REGIONAL JOINTING PATTERNS WITHIN SOUTH-CENTRAL ONTARIO

REGIONAL JOINTING PATTERNS WITHIN THE SURFICIAL GLACIAL SEDIMENTS AND BEDROCK OF SOUTH-CENTRAL ONTARIO

By

SHEILA ELLEN DANIEL, B.SC.

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AUTHOR: Sheila Ellen Daniel, B.Sc., University of Western Ontario

SUPERVISOR: Dr. C.H. Eyles

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ABSTRACT

There is mounting pressure to find suitable disposal sites for both household and industrial waste in south-central Ontario as a solution to Metropolitan Toronto's growing 'garbage crisis'. New data indicate that the fine-grained glacial sediments of south-central Ontario, previously considered to be 'tight' and impermeable, are in fact penetrated by an extensive joint system. This thesis provides basic information regarding the regional character, orientation and origin of joints within the surficial glacial sediments and bedrock of south-central Ontario. Three regional joint sets can be identified. Within the bedrock, the joint sets are oriented northeast/southwest, northwest/southeast and north/south. This trend is consistent with the regional jointing pattern within the overlying glacial sediments and suggests that the joints may have propagated from the bedrock into the glacial sediments. A comparison between the regional jointing pattern identified in bedrock and glacial materials and the orientation of stress release structures suggests that the regional pattern of jointing is controlled by the regional stress field which results from intraplate tectonic stresses. However, the orientation of joints at any individual site may also be controlled by 'local' factors such as face orientation, direction of glacial ice movement and lithology and by randomly oriented joints formed as the result of physical and chemical weathering, synaeresis, subglacial deformation and stress relief. The identification of regional jointing pattern within south-central Ontario allows the prediction of joint characteristics and orientations at potential landfill sites in the region, critical to the accurate evaluation of the permeability of the substrate materials.

ACKNOWLEDGEMENTS

The author wishes to express her thanks to several people who have aided in the completion of this thesis. In particular my thanks go to my advisor, Dr. Carolyn Eyles for her critical advice and financial support without which this thesis would not have been possible. Additional funding was provided by a research grant from the Geological Society of America. Special thanks are extended to my field assistant Genevieve Taeger, who maintained a cheery disposition during the tortuous hours of driving in search of the always elusive and rarely found, non-dessicated glacial exposure. Thanks are also extended to the numerous landowners who allowed me to have access to their land and to all of the quarry/pit superintendants who were interested in my research and permitted me access to the quarry/pit walls (and the many workers who made me feel welcome). I appreciate the help of the members of MAGNEC (Multi-Agency Group for Neotectonics in Eastern Canada) and in particular, Vern Singhroy and Frank Kenny at the Ontario Centre for Remote Sensing and Joe Wallach and the Atomic Energy Control Board of Canada who released unpublished information to me and provided helpful advise. I would like to acknowledge the emotional support and encouragement of Andrew Allison who helped me to maintain my sanity with 'reality checks' and philosophical discussions on 'cracks in dirt'. I would especially like to thank my parents Dave and Dorothy Daniel for their constant support thoughout my entire academic career. This thesis would not have been possible without them.

