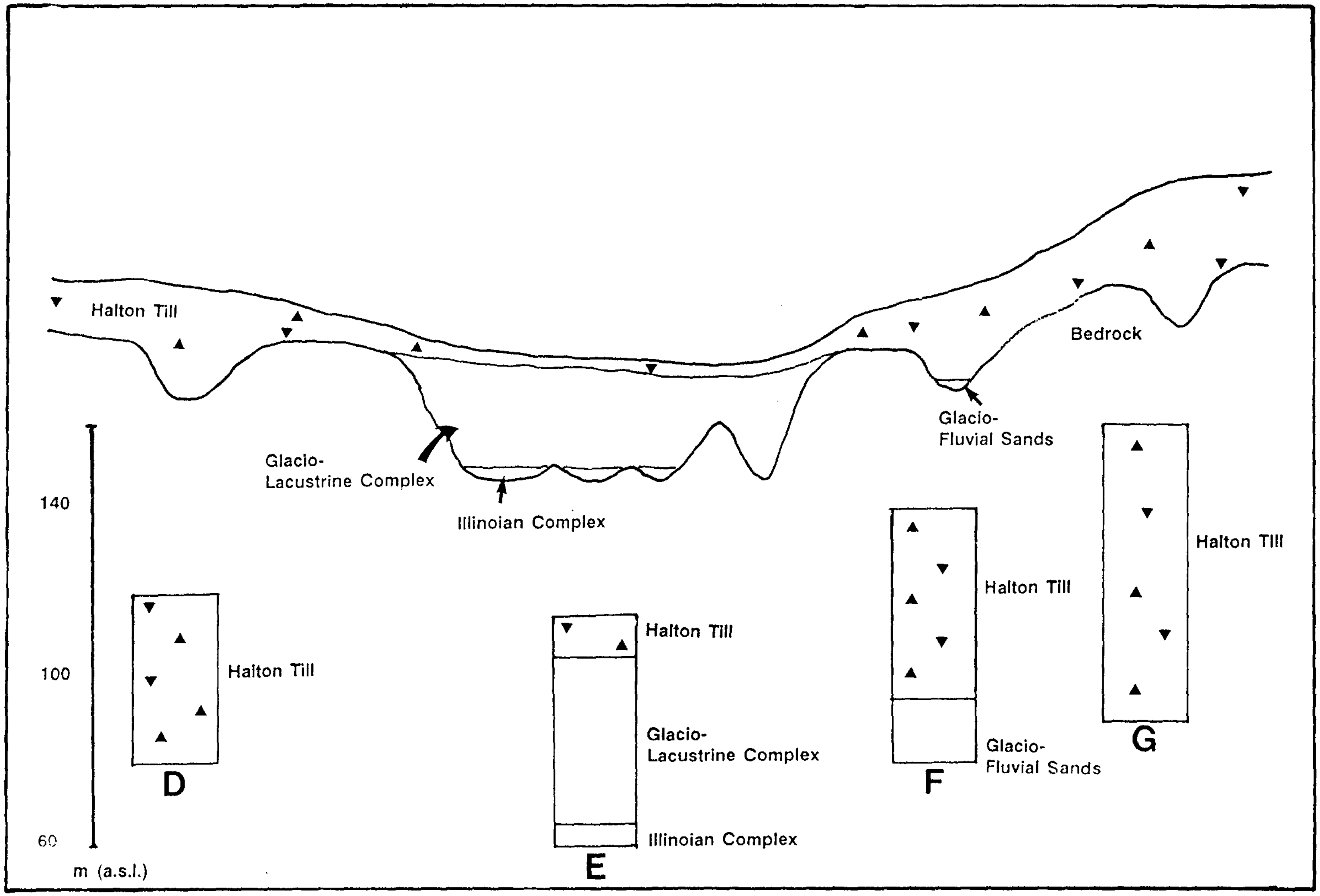

Halton Till
Bedrock
Glacio-
Fluvial Sands
Glacio-
Lacustrine Complex
Illinoian Complex
140
100
60
m (a.s.l.)
Halton Till
D
Halton Till
Glacio-
Lacustrine Complex
Illinoian Complex
E
Halton Till
Glacio-
Fluvial Sands
F
Halton Till
G

FIGURE 19: A representation of the approximate distribution of the over 4,000 wells and outcrops that make up the bedrock subsurface database. Distribution is irregular with some exceptions such as routes for highways and their bridges. Good coverages is provided for the western edge of the study area and the downtown core of Toronto. While fair coverage is given for other areas, data for the Oak Ridges Moraine, western Pickering and western Scarborough are poor. Present rapid development of the Pickering and Scarborough areas will provide data in the near future.

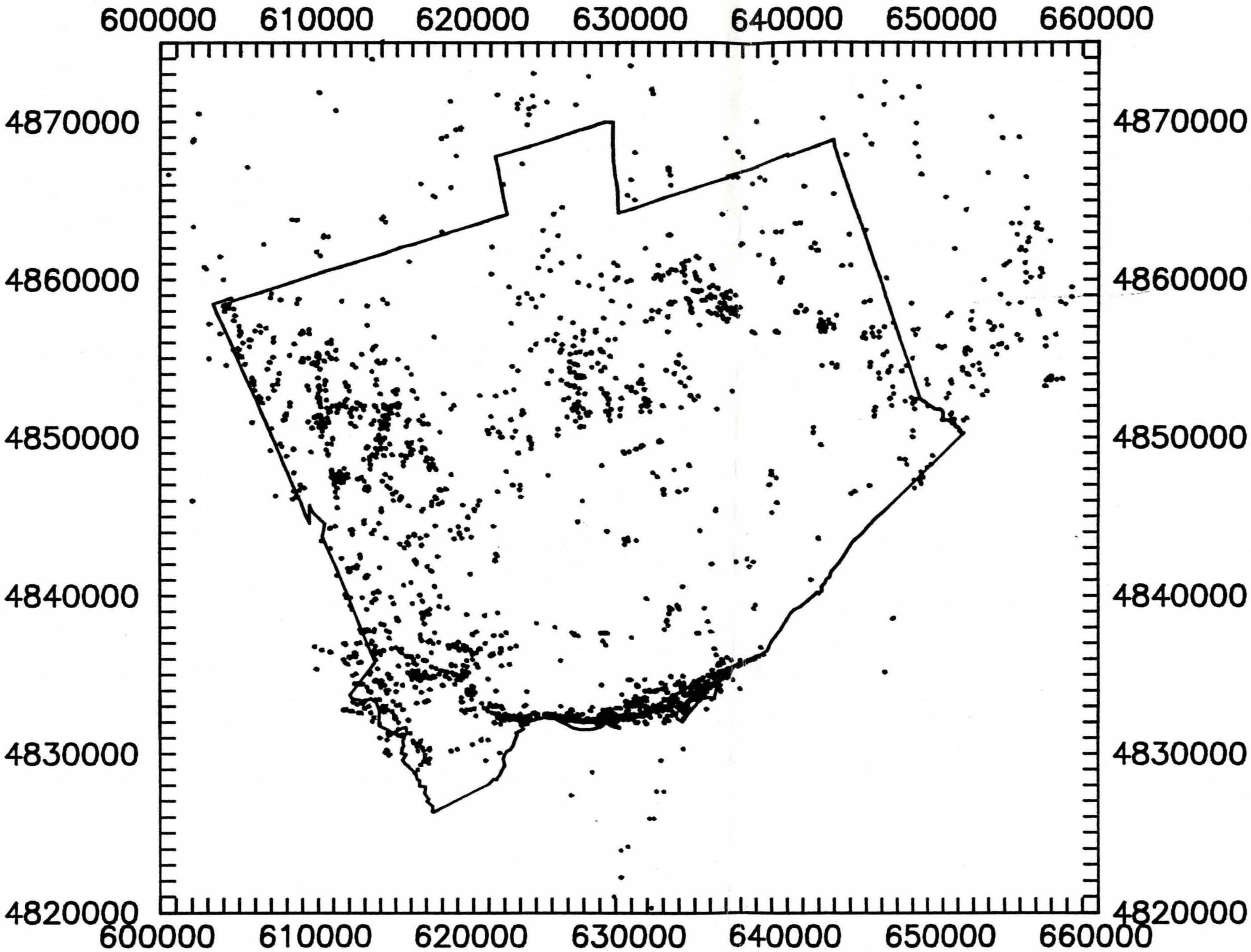
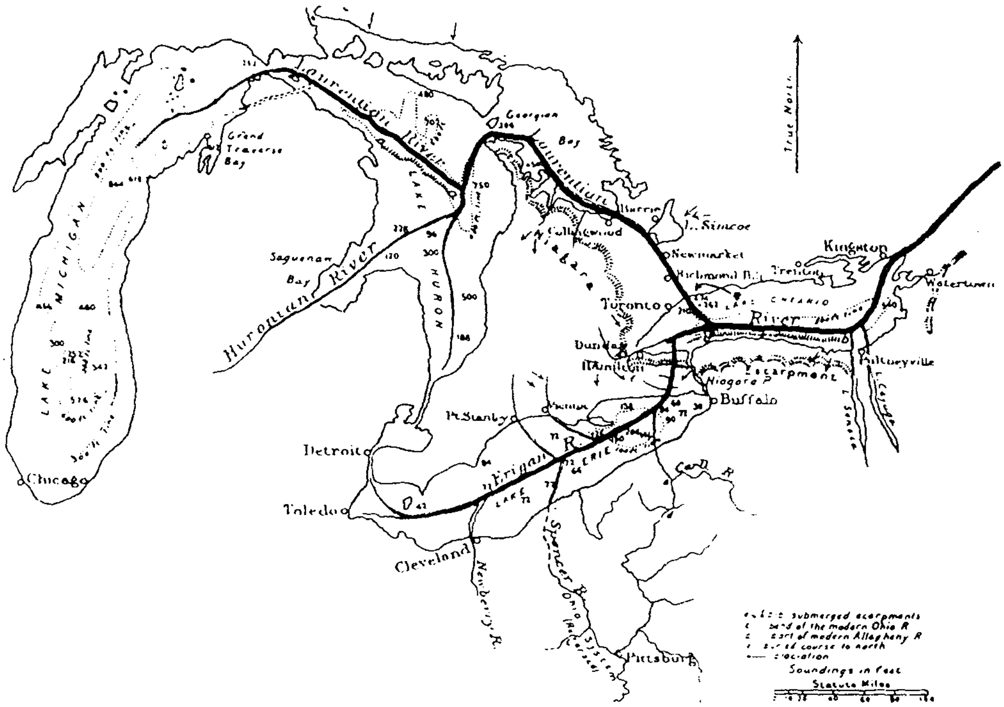

600000
610000
620000
630000
640000
650000
660000
4870000
4860000
4850000
4840000
4830000
4820000

FIGURE 20: Ancient preglacial river channels have been thought to have previously connected the Great Lakes drainage system since the late 1800's. Some were suprizingly accurate (Spencer, 1890).


Laurentian River
Huronian River
Erigan R.
River
Escarpment
Grand Traverse Bay
Saguenaw Bay
Georgian Bay
LAKE MICHIGAN
LAKE HURON
LAKE ERIE
LAKE ONTARIO
Niagara
L. Simcoe
Chicago
Detroit
Toledo
Cleveland
Pt. Stanley
Dundas
Hamilton
Toronto
Newmarket
Barrie
Collingwood
Kingston
Watertown
Buffalo
Niagara F.
Pulteneyville
Pittsburg
Spencer R.
Newberry R.
True North
Soundings in Feet
Statute Miles

Tertiary to early Quaternary period (Eyles, 1986) **(figure 21).** Similar bedrock channels are thought to exist for all the Great Lakes (Flint and Lolcama, 1986).

The subsurface data reveal a large channel along the west-central region of the study area. This channel develops from a single channel in the north into a series of branching distributaries in the south. The extreme southern end of the channel is a broad flat expanse over 30 km wide along the edge of present day Lake Ontario. A slightly smaller channel occupies the north-eastern area and may represent a branch that rejoins the main channel identified above **(figure 22).** Eyles (1986) reported that the large, broad bedrock channel extending from Georgian Bay to Lake Ontario varies in width from 115 to 45 km. Eyles (1986) went further and suggested that this single, large channel may have been selectively overdeepened in some areas by subsequent glacial erosion during the Quaternary into a series of multiple channels up to 5 km in width.

Previously unreported smaller tributary channels to the central Laurentian system can be identified in the regions along the western and eastern edges of the study area **(figure 22).** These channels are much smaller in size (averaging 10 to 15 km in length) and have a steeper gradient (estimated at 5 m/1 km) than the large central Laurentian channel (estimated at 1 m/1 km). Additional small channels with variable gradients (2 m/1 km to 6 m/1 km) can be identified in the vicinity of the Rouge River basin, Highland Creek, Don River, Humber River, Mimico Creek and Etobicoke Creek **(figure 23).**

FIGURE 21: Previous papers using hand contouring to produce maps from limited sets of data have produced maps which support Spencers (1890) proposal of a channel from Georgian Bay to Lake Ontario through Toronto (Eyles, 1986).

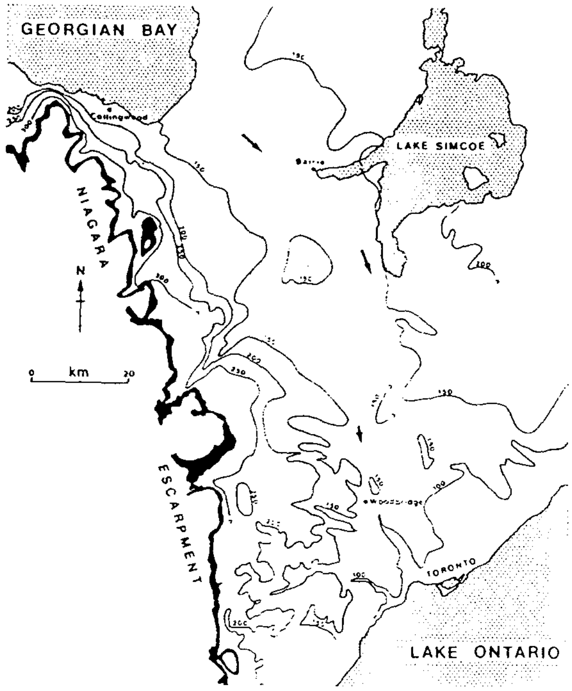

GEORGIAN BAY
Collingwood
LAKE SIMCOE
Barrie
NIAGARA
ESCARPMENT
N
km
0
20
Woodbridge
TORONTO
LAKE ONTARIO

FIGURE 22: A 'fish net' or three dimensional block diagram produced to represent the bedrock topographic map from figure 18. The large white arrows represent probable paths for large channels and their flows. Smaller white arrows indicate smaller channels, some of which were produced during the Late Wisconsin ice sheet advance during which the Halton Till was deposited. From topographic data it appears that the large channel in the upper left of the diagram (north-west) was the dominant entry point for flow from the north. Smaller bedrock channels appear to be better developed on the western side of the main Laurentian channel.

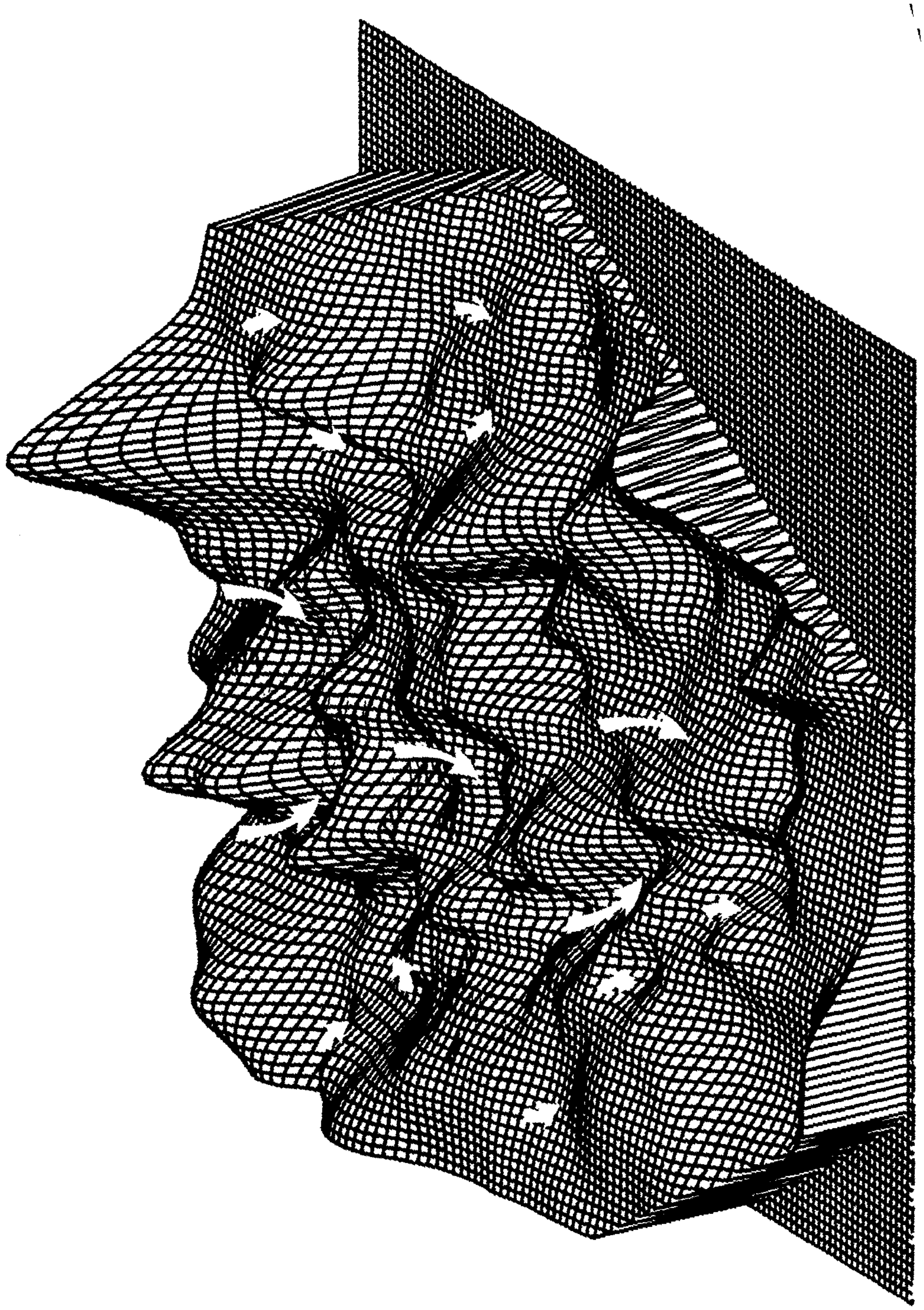
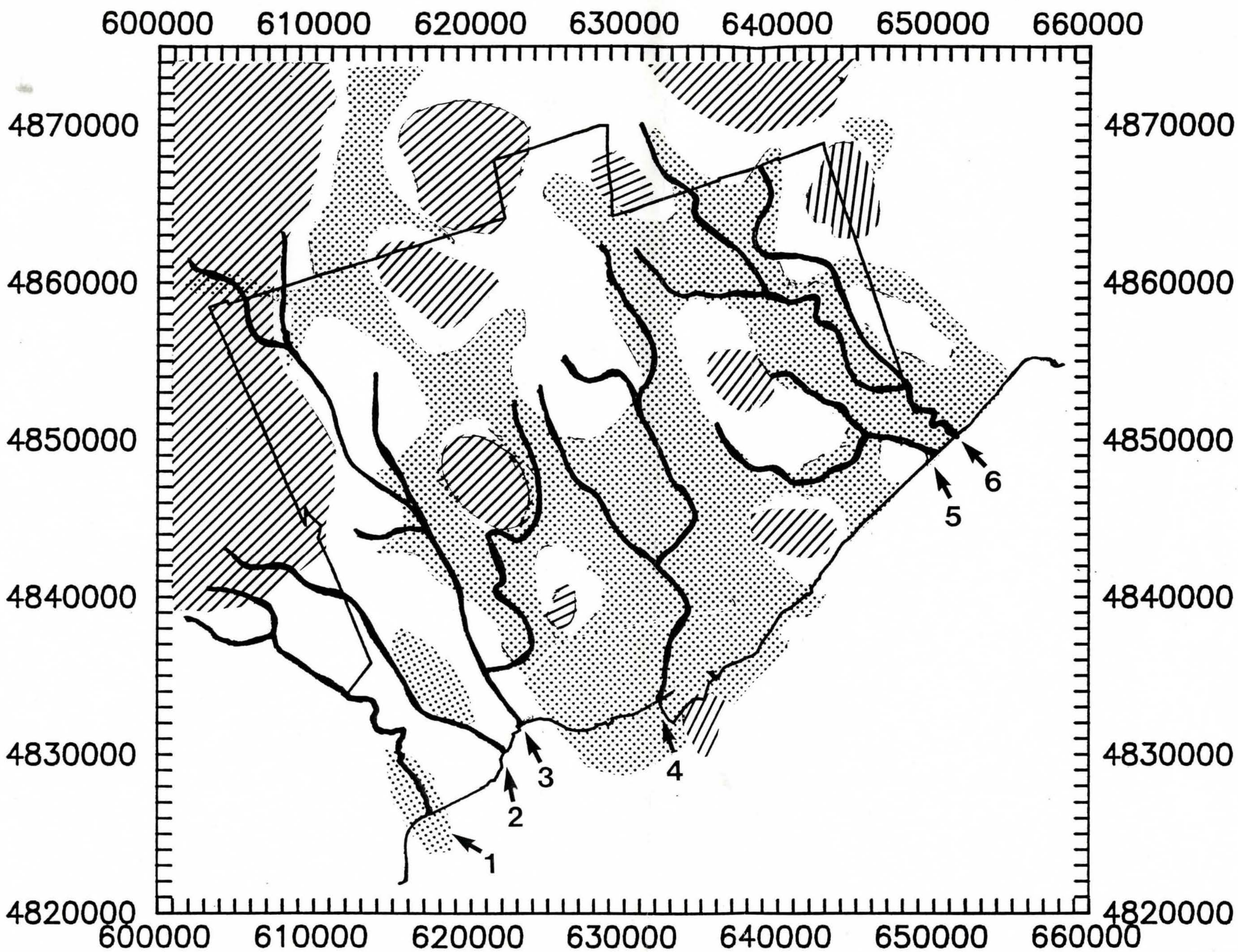


FIGURE 23: The present drainage systems in the field area mirror that which was established before the Illinoian glaciation. Large well developed rivers occupy the larger older bedrock channels while minor creeks occupy the more recently produced smaller bedrock channels. The water systems from west to east (1 to 6) are (1) Etobicoke Creek, (2) Mimico Creek, (3) Humber River, (4) Don River, (5) Highland Creek and (6) Rouge River.


600000
610000
620000
630000
640000
650000
660000
4820000
4830000
4840000
4850000
4860000
4870000
1
2
3
4
5
6

Considerable thicknesses of Pleistocene sediments have been found to be preserved in bedrock lows and channels due to selective preservation from glacial erosion. These generally waterlain sediments often exceed a thickness of 100 meters in the central part of the large channels (coincidently where well control is the lowest). In contrast topographic highs along the western and eastern edges of the study area are capped by a thin veneer of subglacial sediments.

5.2 Regional Isopach Map of the Halton Till

The second phase of the computer data base involved the compilation of Halton Till thickness data (see chapter 2). Only those wells which registered the basal contact of the Halton Till were included within the study. With the data an isopach map of the Halton was prepared in an effort to determine the regional geometry of the till **(figure 24)**.

The total area covered by the isopach map was estimated at 1,500 km^2, containing information on over 300 wells penetrating the Halton Till **(figure 25)**. The distribution of the data points are highly dependant on outcrop exposure and the locations of highways and subway lines. Gaps in the data are apparent in the north along the southern flanks of the Oak Ridges Moraine. In this area the Halton is buried under glaciofluvial outwash and kame deposits and few wells penetrate the surface for more than a few tens of meters. With continued urban development in this area subsurface information on the Halton Till in this area will

FIGURE 24: An isopach map of the Halton Till showing the true thickness of the till and its distribution in the survey area. If we compare this map to the bedrock topographic maps there is a distinct tendency for the Halton Till to be deposited in the 'highland' regions surrounding the Laurentian channel. The elongate distribution of the Halton Till in the east is likely the result of the channeling of the till into narrow bedrock channels which were likely produced during the Late Wisconsin ice advance. The western edge of the area show similar lobe like till concentrations. The central area overlying the Laurentian has noticeably little Halton Till.

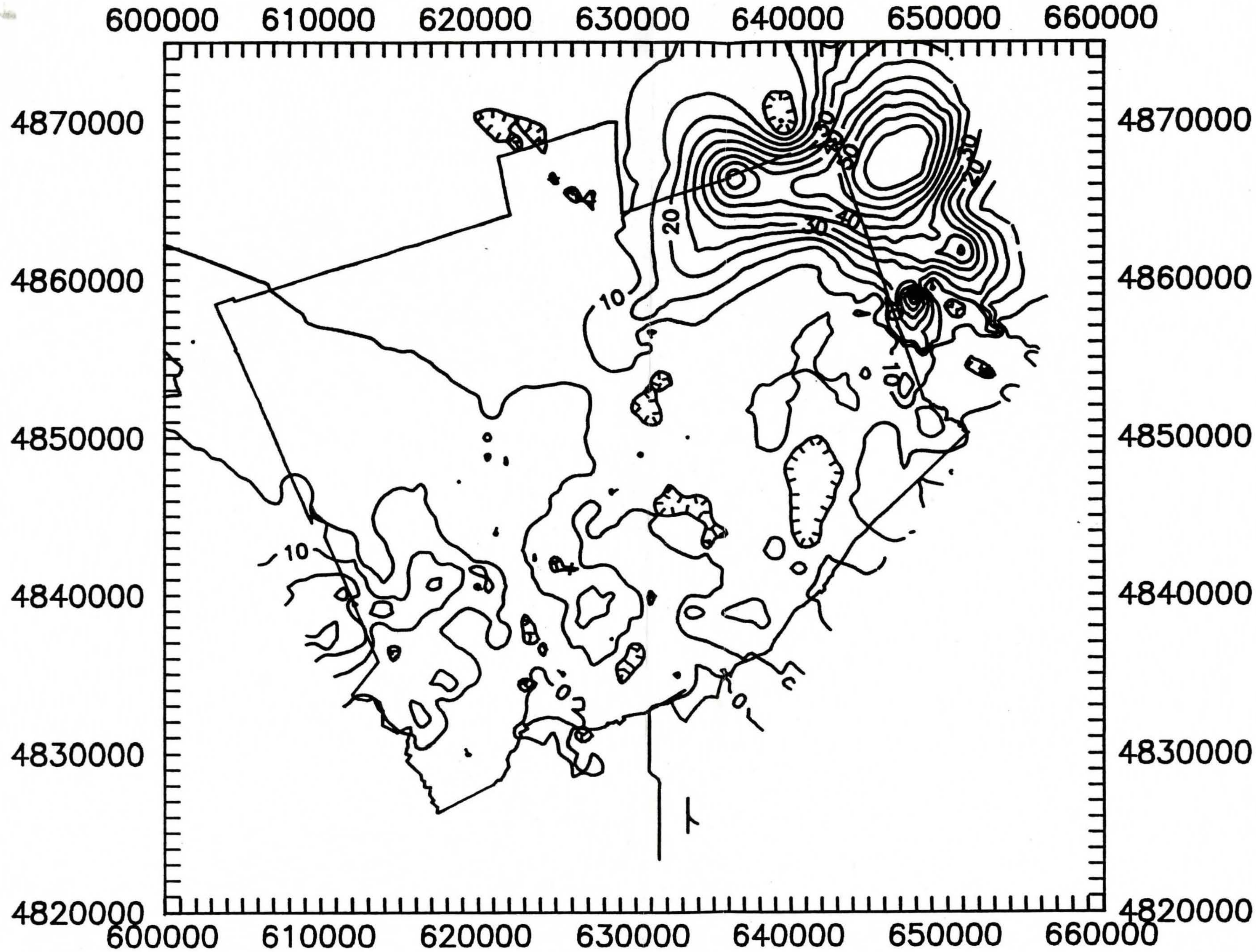
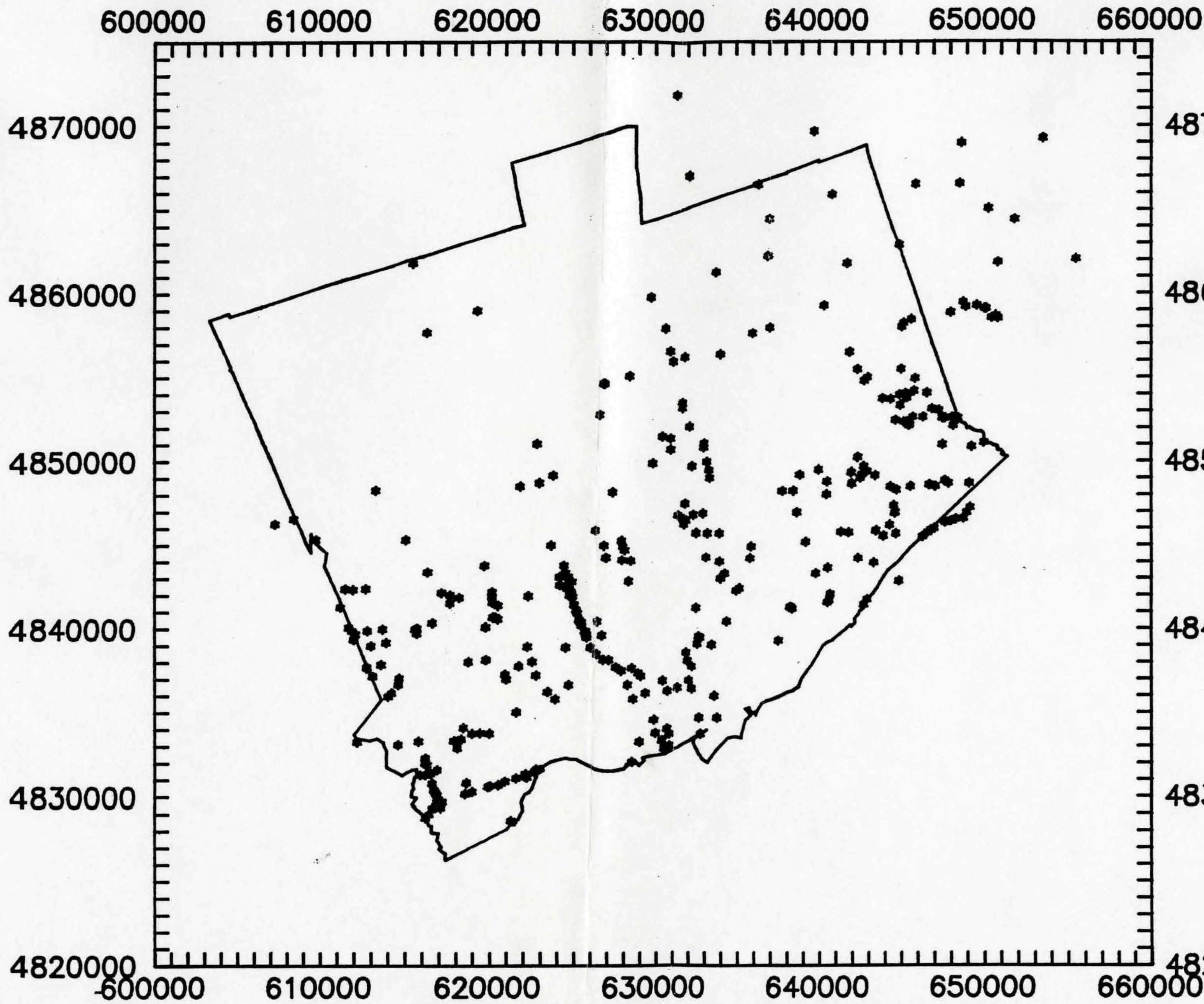

600000
610000
620000
630000
640000
650000
660000
4870000
4860000
4850000
4840000
4830000
4820000
10
20
30
40
50
60

FIGURE 25: A distribution of the outcrop sites and the over 300 wells used to compile the Halton Till database. Data distribution is good for the southern half of the study area. Only scatterd coverage is available for the field area as the Oak Ridges Moraine is approached.


600000
610000
620000
630000
640000
650000
660000
4870000
4860000
4850000
4840000
4830000
4820000

improve.

This isopach map is the first of its kind for the Halton Till in the Toronto area and may prove to be an aid in the search for suitable sites for future waste disposal sites. The isopach shows a general tendency for the Halton Till to be thickest along the western and eastern flanks of the map area **(figure 26)**. Maximum Halton thickness (in excess of 70 m) occurs in the eastern area of the map with three main centres of accumulation. These areas show a very rapid increase in the total thickness of the Halton over a very short distance (eg. an increase in till thickness from 10 m to 70 m over 4 km). This suggests the deposits are focused within contained areas which affects till distribution patterns.

There is a general trend for these 'contained areas' of the Halton Till to be distributed in a series of weak linear bands running approximately northwest/southwest parallel to ice flow. These bands of 'thicker' till are concentrated along the western and eastern edges of the map. The areas to the south along the lakeshore show no distinct trend in the thickness distribution of the Halton Till. This is probably due to erosion modification of the surface topography by Lake Iroquois about 12,000 y.b.p. **(figure 27)**. In the northern-central area where data are scarce the Halton Till is relatively thin (less than ten metres thick) with little thickness variation.

5.3 Discussion of Bedrock Topography and Halton Till Thickness

If a comparison is made between the bedrock topographic map

FIGURE 26: The 'fish net' or three dimensional block diagram stresses the extreme polarized distribution of the Halton Till. The central area overlying the Laurentian channel is deviod of the Halton Till except for areas in the extreme south which represent minor till accumulations on the stoss ends of bedrock highs. Major concentrations of the Halton Till occur to the west and east showing a distribution similar to a buttress effect. The arms of the buttresses may represent minor channels which have infilled with the Halton till.