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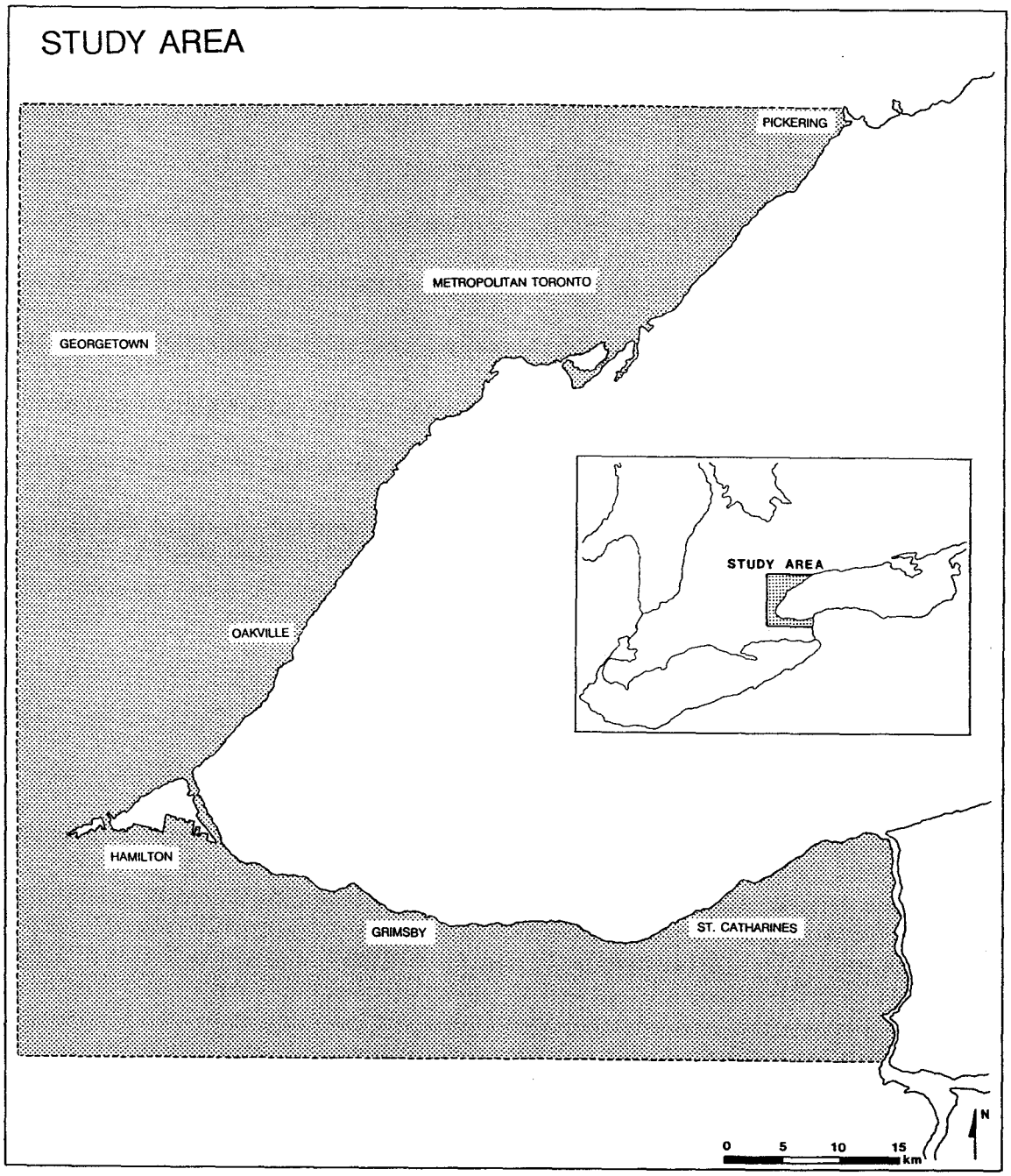
CHAPTER 1: INTRODUCTION

1.1 Introduction

Relatively little is known about the pattern of jointing in surficial glacial deposits. Since most of Canada was glaciated during the Quaternary and is covered by varying thicknesses of glacial deposits, a good understanding of the jointing characteristics of these sediments is necessary for the safe design of many engineering projects requiring impermeable substrate, especially landfill sites.

South-central Ontario is currently involved in a 'garbage crisis' as landfill sites become filled to, and beyond their capacity and few new sites are developed owing to the difficulty of finding environmentally and politically acceptable locations. Heightened public awareness of the environment during the 1970's and 1980's has forced environmental impact and hydrogeologic studies to be completed before any new landfill site may be developed. However, an integral aspect of landfill site safety has generally been neglected in the search for potential sites: jointing within the substrate. This thesis will provide basic information regarding the characteristics and origin of jointing within the Late Wisconsinan glacial sediments and underlying bedrock of south-central Ontario (Fig. 1-1), on which any proposed landfill site must be situated. Emphasis will be placed upon jointing in fine-grained glacial materials (predominately

FIGURE 1-1: Location of study area (south-central Ontario) defined to the east and west by 79° and 80° longitude and to the south and north by 43° and 43° 45' latitude.