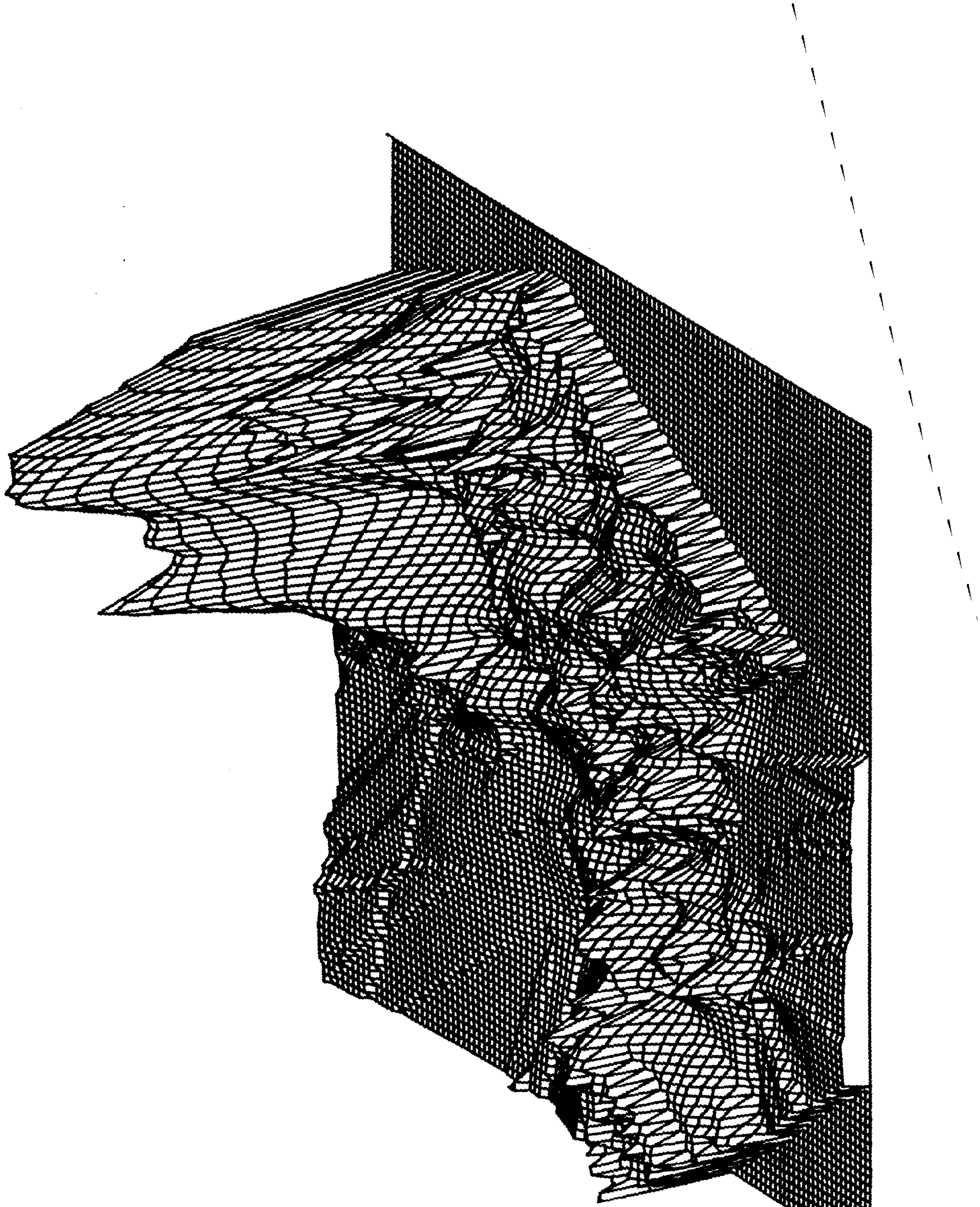
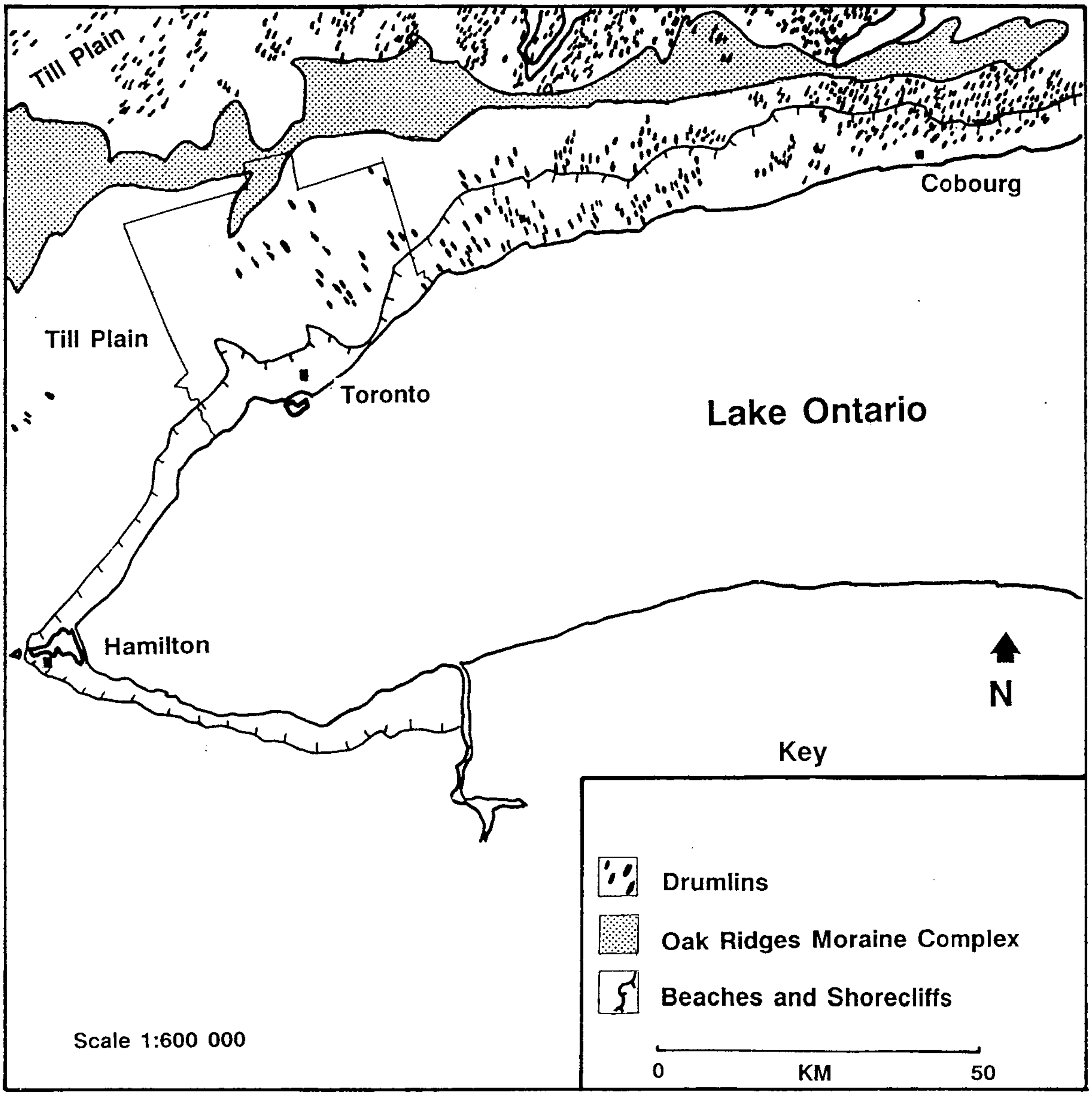


FIGURE 27: The general physiography of the database area (outlined in this figure) and the Halton Till basal contact field study area. A drumlinized till plain occupies much of the western Lake Ontario region with some erosion and modification of this plain by post glacial Lake Iroquois beaches and shorecliffs. Note the swing in drumlin orientation from east to west indicating ice flow pattern out of the Lake Ontario basin.


Till Plain
Till Plain
Toronto
Lake Ontario
Cobourg
Hamilton
N
Key
Drumlins
Oak Ridges Moraine Complex
Beaches and Shorecliffs
0
KM
50
Scale 1:600 000

and the Halton Till isopach map there are several strong relationships. The Halton Till has a maximum thickness in those areas where bedrock topography slopes upward from the Lake Ontario basin. These bedrock slopes have been heavily modified by Early Quaternary stream erosion and glacial overdeepening creating small bedrock valleys with a general northwest/southeast trend.

The larger bedrock channels (eg. Laurentian Channel) are often filled with a preserved stratigraphy of both glacial and interglacial deposits from Illinoian to Wisconsinan in age suggesting these large channels formed earlier than the last glaciation--possibly during the Tertiary (Eyles, 1986). These sediments are primarily pre to Late Wisconsin in age and survived the erosion associated with the final ice advance in the Toronto area approximately 18,000 y.b.p.

The smaller bedrock channels (eg. those on the western and eastern flanks of the Laurentian channel) are generally filled with gravels and sands capped by till or entirely filled by till. The presence of sands and gravels in some of these channels may indicate a fluvial or glaciofluvial origin while channels with till directly on bedrock suggest direct glacial erosion. The size of these smaller bedrock channels (15 km long by 2 to 5 km wide) underlines the importance of good well control and the 'hit and miss' nature of determining the exact location and number of these channels.

Considering the steep gradient and the short length of the smaller channels it is unlikely that they were formed entirely by 'normal' fluvial processes. The presence of interbedded tills and 'sandy gravels' which are not preserved in older channel sequences (eg. Laurentian channel) provides evidence for a glaciofluvial origin with later modification by direct glacial abrasion. Roughly half of the smaller channels are formed in shales and are filled with a thick layer of till containing shale clasts (probably of local origin) suggesting direct glacial abrasion (examples can be seen in Sibul, 1977). Evidence suggests that a combination of glaciofluvial and direct glacial abrasion produced many of the smaller bedrock channels during the Quaternary, probably during the ice sheet advance phase which deposited the Halton Till. The till located in these smaller channels has been interpreted as being the Halton Till.

It is assumed from drumlinoid forms and flutings on the Halton Till (Karrow, 1967) that ice flow was out of the Lake Ontario basin in the Toronto area **(figure 27)**, northwest to the Oak Ridges Moraine along a path that was approximately parallel to bedrock forms (eg. the central Laurentian channel and smaller tributaries).

If ice flow was approximately up valley with respect to these small channels (with gradients in excess of 5 m/1 km) it is probable that the heads and flanks of these valleys acted as areas for basal till accumulation. If this is true it is also likely that these channels were primarily infilled from their heads downvalley. Because of the extreme gradients associated with these small channels (see chapter 5.1) and the tremendous amounts of subglacial meltwater which accompany a warm based glacier it is possible that debris like flows may have redeposited till downslope in catastrophic events producing crudely stratified Halton Till (see chapter 6).

These stratified till deposits are generally confined to lakeshore areas where it is likely several of these smaller bedrock channels exist (eg. small bedrock channels exist beneath the Rouge R., Mimico Ck. and other present day streams) **(figure 28).** The smaller channels are located in the bedrock scarps on the western and eastern edges of the central Laurentian channel and along a bedrock scarp which seems to parallel the present Lake Ontario shoreline.

The central Laurentian channel contains isolated elongate bedrock highs of moderate relief (20 m higher than the base of the channel) where the large channel divides into distributaries. Further upstream the bedrock highs exhibit greater changes in relief (60 to 90 m higher than the channel floor) indicating a more confined channelized flow system. A broad bedrock area (roughly 20 km wide by 35 km long) of low relief separates the incised channel area from the distributary channels **(figure 23).**

The thickness of the Halton Till is at a minimum (less than 10 m thick) in the broad bedrock area of low relief (discussed above) and in those areas which have been highly modified by Lake Iroquois surface erosion **(figures 29 and 30).** Total erosion of the Halton Till occurred from the downtown area of Toronto to Mimico Creek up to 3 km inland. The lee ends and peaks of bedrock highs in the Laurentian channel are generally devoid of thick deposits (less than 10 m thick) of the Halton Till. There is weak indications of slightly thicker deposits of Halton Till (10 to 20 m thick) on the stoss ends of those Laurentian channel bedrock

FIGURE 28: In the vicinity of the Scarborough Bluffs minor bedrock channels have been delineated from water well data by Eyles (1986). The density of these minor channels along the present shore of Lake Ontario was probably produced during the Late Wisonsin ice advance and co-deposition of the Halton Till. Crudely stratified deposits of the Halton Till discussed by Karrow (1967) may be the result of channelized deformation till.

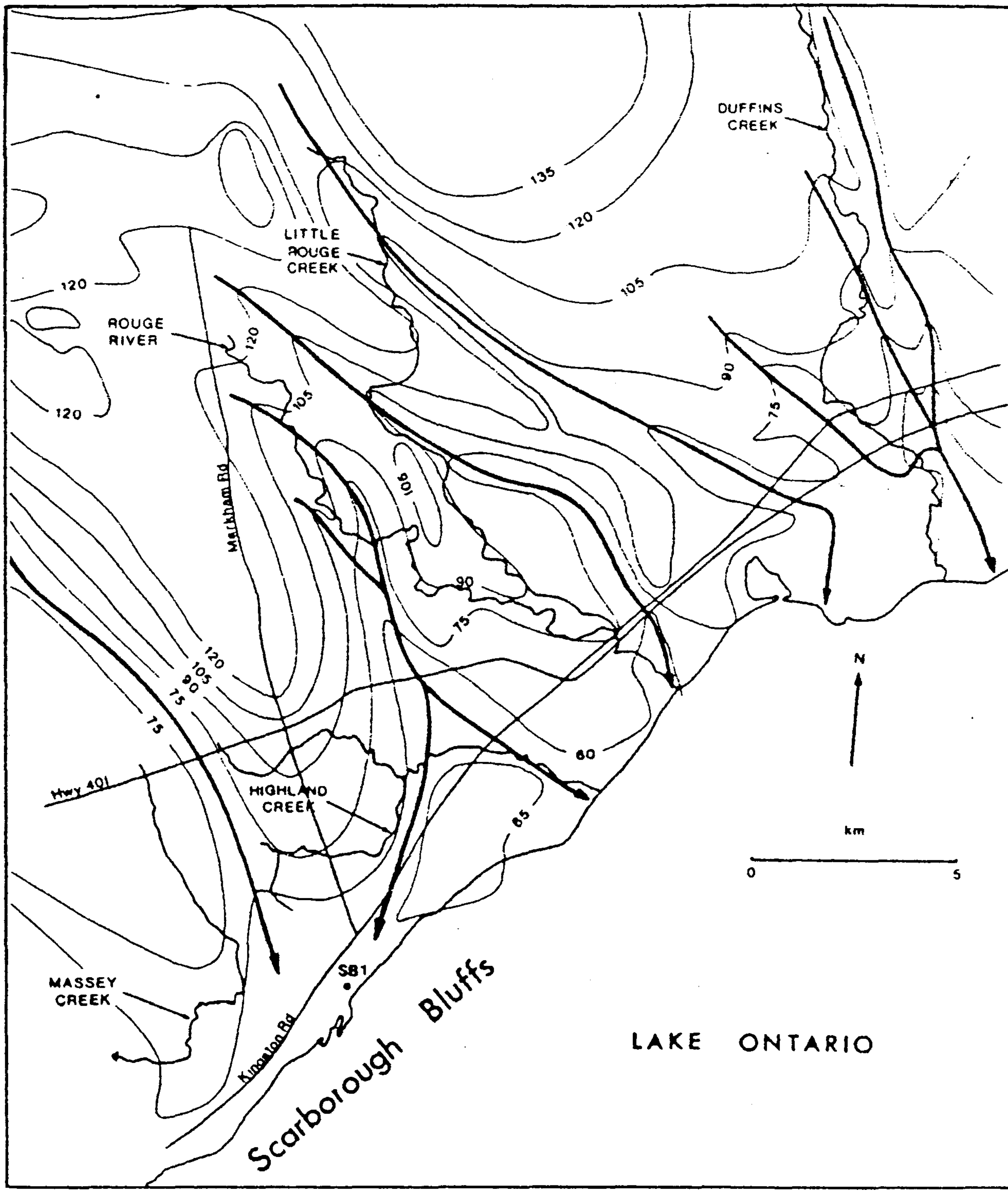

DUFFINS CREEK
135
120
105
90
75
LITTLE ROUGE CREEK
120
ROUGE RIVER
120
120
105
106
Markham Rd
90
75
120
105
90
75
75
60
Hwy 401
HIGHLAND CREEK
65
N
km
0
5
MASSEY CREEK
SB1
Kingston Rd
Scarborough Bluffs
LAKE ONTARIO

FIGURE 29: An alternative three dimension block diagram plot of the Halton TIll thickness distribution produced using only a Z-contour plot. The contours have a 5 meter interval and the colour was not produced by direct output. The relative thickness of till in each general area is well illustrated showing very thick deposits of the Halton Till in the highland areas to the east.

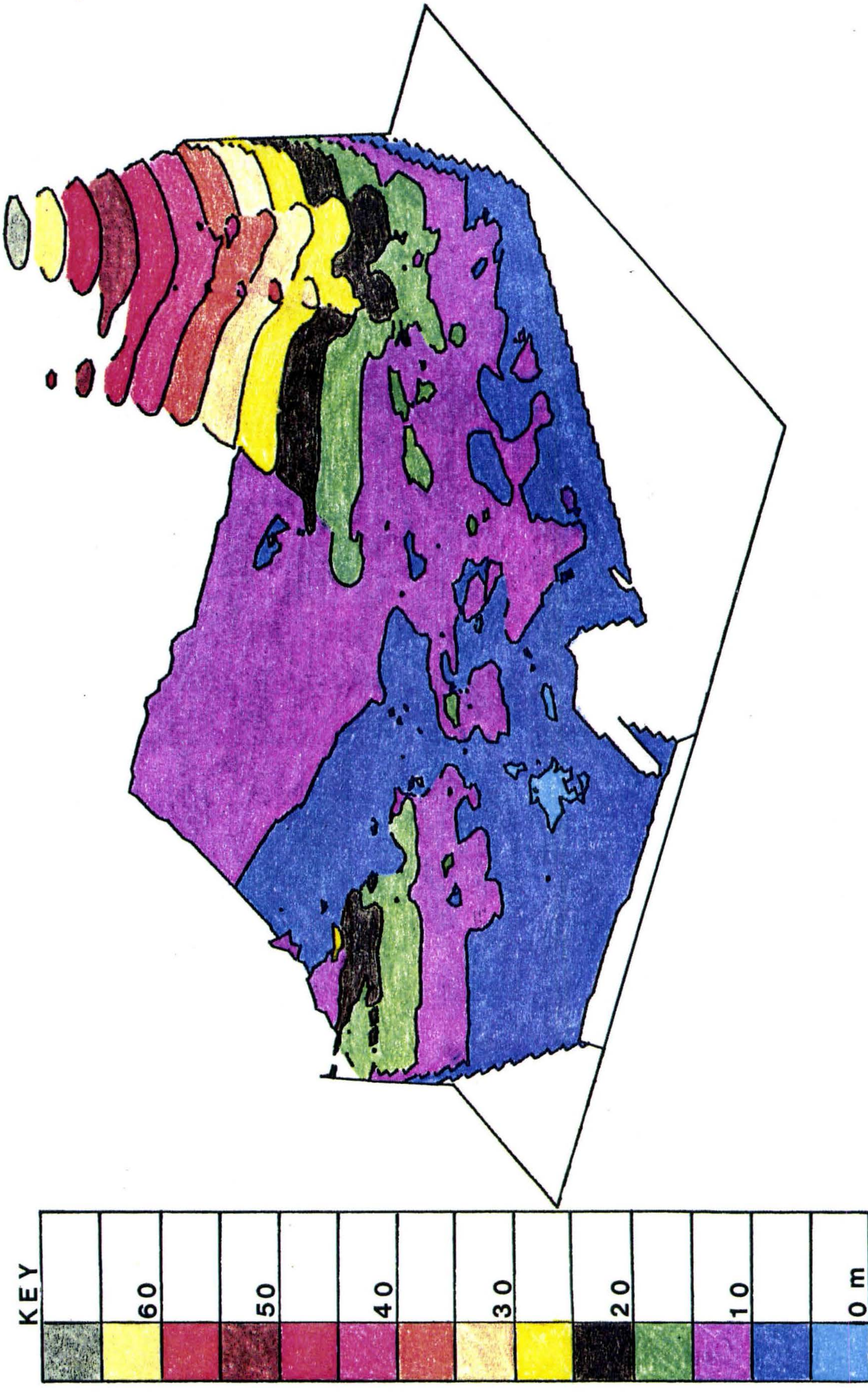
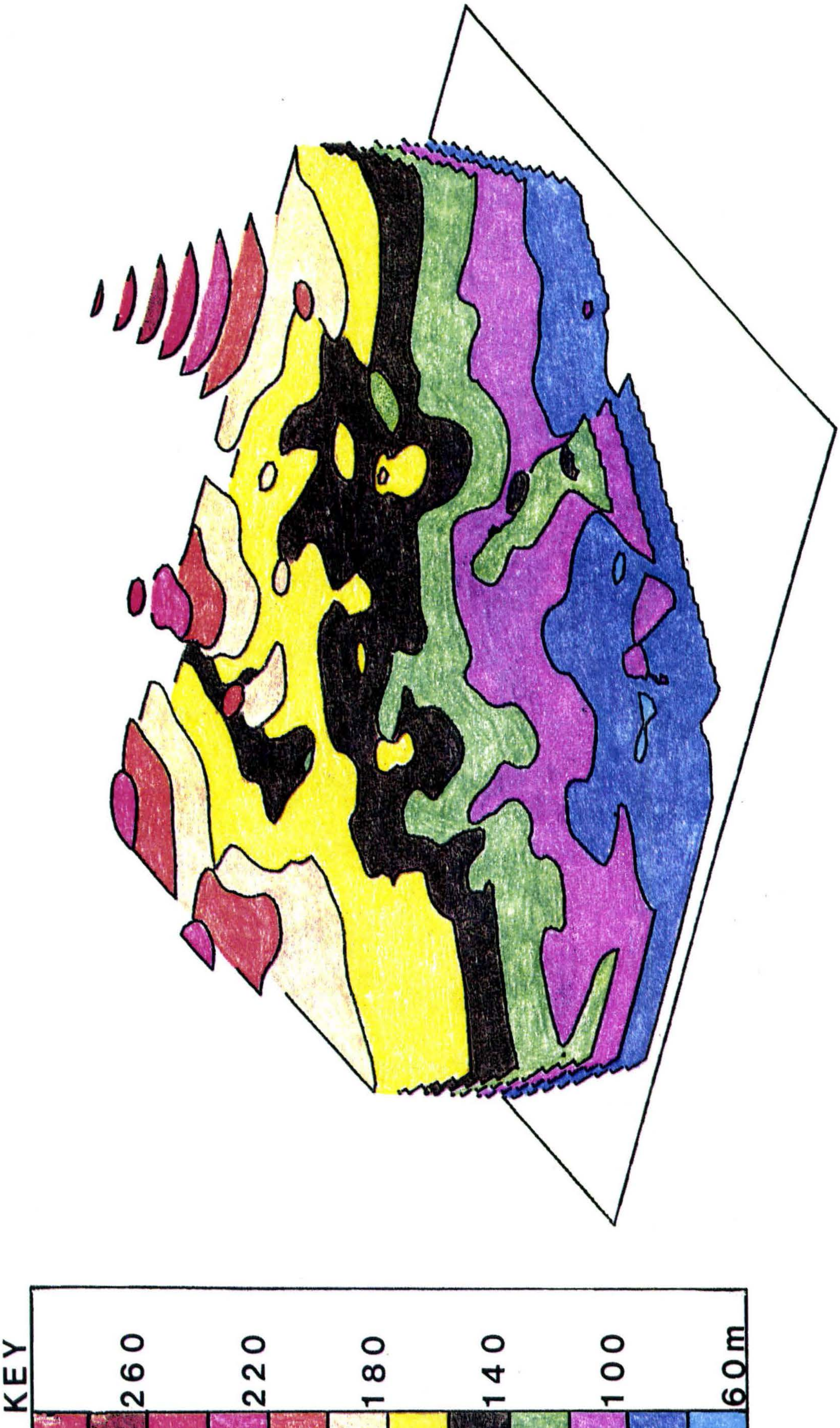

KEY
60
50
40
30
20
10
0 m

FIGURE 30: An alternative three dimensional block diagram plot of the bedrock subsurface topography. The main Laurentian channel in the north west shows a strong presence even with a 20 m contour interval. The division of this single channel into smaller distributaries is well illustrated by the colours used to represent the bedrock elevations from 100 to 140 m.


KEY
260
220
180
140
100
60m

highs located in the distributary area (near the present lakeshore). These stoss deposits in the Laurentian channels distribute the Halton Till in a series of weakly developed bands parallel to ice flow.

The bedrock scarps which surround the Laurentian channel and border the present shoreline of Lake Ontario contain thick pockets of till **(figures 29 and 30)**. The smaller bedrock valleys in the scarp to the west of the Laurentian channel consistently contain deposits between 20 to 40 m thick of the Halton Till. The thickest deposits are concentrated in the upper reaches or the 'heads' of the smaller bedrock valleys where the gradient of the valley is highest.

The small bedrock valleys in the eastern scarp of the Laurentian channel and those in the scarp that parallels the present Lake Ontario shoreline show 20 to 60 m thick accumulations of the Halton Till **(figures 29 and 30)**. Similar to till thickness distributions in the western scarp, the Halton Till shows its greatest accumulation at the 'heads' of the small bedrock valleys.

CHAPTER 6

CONCLUSIONS

6.1 Conclusions

The Halton Till exposed in the Toronto area exhibits many characteristics of a basal glacial diamict (Eyles and Eyles, 1983). The subglacial origin of the Halton Till is strongly supported by the presence of flutings, drumlins and bullet shaped boulders (Sharpe, 1988). Published fabric data often show a wide variety of clast orientations ranging from a northwest/southeast alignment parallel to subglacial landforms such as drumlins (Karrow, 1967), to a random pattern (Ostry, 1962), to a variety of orientations dependent on till thickness (Dreimanis and Terasmae, 1958). The highly variable clast orientation is an indication that the Halton Till was formed by processes more complicated than those produced by simple lodgement.

The Halton Till shows considerable variability in its sedimentology when examined in the field. A poorly defined zone approximately 2 to 4 meters thick occupies an area directly above the Halton Till basal contact. This zone contains a large number of glacitectonic structures which indicate some subglacial deformation of the lower Halton Till accompanied by large scale deformation and shearing of underlying prexisting sediments. Stringers and pods of these older sediments are located in the basal area of the Halton Till indicating direct incorporatation of overridden sediments into the diamict.

The presence of dewatering pipes and gravel lags along the basal contact of the Halton Till indicate large amounts of meltwater were present at the time of incorporation. Coarse grained gravel and sand pods near the base of the Halton Till reveal that the basal area must have been highly saturated to transport these rounded sediment rafts upwards into the till roughly 0.5 to 1.0 meters.

Stratigraphically higher in the Halton till there are thin stringers of sands. These probably formed from the traslocation of finer sediments during periods where the till experienced influxes of diffuse meltwater and where the liquifaction limit was approached. Local incorporation of subglacial meltwater channels may also play an important role in the distribution of these stringers located above the basal zone. Large crudely stratified channel shaped deposits of the Halton till indicate evidence for slurry type flows beneath the glacier base downslope from the bedrock highs. These till channels have an erosive base and generally appear only in those areas where bedrock channels are suspected of being located.

Grain size analyses of the Halton Till matrix show distinct trends in both the lateral and vertical distribution of sand, silt and clay. A strongly developed lateral trend shows a general increase in the total sand content of the Halton Till from east to west. This is due to the incorporation of sediments from the Scarborough and Thorncliffe Formation's which exist primarily in the west. Vertical variation in the grainsize distribution of the Halton Till shows a consistant relationship between the grain size distribution of the Halton Till's basal zone and the lithology of the underlying sediments (eg. a sandy Halton Till base exists where overlying sandy units). This dependant relationship between the grain size variation in the Halton Till basal zone and underlying units (both sands and diamicts) generally weakens upwards through the basal zone.

Maps of the bedrock topography produced of the Toronto basin by the software SURFER indicate the presence of a large central Laurentian channel entering from the northwest. This channel broadens to fill a bedrock low and is disected into a series of distributary channels when it enters the present Lake Ontario basin. Smaller bedrock channels representing tributaries to the Laurentian channel are located in surrounding highland areas with gradients 5 to 10 times that of the main channel. Subsurface information suggests these channels oriented rougly parallel to ice flow were likely carved during the advance phase of the Halton Till by meltwater and/or direct glacial abrasion.

Isopach maps of the Halton Till distribution display a series of poorly defined linear bands of till oriented in a northwest/southeast trend. Centers of Halton Till accumulation are located in the bedrock highland areas. Maximum till thickness of over 70 meters in the east and 30 meters in the west exist in the bedrock highs surrounding the Laurentian channel. It is suspected that the till has preferentially accumulated in the heads of these high gradient small bedrock valleys. The broad Laurentian channel is devoid of thick accumulations of the Halton Till (eg. less than 5 m thick) except for pockets on the stoss ends of isolated bedrock highs.

The continued development of this large database is likely to have widespread implications for applied engineering projects in the Toronto region. Mapping the geometry of the Halton Till enables the rapid identification of thick areas of till accumulation. The urgent demand for environmentally safe waste disposal sites (eg. those requiring impermeable substrates) may be answered by examining areas of thick Halton Till.

Understanding the relationships between bedrock topography and the variation in thickness of the Halton Till will further aid in the identification of potential waste disposal sites. The lithology of the permeable sediments underlying the Halton Till will affect all evaluations of potential landfill sites. Large bedrock channels (eg. Laurentian channel) are not be suitable for landfill and liquid waste disposal sites due to the very thin veneer of Halton Till which overlies thick sequences of highly permeable glaciolacustrine and deltaic sediments. Smaller bedrock channels containing thick deposits of Halton Till overlying thin discontinious glaciofluvial sequences may represent more suitable sites.

This approach to basin analysis can be expanded as the data base grows to include information on the geometry of aquifers, measurement of aquifer discharge rates, storage capacities and the impact of development on 'recharge' areas. Environmental concerns may also be addressed by tracking leacheate migration in permeable sediments and determining potential sites of future contamination. Transportation projects requiring stable platforms (eg. bridges) may find potential use for regional subsurface sedimentology and its geometry.

The new data provided by both the bedrock and isopach maps accompanied by sedimentological and grain size analysis provides further information on the depositional origin of the Halton Till. The highly variable thickness of the Halton Till, its concentration in small bedrock channels and field evidence of a highly water saturated basal zone in the Halton Till suggests a deformable till capable of limited slurry type flow. Observation in the field and laboratory analyses of matrix samples indicate widespread incorporation of underlying older sediments into the Halton Till's basal zone. Fabric data from published sources (Karrow, 1967; Ostry, 1962) indicate highly variable (sometimes random) clast orientations which would suggest emplacement by means other than lodgement.

Consideration of the Halton Till as a 'deformation till' is much more suitable than the traditional view of the emplacement of the till sheet by 'lodgement' processes.

BIBLIOGRAPHY

Babaris, A. 1975. Petrographic characteristics of tills along the north-west shore of lake Ontario and north to the Oak Ridges Moraine. B.Sc. Thesis, Brock University. 1975.

Bancroft, B. A., and Hobbs, G. R., 1986. Distribution of Kriging Error and Stationarity of the Variogram in a Coal property. Mathematical Geology, v 18, no. 7, p. 635-651.

Boulton, G.S. 1975. Processes and patterns of subglacial sedimentation: a theoretical approach. (In Wright, A.E., and Moseley, F., eds. Ice Ages: ancient and modern. Liverpool, Seel House Press, p. 7-42.)

Boulton, G.S. 1979. Processes of glacier erosion on different substrata. Journal of Glaciology, v 23, p. 15-38.

Boulton G.S. 1987. A theory of drumlin formation by subglacial sediment deformation in Drumlins: a Symposium, 1985, ed. by J. Rose and J. Menzies, Balkema, Rotterdam, 1987.

Boulton, G.S., and Hindmarsh C.A. 1987. Sediment deformation beneath glaciers: rheology and geological consequences. Journal of Geophysical Research, v 92, No. B9, p. 9059-9082.

Boulton G.S., and Jones A.S. 1979. Stability of temperate ice sheets resting on beds of deformable sediment. Journal of Glaciology, v 24, p. 29-43.

Burgess, T. M., and Webster, R., 1980a. Optimal Interpolation and Isarithic Mapping of Soil Properties I The Semi-variogram and Punctual Kriging. J. of Soil Science, v 31, p. 315-331.

Burgess, T. M., and Webster, R., 1980b. Optimal Interpolation and Isarithic Mapping of Soil Properties II Block Kriging. J. of Soil Science, v 31, p. 333-341.

Burgess, T. M., Webster, R., and Mc Bratney, A. B., 1981. Optimal Interpolation and Isarithic Mapping of Soil Properties IV Sampling Strategy. J. of Soil Science, v 32, p. 643-659.

Burrough, P. A., 1987. Principles of Geographical Information Systems for Land Resources Assessment; Ed. by Beckett, P. H. T., Clarendon Press. Oxford, p. 194.

Carr, J. R., Deng, E. D., and Glass, C. E., 1986. An Application of Disjunctive Kriging for Earthquake Ground Motion Estimation. Mathematical Geology, v 18, no. 2, p. 197-209.

Carr, J. R., and Bailey, R. E., 1986. An Indicator Kriging Model for Investigation of Seismic Hazard. Mathematical Geology, v. 18, no 7, p. 409-427.

Carruthers, R.G. 1947-48. The secret of glacial drifts. Proceedings of the Yorkshire Geological Society, v 27, p. 43-57 and 129-172.

Chamberlain, T.C. 1894. Proposed genetic classification of Pleistocene glacial formations. Journal of Geology, v 2, p. 517-38.

de Raaf, J.F.M., Reading, H.G., and Walker, R.G. 1965. Cyclic Sedimentation in the lower Westphalian of North Devon, England. Sedimentology, v 25, p. 773-779.

Dreimanis, A., and Terasmae, J. 1958. Stratigraphy of Wisconsin glacial deposits of Toronto area, Ontario; Geological Association of Canada Proceedings, Toronto, v 10, p. 119-136.

Duncan, G. A., and Lahaie, G. G., 1979. Size analysis procedures used in the sedimentology laboratory; NWRI, CCIW, Hydraulics Division Manual.

Elson, J.A. 1961. The geology of tills. Proceedings of the 14th Canadian Soil Mechanics Conference, le Oct. 13-14, 1960. Ottawa National Research Council, p. 5-35.

Eyles, N. 1986. Late Pleistocene depositional systems of Metropolitan Toronto and their engineering and glacial geological significance. Canadian Journal of Earth Science, v 24, p. 1009-1021.

Eyles, C.H., and Eyles N. 1983. Sedimentation in a large lake: a reinterpretation of the late Pleistocene stratigraphy at Scarborough Bluffs, Ontario, Canada. Journal of Geology, v 11, p. 146-152.

Eyles, N., Eyels, C.H., and Maill A.D. 1983. Lithofacies types and vertical profile models: an alternative approach to the description and environmental interpretation of glacial diamict and diamictic sequences. Sedimentology, v 30, p. 393-410.

Eyles, N., and Maill A.D. 1984. Glacial Facies Models, in Walker, R.G. (ed.) Facies Models: Geoscience Canada Reprint Series: Geological Association of Canada, Toronto, p. 15-38.

Eyles, N., Clark, B.M., Kaye, B.G., Howard, K.W.F., and Eyles C.H. 1985. The application of Basin Analysis Techniques to Glaciated Terrains: An Example from the Lake Ontario Basin, Canada. Geoscience Canada, v 12, No. 1, p. 22-32.

Flint, J.J., and Lolcama, J. 1986. Buried ancestral drainage betweeen lakes Erie and Ontario. Geological Society of America Bulletin, v 97, p. 75-84.

Goodchild, J.G. 1875. The glacial phenomena of the Eden Valley and the western part of the Yorkshire Dales district. Quarterly Journal of the Geological Society of London, v 31, p. 55-99.

Gripp, K. 1929. Glaziologische und geologische Erebnisse der Hamburgischen Spitzbergen Expedition 1927. Naturwissenschaftlicher Verein in Hamburg. Abhandlungen der Gebiet von Naturwissenschaften, Bd. 22, Nos. 2-4, p. 146-249.

Hartshorn, J.H. 1958. Flowtill in southeastern Massachusetts. Geological Society of America. Bulletin, V 69, p. 477-82.

Hoppe, G., and Schytt, V. 1953. Some observations on fluted moraine surfaces. Geografiska Annaler, Bd. 35, Ht. 2, p. 105-15.

Journel, A. G., 1986a. Geostatistics: Models and Tools for Earth Sciences. Mathematical Geology, v 18, p 134-135.

Journel, A. G., 1986b. Constrained Interpolation and Qualitative Information--The Soft Kriging Approach. Mathematical Geology, v 18, no. 3, p. 269-285.

Kamb, B., and LaChapelle, E. 1964. Direct observation of the mechanism of glacier sliding over bedrock. Journal of Glaciology, v 5, No, 38, p. 159-72.

Karrow, P.F., 1967. Pleisticene geology of the Scarborough area. Ontario Department of Mines, Geological Report 46.

Karrow, P.F., 1972. Pleisticene geology of the Scarborough area. Ontario Department of Mines, Geological Report 46.

Lamplugh, G.W. 1911. On the shelly moraines of the Sefstrom Glacier. Proceedings of the Yorkshire Geological Society, v 17, p. 215-41.

Lawson, D.E. 1979. Sedimentological analysis of the western terminus regoin of the Matanuska Glacier, Alaska. CRREL Report 79-9.

Ostry, R.C. 1962. An analysis of some tills in Scarborough Township and vicinity. M.A. Thesis, University of Toronto, 1962.

Puente, C. E., and Bras, R. L., 1986. Disjunctive Kriging, Universal Kriging, or No Kriging: Small Sample Results with Simulated Fields. Mathematical Geology, v 18, no. 3, p.

287- 305.

Shaw, J., 1969. Drumlin formation related to inverted erosion marks. Journal of Glaciology, v 29, p. 461-479.

Sharpe, D.R. 1988. The internal structure of glacial landforms: na example from the Halton till plain, Scarborough Bluffs, Ontario. Boreas, v 17, p. 15-26.

Smalley, I.J., and Unwin, D.J. 1968. The formation and shape of drumlins and their distribution and orientation in drumlin fields. Journal of Glaciology, v 7, p. 377-400.

Solow, A. R., 1986. Mapping by Simple Indicator Kriging. Mathematical Geology, v 18, no. 3, p. 335-351.

Spencer, J. W. 1890. Origin of the basins of the Great Lakes of America. American Geologist, v 7, p. 86-97.

Tarr, R.S. and Martin, L. 1914. Alaskan glacier studies. Washington, D.C., National Geographic Society.

Walker, R.G. 1984. General Introduction: Facies, facies sequences and facies models, in Walker R.G. (ed.) Facies Models, second edition, Geoscience Canada Reprint Series 1, p. 1-10.

Warnes, J. J., 1986. A Sensitivity Analysis for Universal Kriging. Mathematical Geology, v 18, no. 7, p. 653-675.

Webster, R., and Burgess, T. M., 1980. Optimal Interpolation and Isarithmic Mapping of Soil Properties III Changing Drift and Universal Kriging. J. of Soil Science, v 31, p. 505-523.

Weertman, J. 1961. Mechanism for the formation of inner moraines found near the edge of cold ice caps and ice sheets. Journal of Glaciology, v 3, No. 30, p. 965-78.

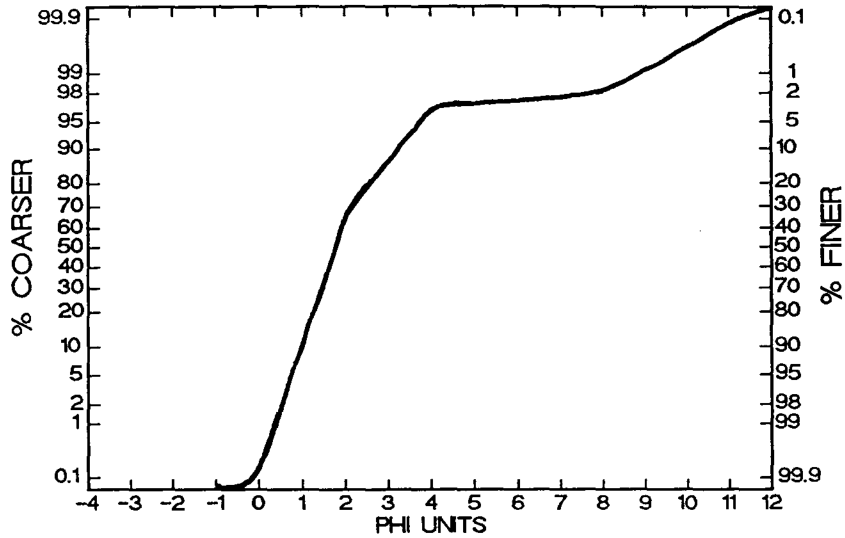
Appendix I

The equipment used in the data sample collection included a square ended garden spade, a twenty cm trowel, a twenty meter measuring tape, a rock hammer, a hollow metal sampling tube 10 cm in diameter, plastic sample bags, elastics, field notebooks, boots and writing instruments.