STUDY AREA
PICKERING
METROPOLITAN TORONTO
GEORGETOWN
OAKVILLE
HAMILTON
GRIMSBY
ST. CATHARINES
STUDY AREA
0
5
10
15
km
N

clay-rich tills and glaciolacustrine diamicts) and bedrock since these materials were seen in the field to show the most jointing and are viewed as the best substrate for landfill sites because of their impermeability.

Jointing is of prime importance to the safety of landfill sites, since it exerts a fundamental control on substrate permeability in fine-grained sediments and can strongly control the movement of leachate within and around the landfill site. Joints act as natural conduits through which leachate may pass easily into an aquifer below (Williams and Farvolden, 1967). Basic information regarding the nature and characteristics of jointing in surficial glacial sediments necessary to the safe planning of landfill sites is currently unavailable in south-central Ontario.

1.2 Joints

Joints are a specific type of elementary structure found within unconsolidated materials and rock. Joints are tight vertical, horizontal or otherwise aligned fractures along which there is no visible displacement (Billings, 1972; International Society for Rock Mechanics, 1978). Within this general category of joints are regional joints which are a specific group of vertical or near-vertical joints whose origin can be ascribed to the regional stress field (Uemura and Mizutani, 1984). Regional joints may be differentiated into two or three joint sets which show relatively uniform orientation over a large area. These joint sets are termed longitudinal, transverse and oblique. Longitudinal joints are oriented parallel to other major geologic structures such

as faults and lineaments, transverse joints lie normal to the major structural trend and oblique joints cut across the trend of the former two joint sets (Uemura and Mizutani, 1984). By analyzing the joint characteristics at many sites spread over a large area, it may be possible to identify distinct joint sets and develop an understanding of the regional jointing pattern. This thesis attempts to determine regional jointing patterns in bedrock and glacial sediments of south-central Ontario; identification of these patterns may allow prediction of jointing characteristics for potential landfill sites under investigation.

1.3 Previous Work

There is considerable research into joint characteristics and regional jointing patterns in bedrock within North America (Priest and Hudson, 1976; Hudson and Priest, 1979, 1983; Engelder and Geiser, 1980; Holst and Foote, 1981; Ladeira and Price, 1981; Engelder, 1982; LaPointe and Hudson, 1985; Hancock and Engelder, 1989). This thesis will not attempt to discuss this literature. The author directs interested persons to the above studies or to the International Journal of Rock Mechanics, Mining Science and Geomechanics Abstracts for further information. General information regarding bedrock jointing may be found in most structural geology texts including, Badgeley, 1965; Billings, 1972 and Uemura and Mizutani, 1984. Information regarding bedrock jointing in south-central Ontario has been published by several authors (Scheidegger, 1977; Flint and Lolcama, 1985; Williams *et al.*, 1985). The bedrock jointing pattern within south-central Ontario identified by these authors will be discussed in detail within Chapter 4.

There are no published data regarding regional jointing patterns within the surficial glacial sediments of south-central Ontario, although several authors have mentioned joints briefly in their discussions of sediment characteristics (for example: Karrow, 1967, p.54; Barnett, 1975, p.19; Eyles *et al.*, 1985, pp.99-101; Westgate *et al.*, 1987, p. 2301; Eyles and Howard, 1988, p.464). In fact, little research appears to have been carried out on jointing patterns in unconsolidated sediments *per se*. The majority of research pertaining to jointing in unconsolidated sediment concentrates on the effects of joints on the hydrogeologic characteristics of the sediment. Within Canada, hydrogeologic research on jointed glacial sediments has been concentrated either on modelling groundwater flows or on field studies in the Prairies, where the relatively simple glaciogeologic history is reasonably well understood. Early studies by Grisak and Cherry (1975), Grisak *et al.* (1976), Grisak and Pickens (1980) and Grisak *et al.* (1980) modelled solute transport through jointed clay and determined the hydrogeologic response within these units to changes in the underlying aquifer, concluding that ground water response within a fractured clay unit is faster than would be anticipated by permeability alone. Later research on fracture permeability and hydrogeology within till in Saskatchewan (Keller, 1985; Keller *et al.*, 1986; Penner, 1986), confirmed earlier conclusions; that fractured till is considerably more permeable than its unfractured counterpart, and that the joints in glacial sediments may be active groundwater conduits to considerable depths (oxidized and weathered zones have been reported at up to 21 metres depth)(Grisak *et al.*, 1976).