The equipment used in the laboratory work included one litre beakers, 250 ml flasks, a Regant 1000 measuring scale (with 3 decimal places), crucibles, porcelin soil dishes, a soil drying oven, grinding pedestal, distilled water, soil sieves a large bucket, hot plate and Calgon (a water softener agent).

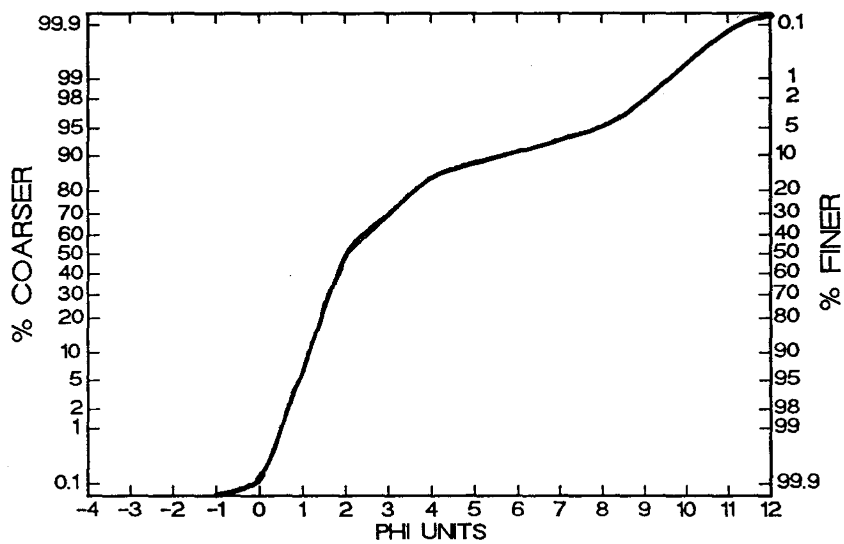
Appendix II

S1-1



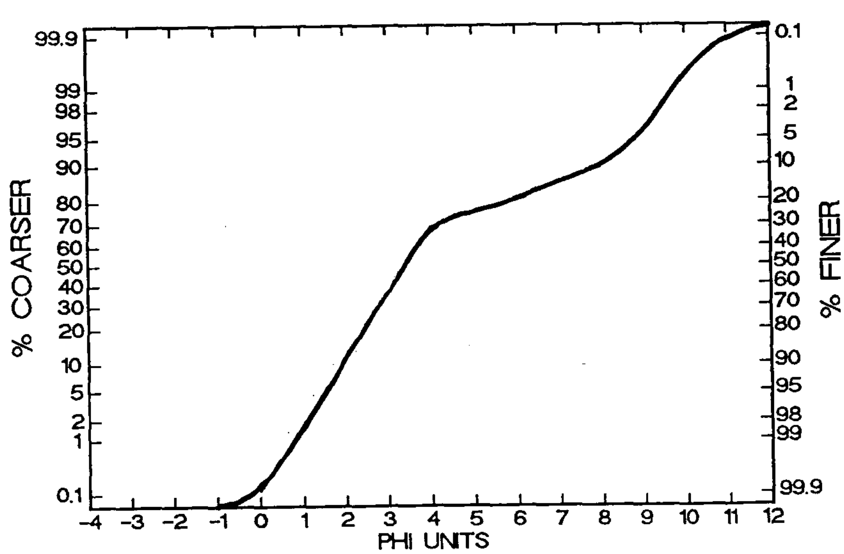
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% COARSER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
% FINER
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

S1-2



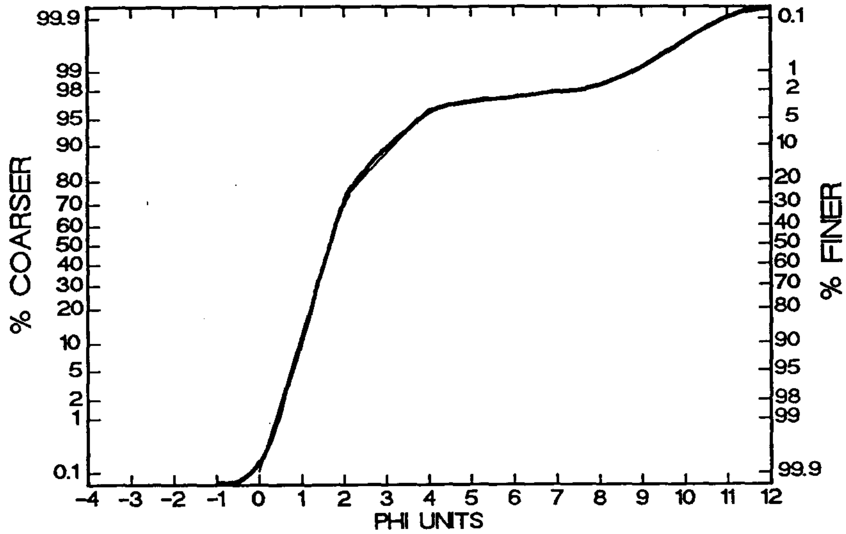
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% COARSER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
% FINER
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

S1-3

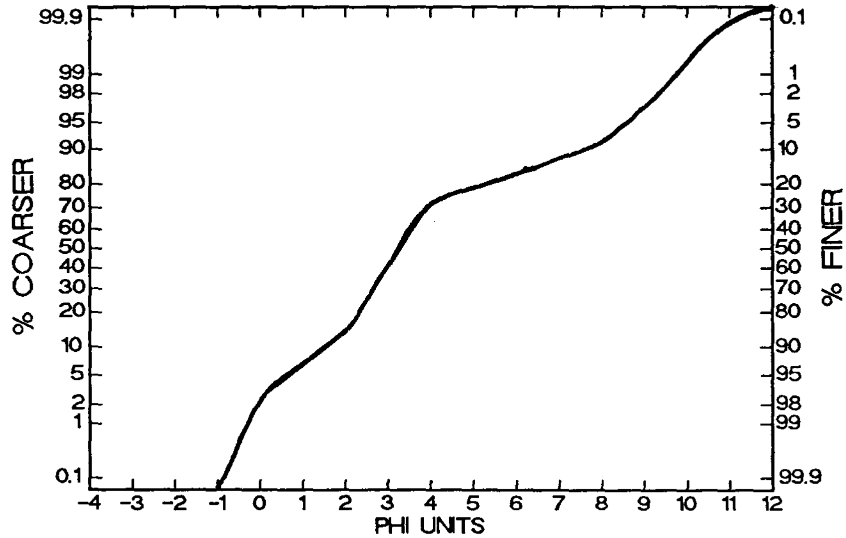


99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% COARSER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
% FINER
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

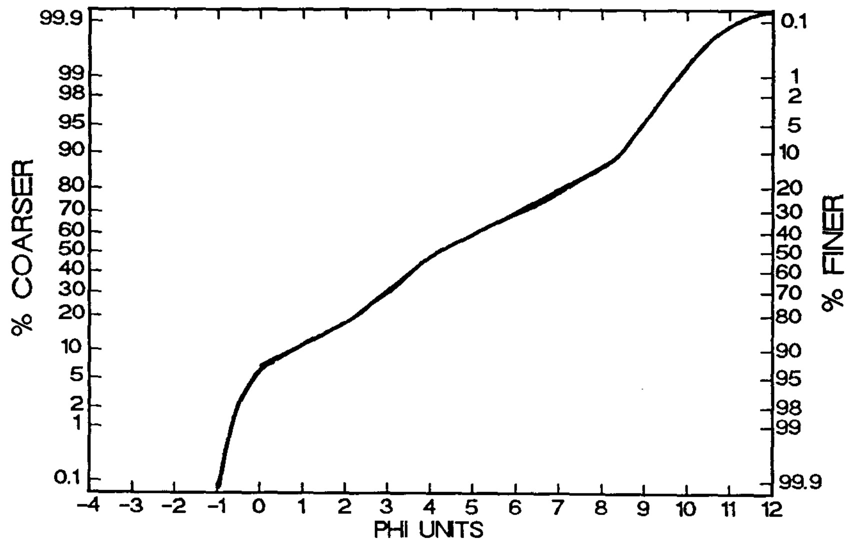
S2-1

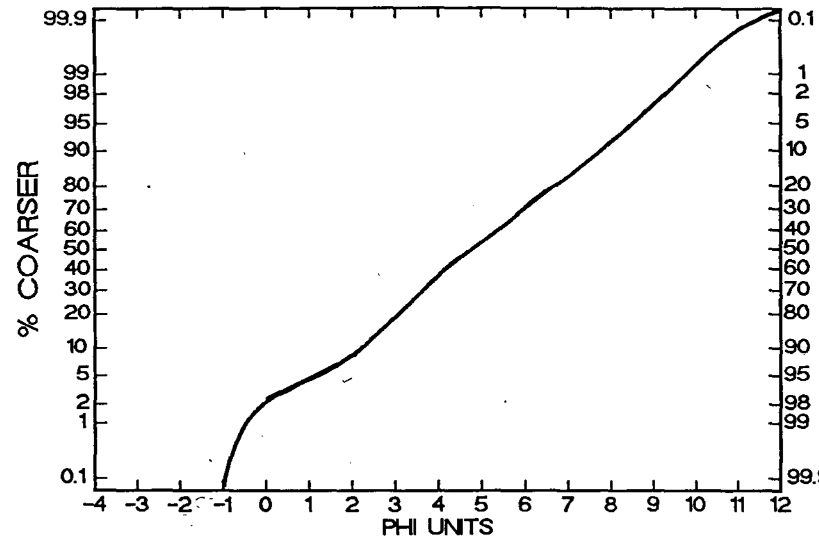

99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% COARSER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
% FINER
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

S2-2

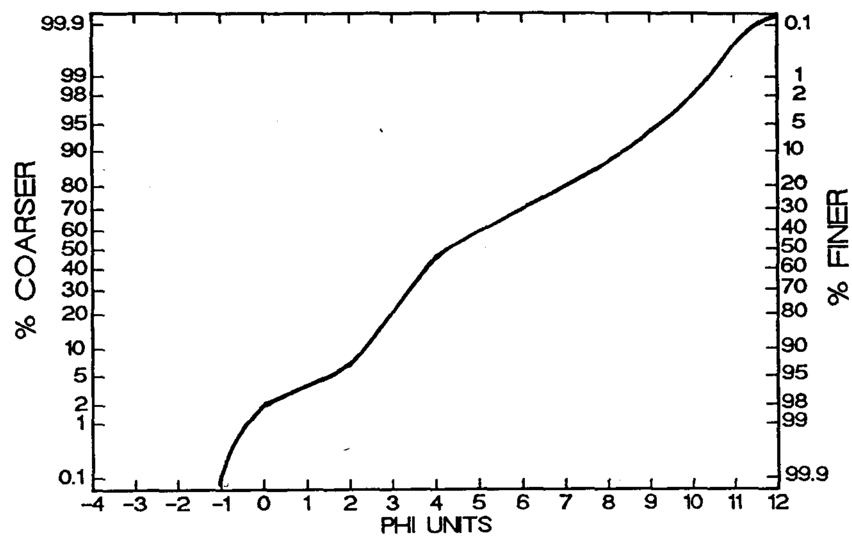

99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% COARSER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
% FINER
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

S2-3

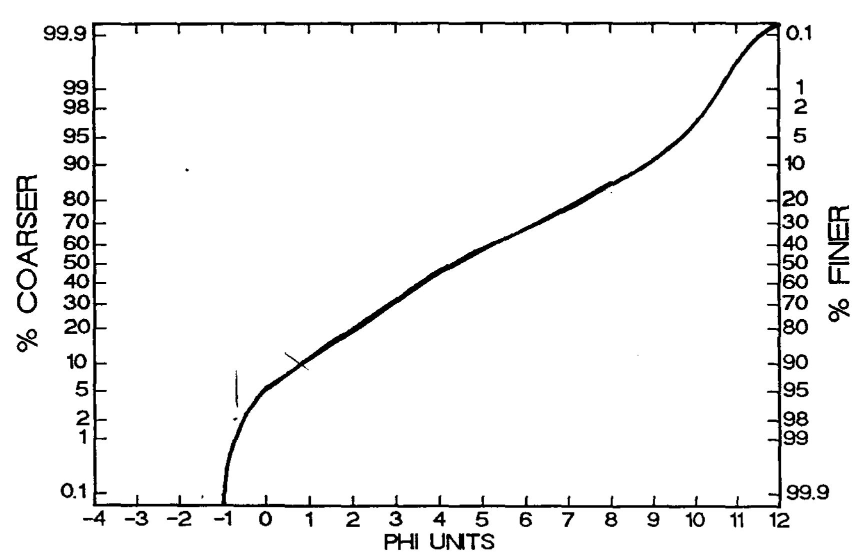

99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% COARSER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
% FINER
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS


% COARSER
% FINER
PHI UNITS
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12

S3-1

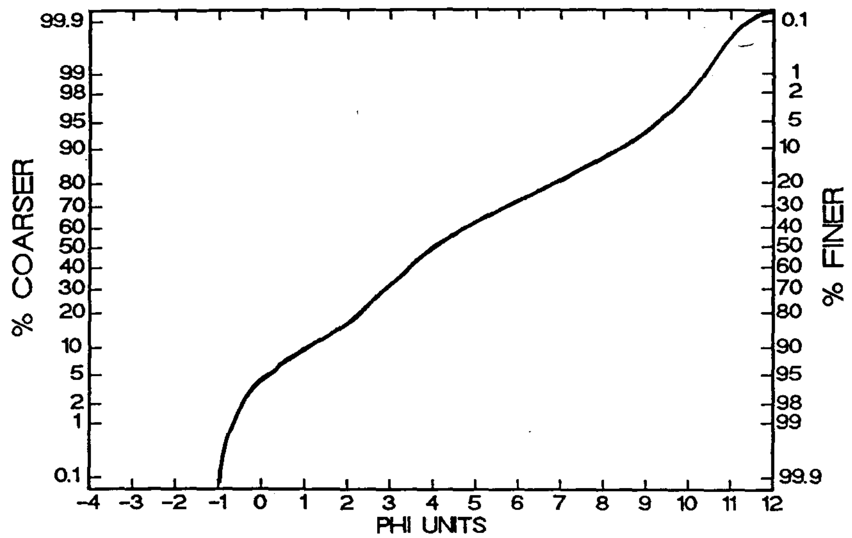

% COARSER
% FINER
PHI UNITS
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12

S3-2

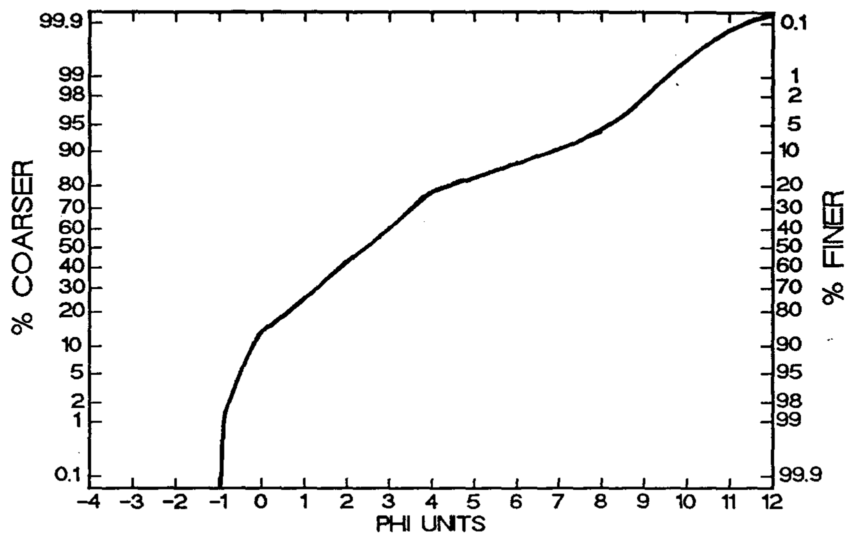

% COARSER
% FINER
PHI UNITS
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12

S3-3

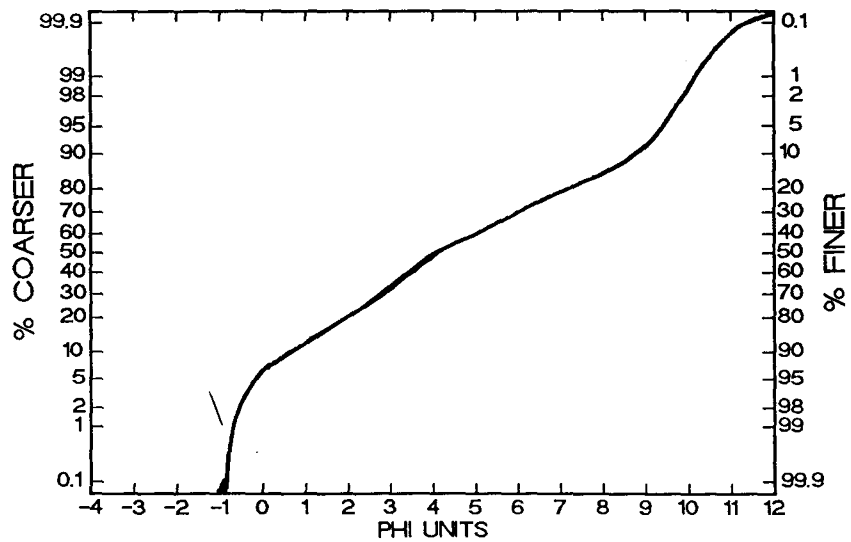
S3-4

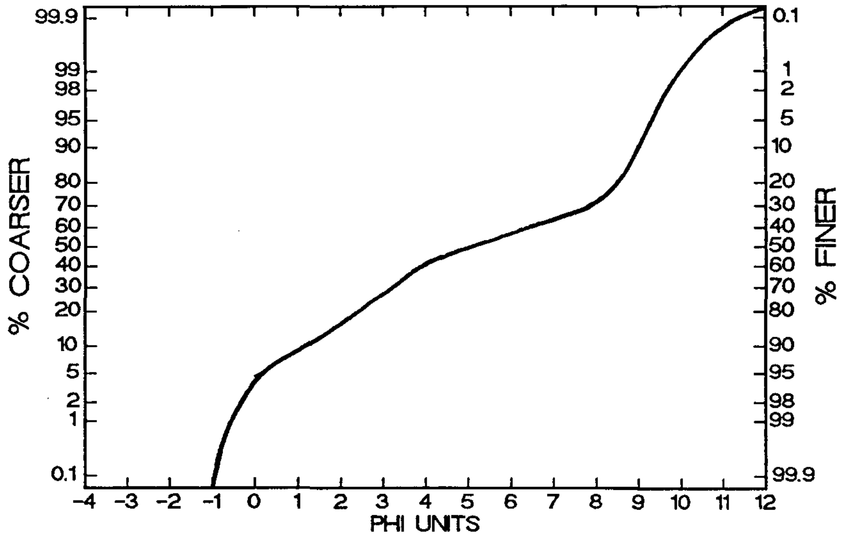

% COARSER
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% FINER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

S3-5


% COARSER
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% FINER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

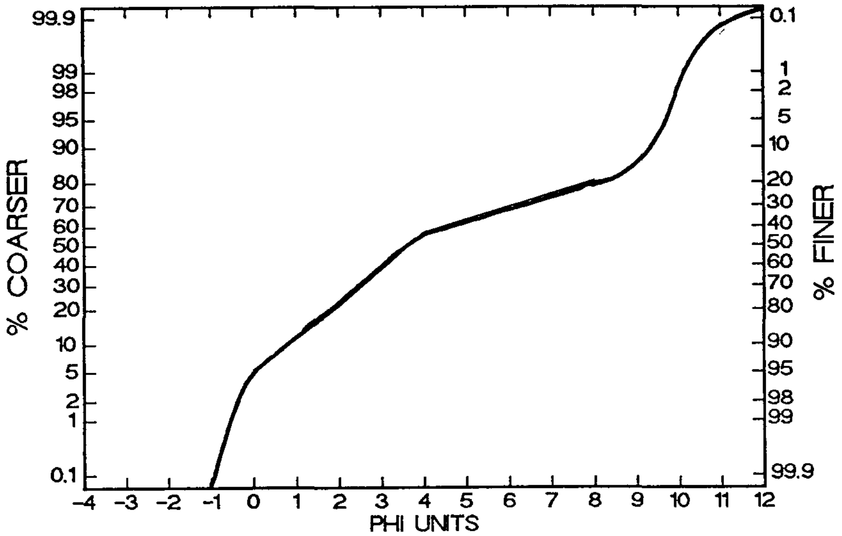
S3-6


% COARSER
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% FINER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS



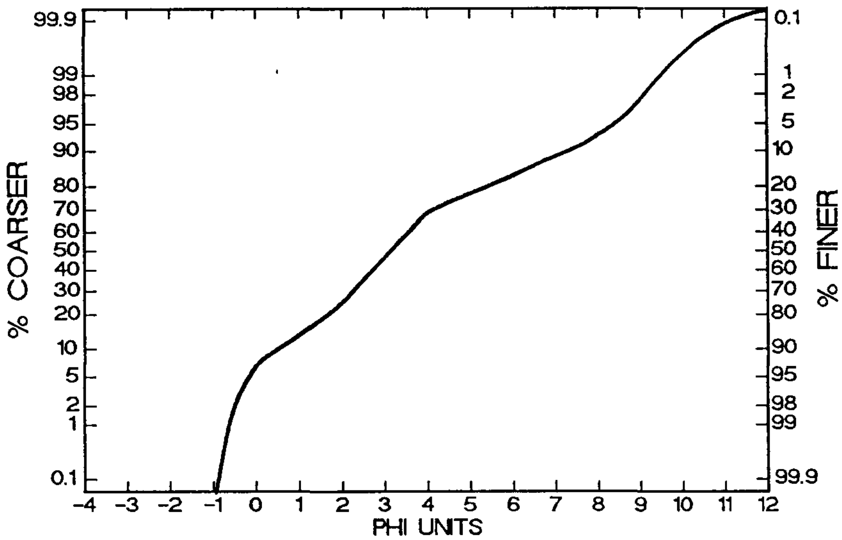
% COARSER
% FINER
PHI UNITS

S4-1



% COARSER
% FINER
PHI UNITS

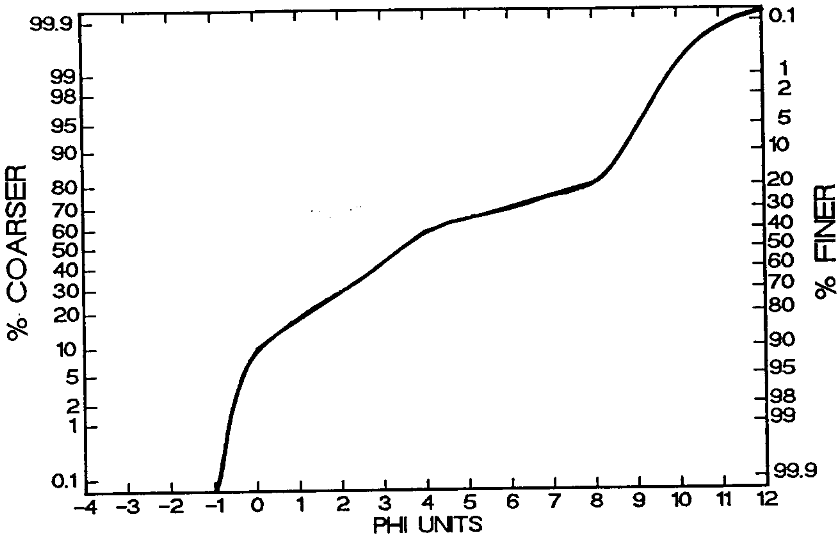
S4-2



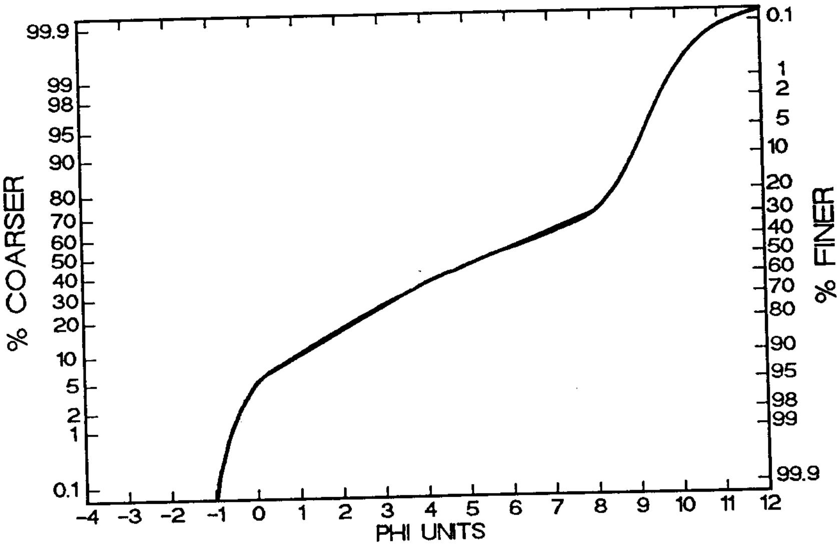
% COARSER
% FINER
PHI UNITS

S4-3

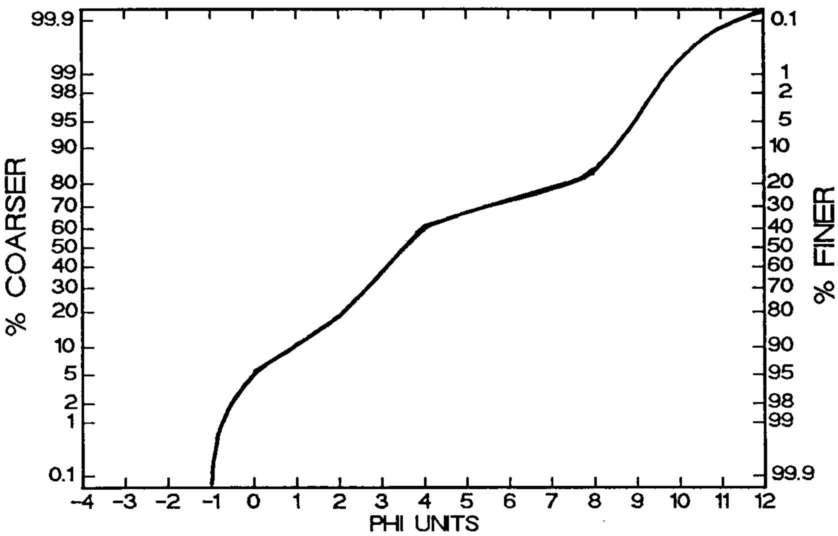
S4-4

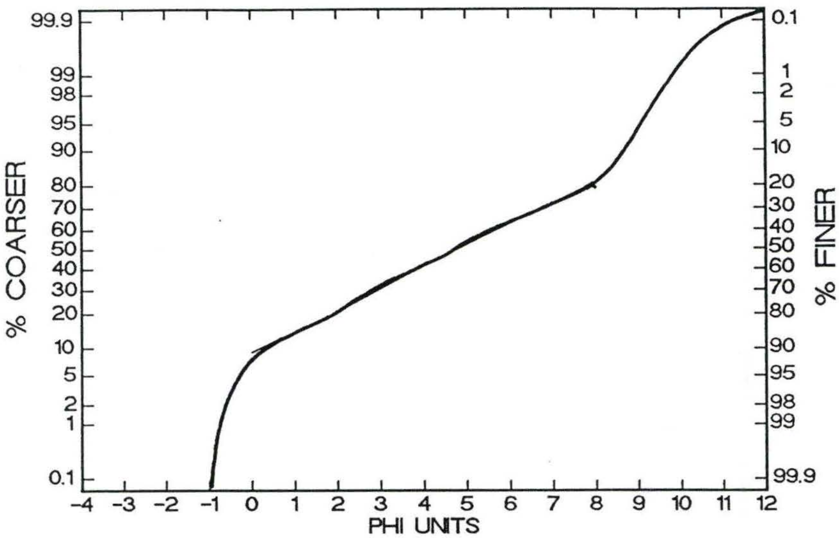

% COARSER
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% FINER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
PHI UNITS
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12

S4-6

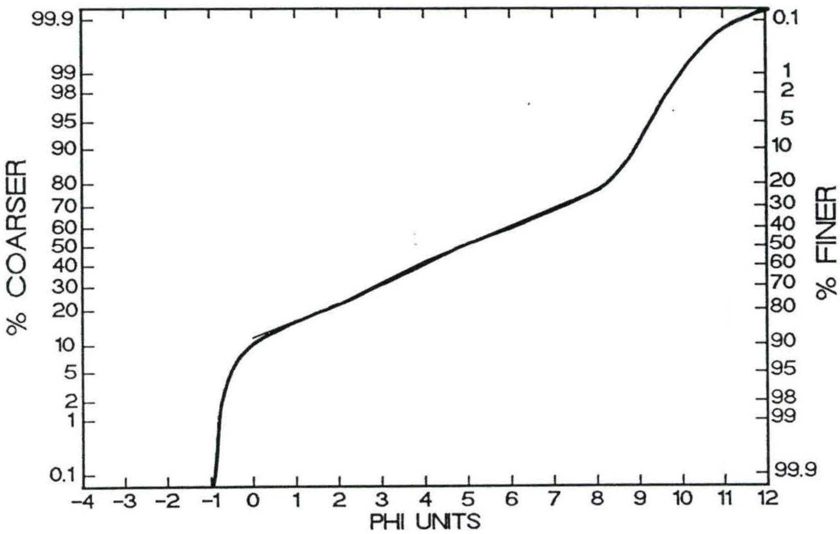

% COARSER
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% FINER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
PHI UNITS
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12

S4-

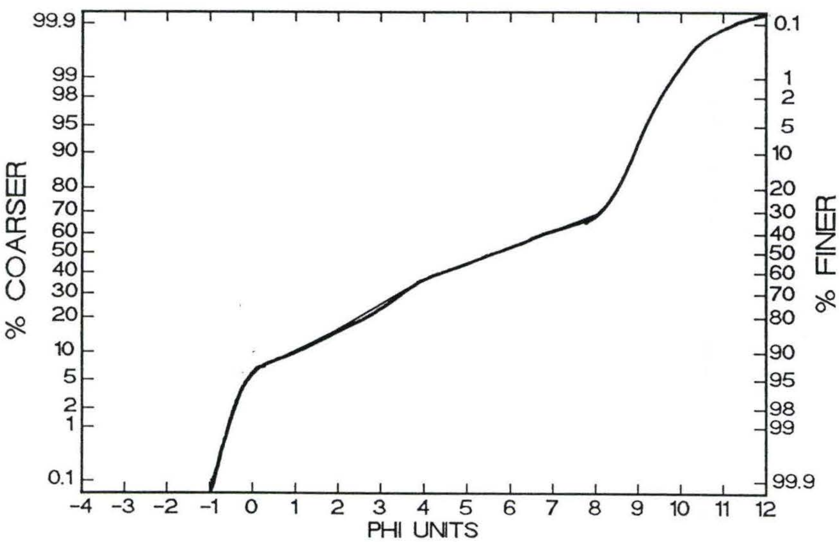

% COARSER
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% FINER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
PHI UNITS
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12


99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% COARSER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
% FINER
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

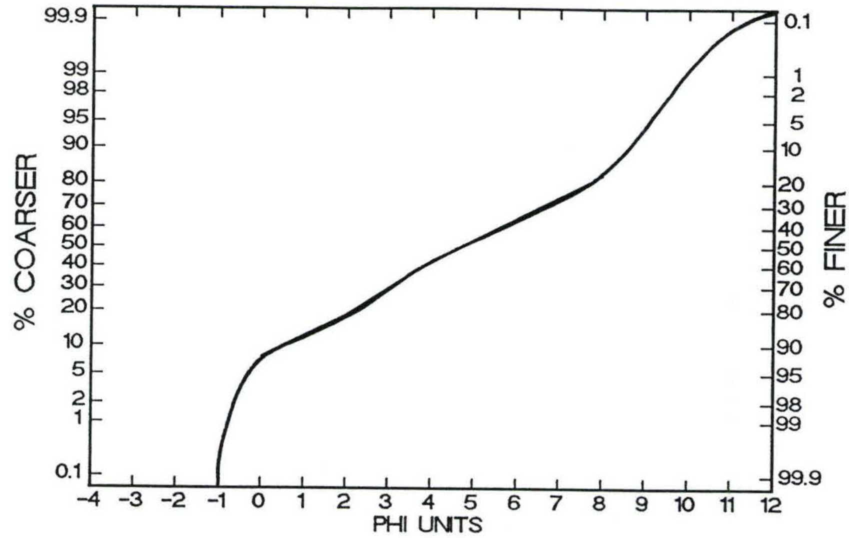
S4-8


99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% COARSER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
% FINER
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

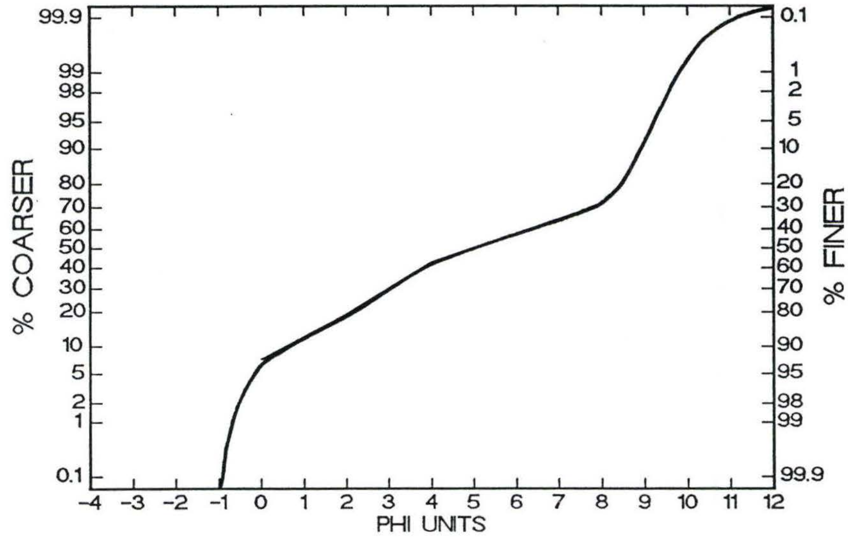
S4-9


99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% COARSER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
% FINER
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