Several researchers have attempted to determine the origin of joints in Late Wisconsinan, clay-rich glacial materials. Vonhof (1970), and Grisak *et al.* (1976) suggest that glacial unloading, crustal rebound, glacial shearing and tension fracturing may be mechanisms for joint development within clay-rich sediments of the Interior Plains. Babcock (1977) suggests that weathering of the outcrop face may also cause joints to form. Burford and Dixon (1978) suggest that jointing within lake clays and clay tills may result from isostatic rebound, earth rock tides or neotectonic (recent) stress. In addition, Keller (1985) has suggested that fracturing in surficial sediments lying above the water table occurs as a result of repeated wetting and drying of sediment. Below the water table, such jointing may be a remnant of a similar processes acting when a lower water table existed during a past drier climate (Hendry, 1984).

Outside of the Canadian Prairies and Interior Plains Region of the United States, most research into the jointing characteristics of unconsolidated glacial materials has focused on the geomechanical aspects of jointing and its importance to the strength of material for construction purposes (Skempton *et al.*, 1969; Kazi and Knill, 1973; McGown *et al.*, 1974; McGown and Radwan, 1975; Harding, 1986). Connell (1983, 1984) however, completed a broader and more extensive study on joints within clay-rich till and glaciolacustrine sediments of Northeastern Wisconsin to determine their distribution, characteristics and genesis. He concluded that the orientation of near-vertical joints was commonly perpendicular to and conjugate around the direction of ice flow inferred from microfabric, but allowed that slope failure, neotectonic stress and

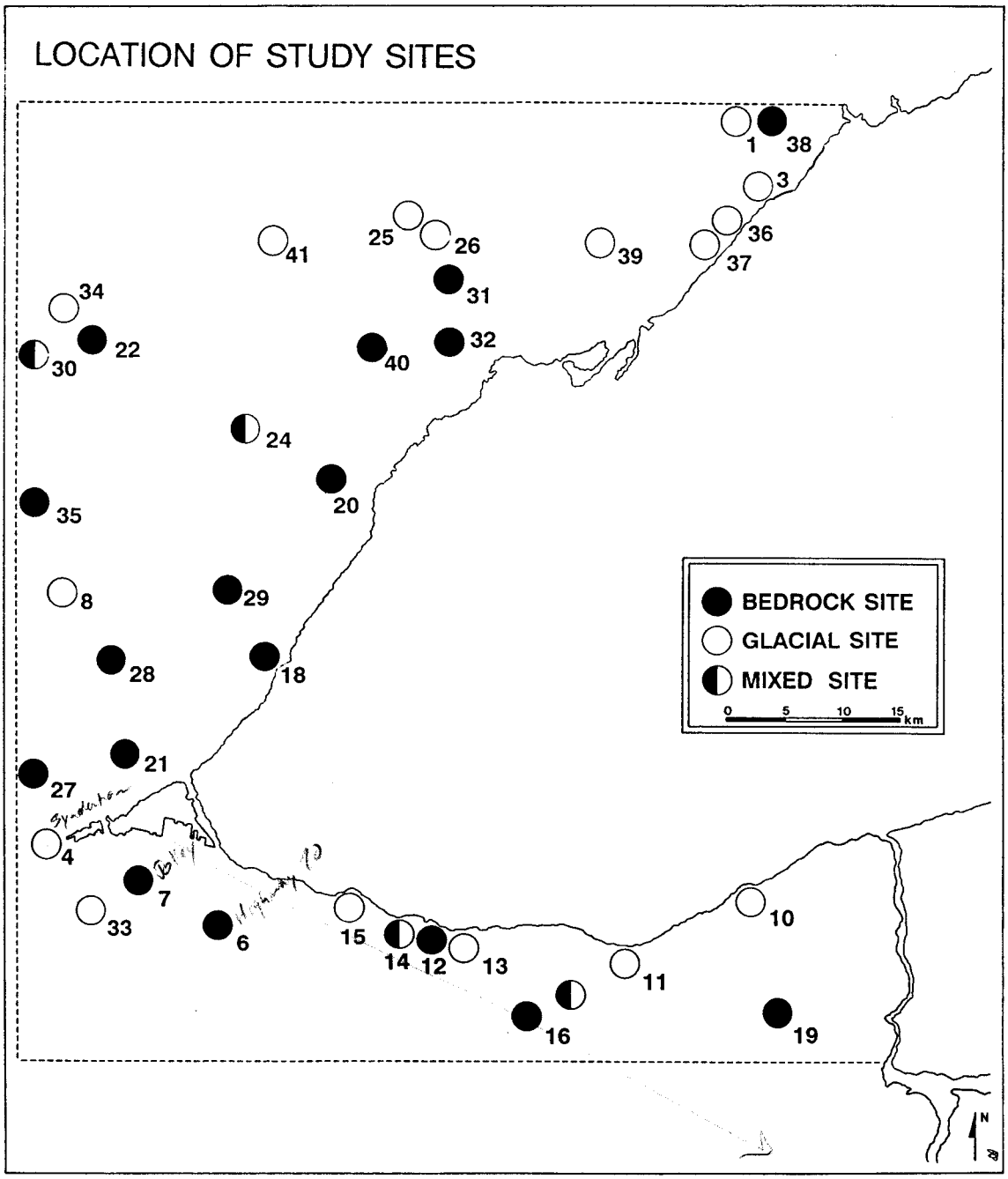
propagation up from underlying bedrock were also important factors in the orientation of joints within glacial sediments. A complete discussion of the origin and pattern of joints within the surficial glacial sediments of south-central Ontario is found in Chapter 5.