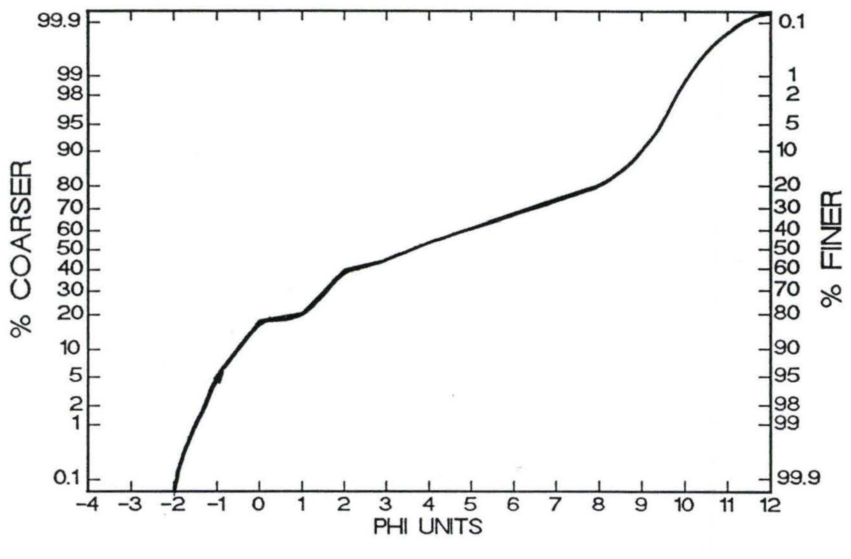
S4-10



S4-11

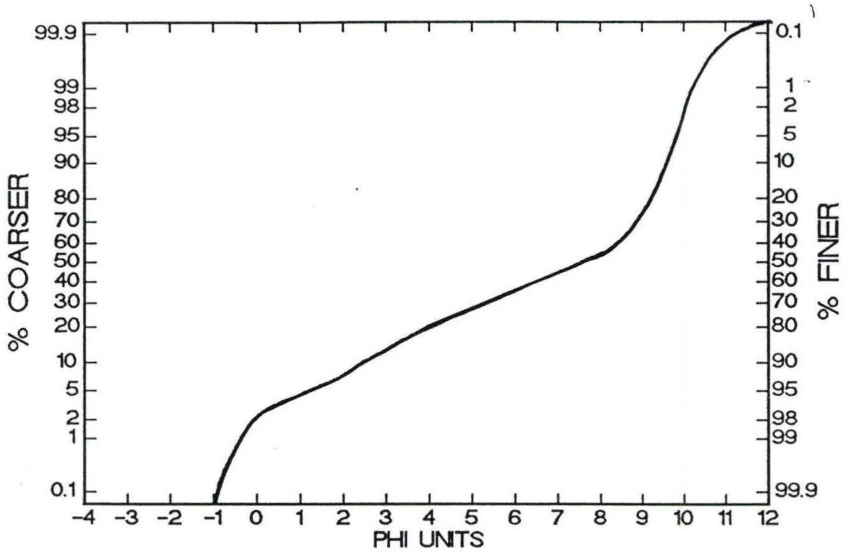


S4-12

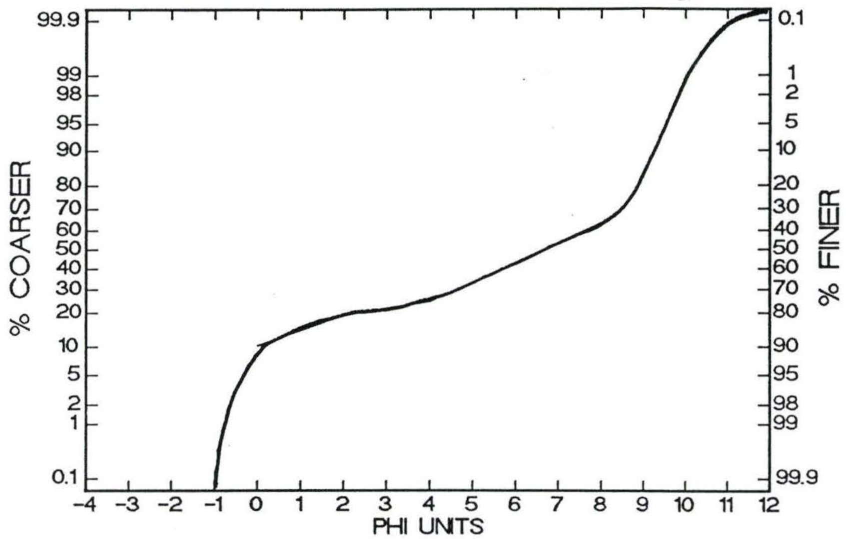


S4-13

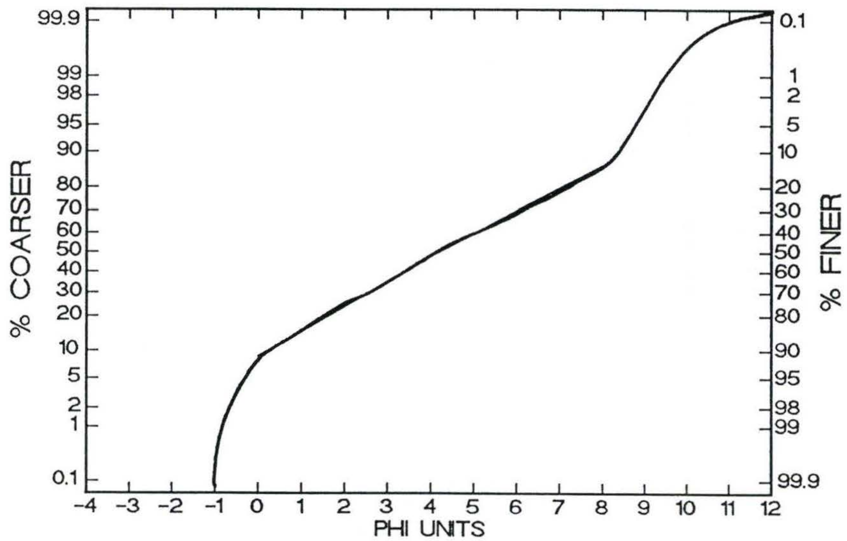
S5-1


% COARSER
% FINER
PHI UNITS
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12

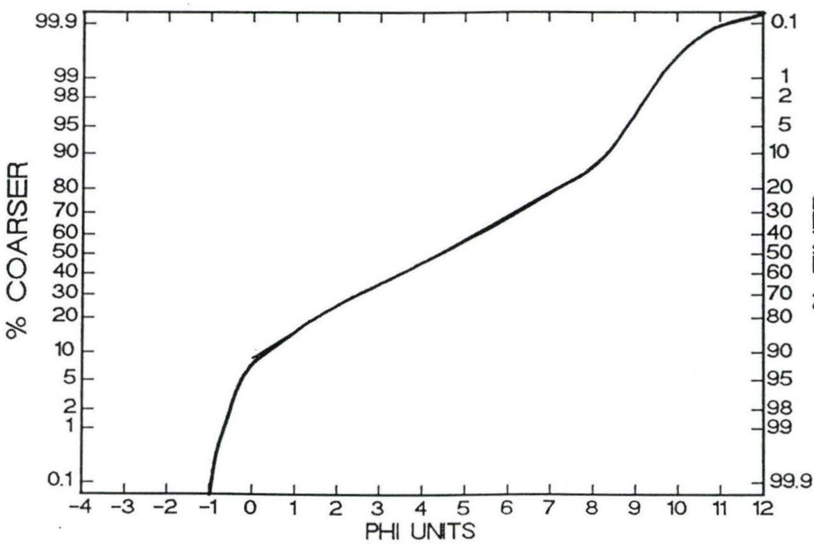
S5-2


% COARSER
% FINER
PHI UNITS
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12

S5-3

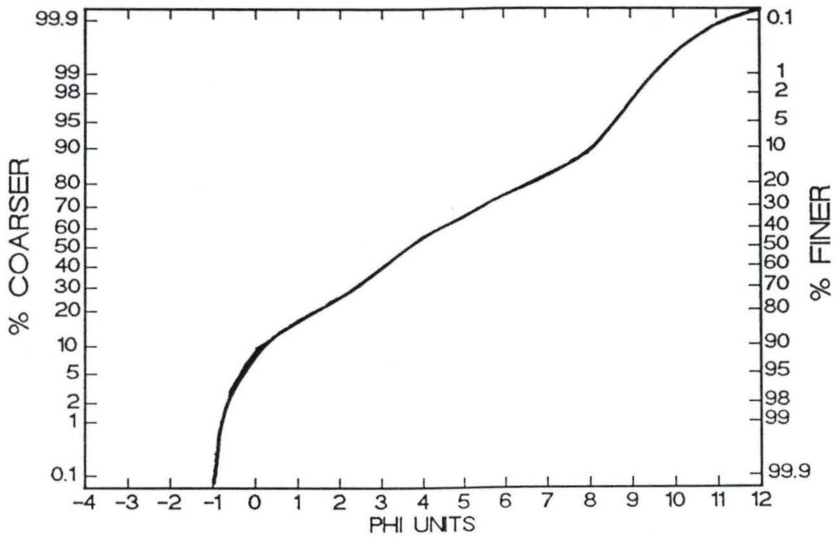

% COARSER
% FINER
PHI UNITS
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12

S5-4



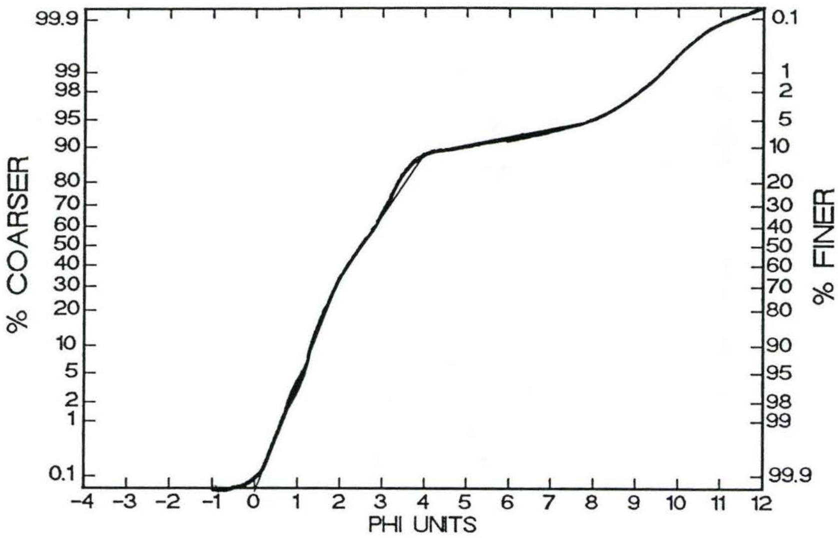
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% COARSER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
% FINER
−4 −3 −2 −1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

S5-5



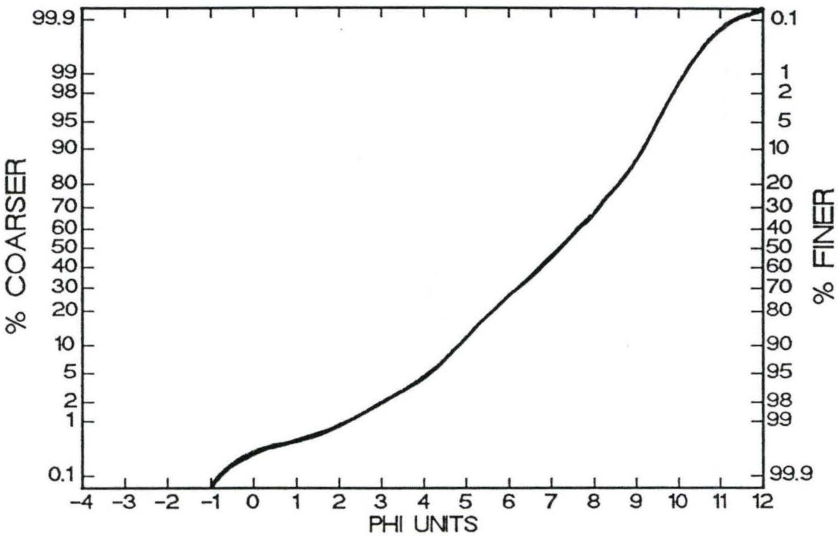
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% COARSER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
% FINER
−4 −3 −2 −1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

S6-1



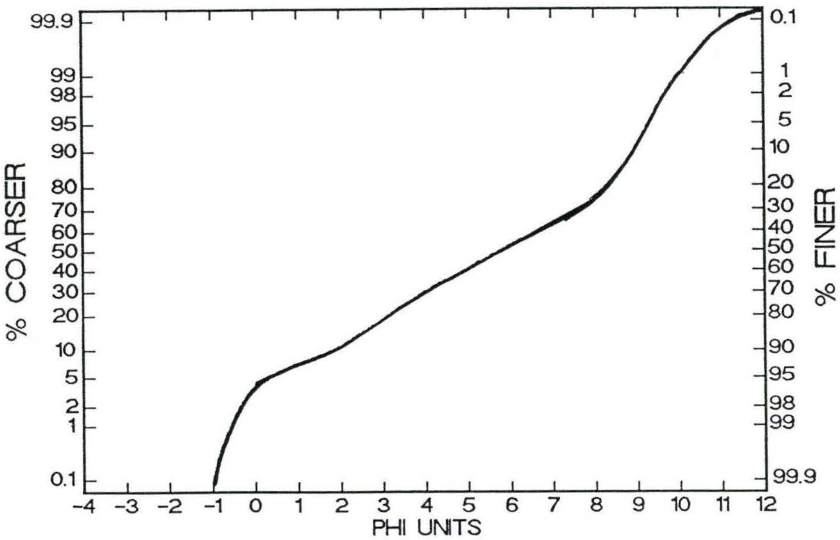
% COARSER
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% FINER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

S6-2



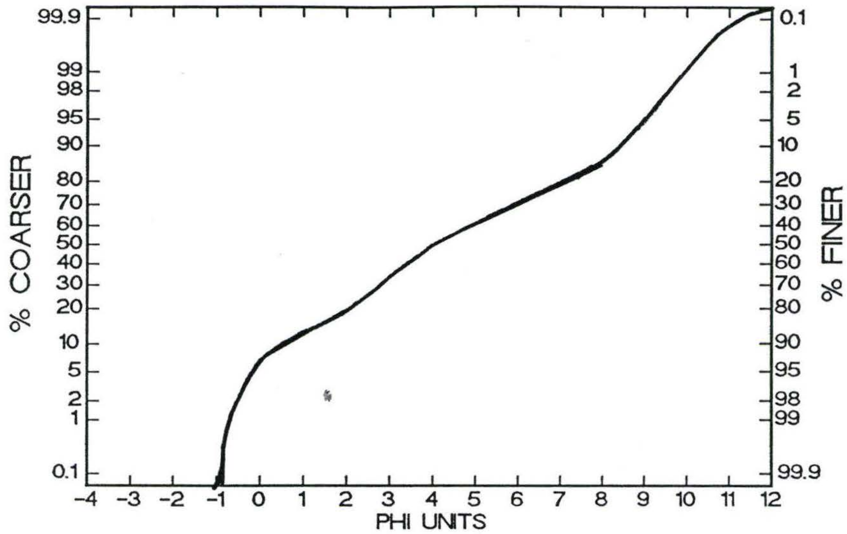
% COARSER
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% FINER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

S6-3

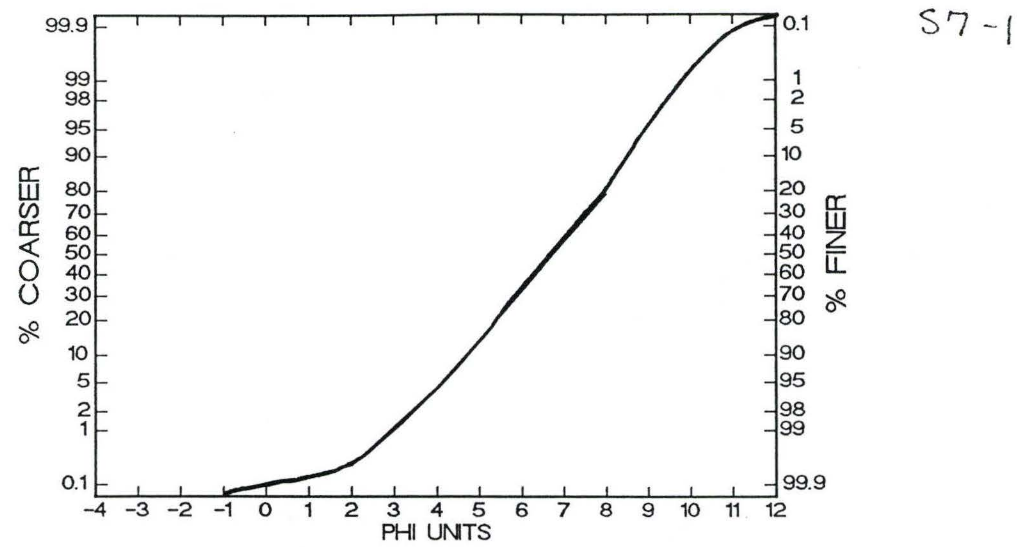


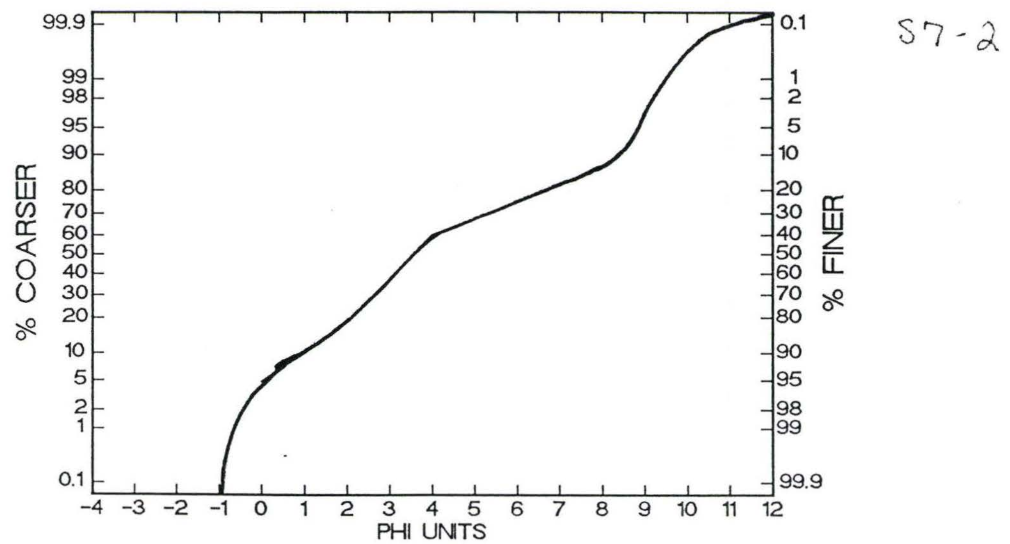
% COARSER
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% FINER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

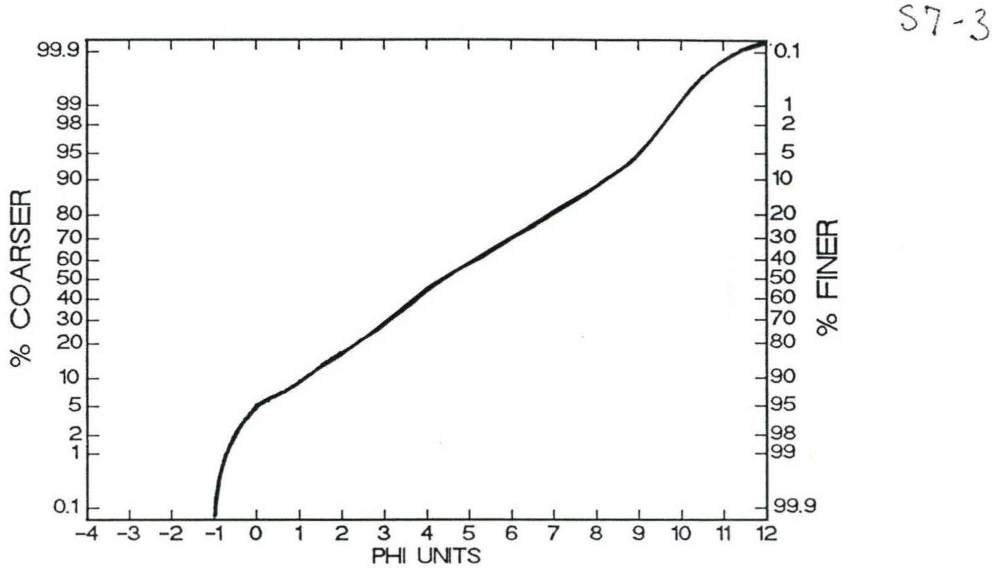
S6-4

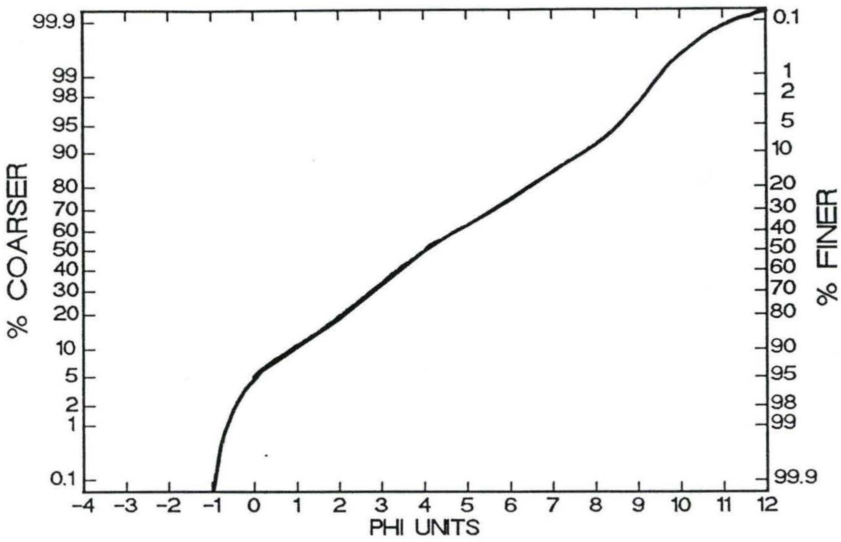


% COARSER
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% FINER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

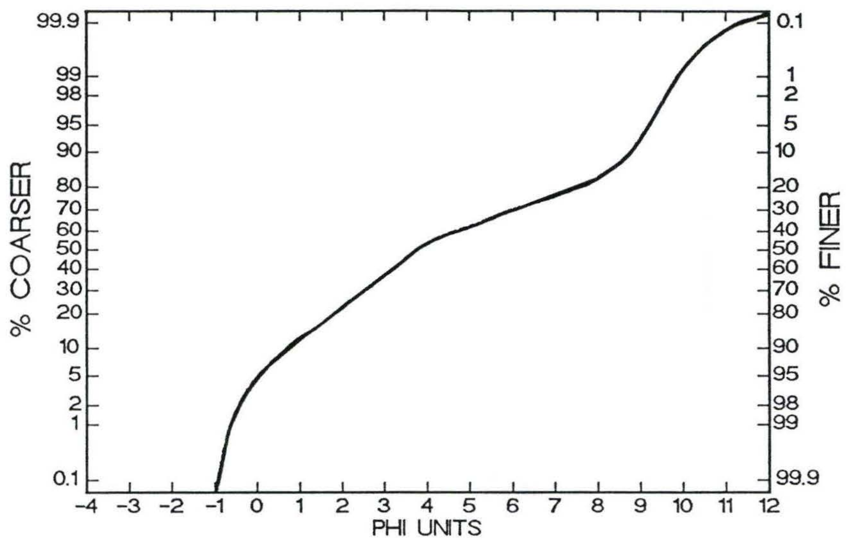

S7-1
% COARSER
% FINER
PHI UNITS


S7-2
% COARSER
% FINER
PHI UNITS

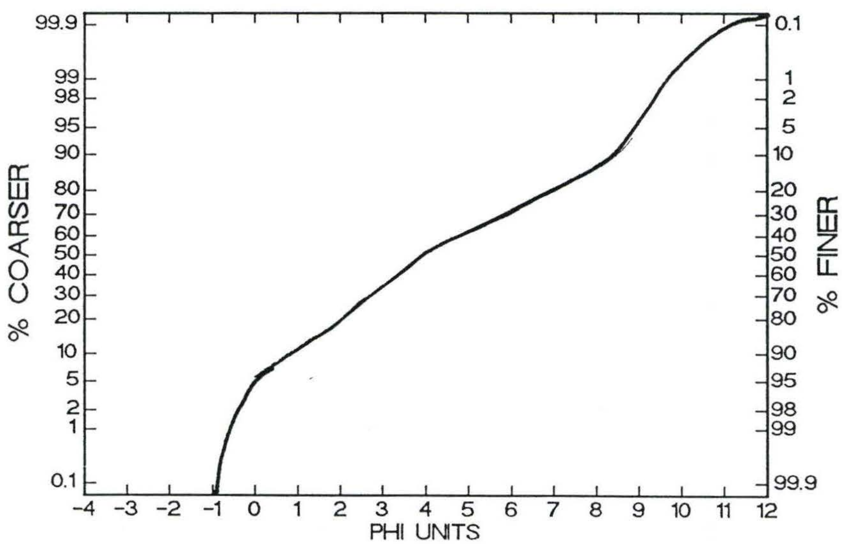

S7-3
% COARSER
% FINER
PHI UNITS


% COARSER
% FINER
PHI UNITS

S7-4

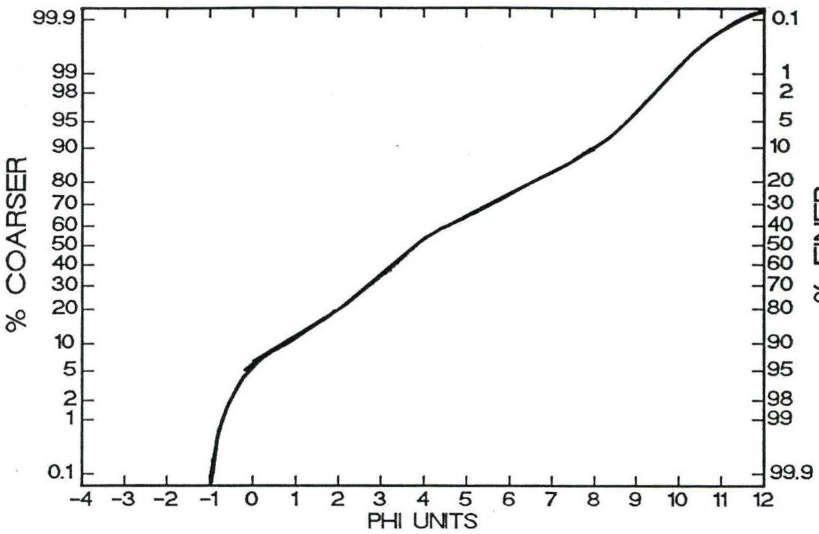

% COARSER
% FINER
PHI UNITS

S7-5


% COARSER
% FINER
PHI UNITS

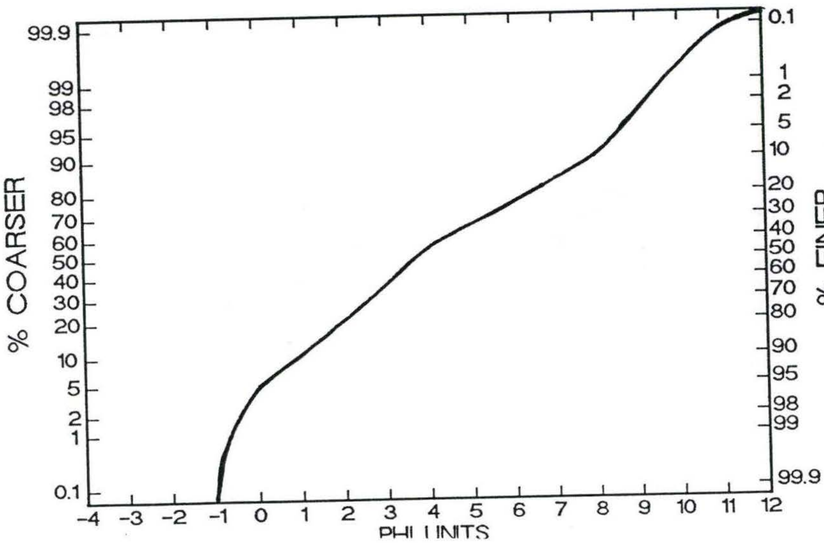
S7-6

S7-7

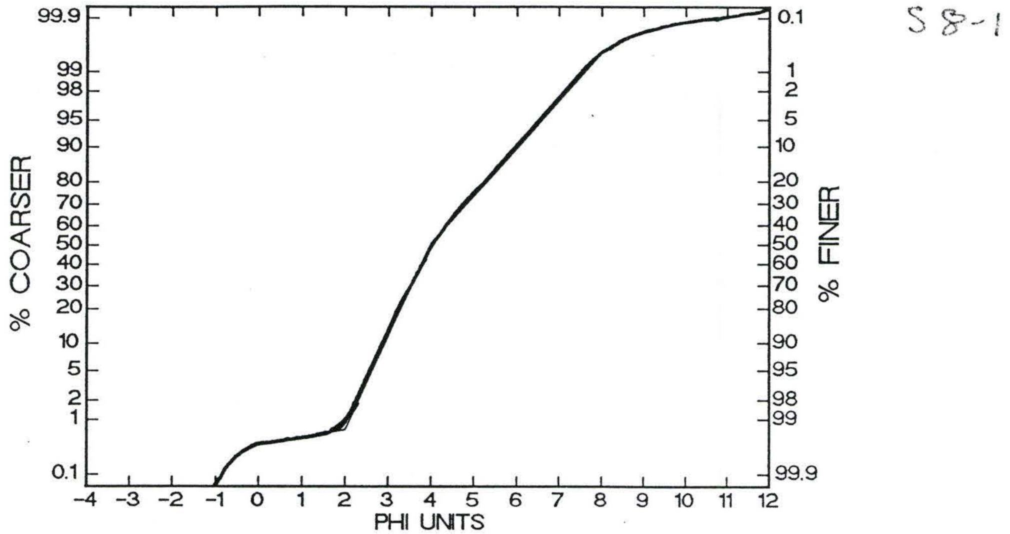


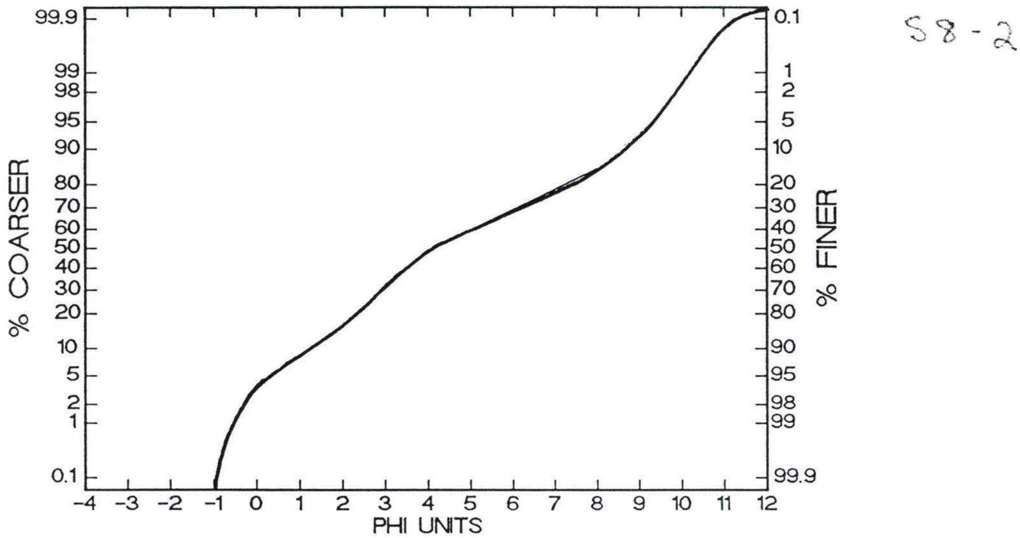
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% COARSER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
% FINER
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

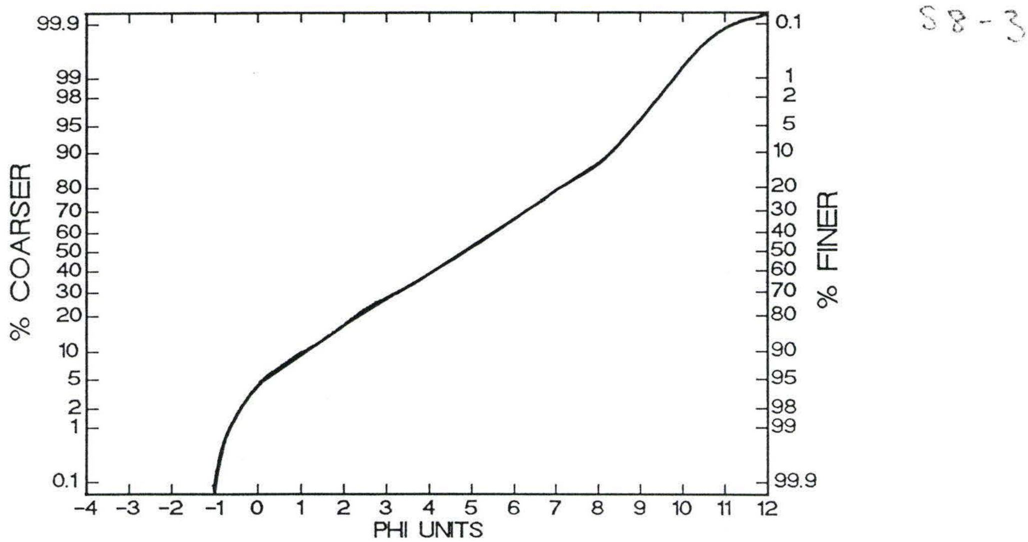
S7-8



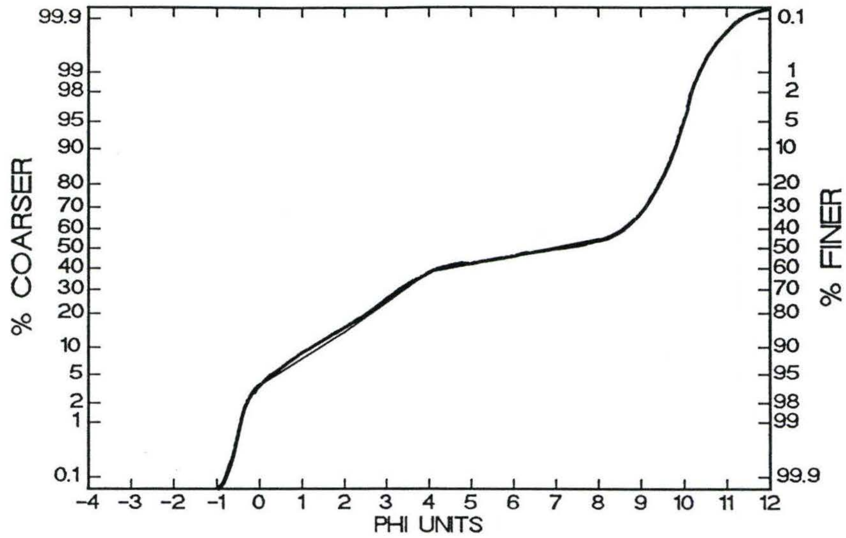
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% COARSER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
% FINER
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12


S8-1
% COARSER
% FINER
PHI UNITS

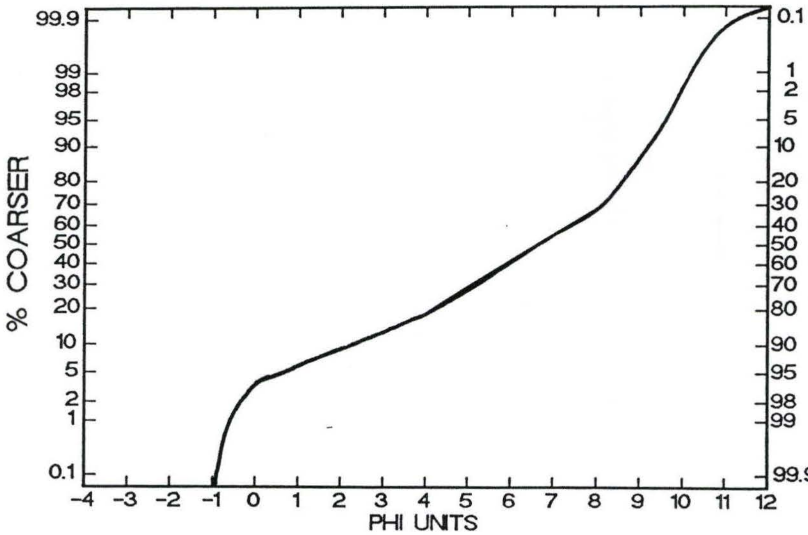

S8-2
% COARSER
% FINER
PHI UNITS


S8-3
% COARSER
% FINER
PHI UNITS

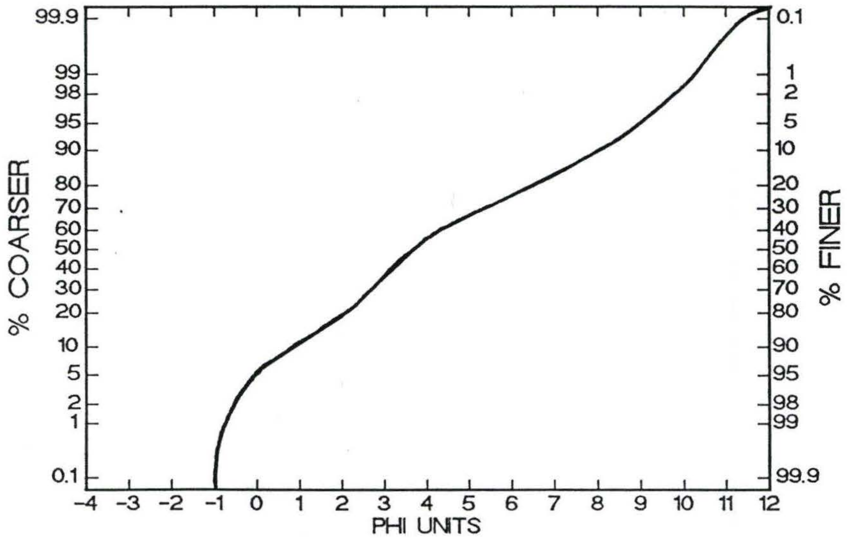
S8-4



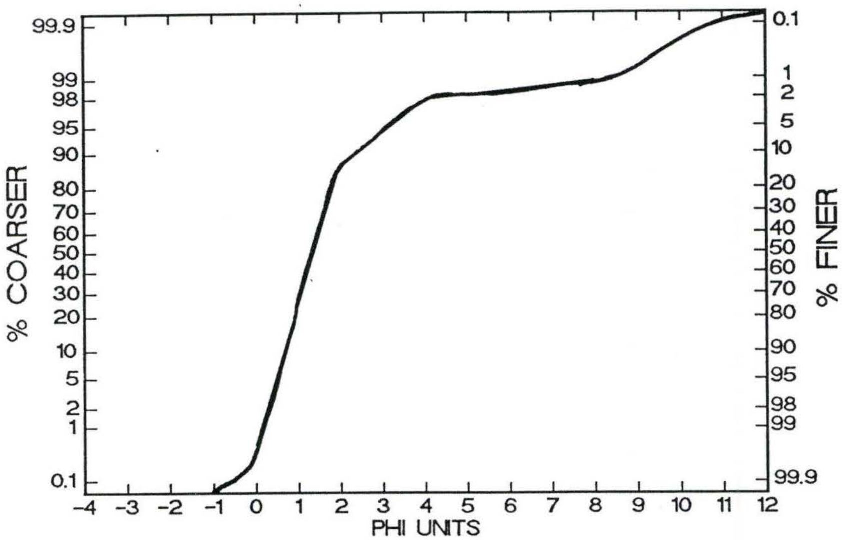
99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% COARSER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
% FINER
−4 −3 −2 −1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS


99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% COARSER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
% FINER
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

S9-1


99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% COARSER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
% FINER
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

S9-2


99.9
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.1
% COARSER
0.1
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
% FINER
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
PHI UNITS

S9-3