1.4 Selection of Sites

This thesis focuses on the field measurement of joint orientations in surficial glacial sediments and bedrock within south-central Ontario (Fig. 1-2). The aim of this research is to provide a regional analysis of joint orientation within south-central Ontario, particularly patterns and trends that can be identified within the surficial glacial deposits. The study area loosely coincides with the regional extent of the Late Wisconsinan Halton Till, as mapped by a various of authors (Karrow, 1962; White, 1964; Watt, 1968; Karrow, 1970; Feenstra, 1972; Gwyn and DiLabio, 1973; Feenstra, 1975; Sharpe, 1980; Karrow, 1987).

Potential field sites were identified from several different sources. These include unpublished theses (Hughes, 1970; Barnett, 1975; Eyles, 1982; Rutka, 1986), recent conference guidebooks of the region (Segall and Dunn, 1972; Telford, 1975; Currie and Mackasey, 1978; Davidson-Arnott *et al.*, 1982; Karrow *et al.*, 1982; Barnett and Kelly, 1987), and government published Pleistocene or Quaternary Geological Reports (Watt, 1968; Karrow, 1967; White, 1975; Karrow, 1987). Most of the field sites examined were located along lakeshore bluffs, inland ravines or within quarries and pits.

FIGURE 1-2: Distribution of bedrock and glacial sites within south-central Ontario (bedrock sites, closed circle; glacial sites, open circle; bedrock and glacial sites, half closed/half open circle).


LOCATION OF STUDY SITES
1
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3
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12
13
11
10
16
19
BEDROCK SITE
GLACIAL SITE
MIXED SITE
0 5 10 15 km
N

Many of the quarries and pits visited were located by means of the 1989 Annual Directory for the Aggregate Producers' Association of Ontario and the Aggregate Resource Inventory or Industrial Mineral Reports (Ontario Geological Survey) for each township or region. Unfortunately, many of the potential sites identified from these sources were either overgrown, highly weathered or no longer accessible. Additional sites were therefore identified by searching topographic maps of the region for potential exposures along rivers, and by visiting accessible locations along the Lake Ontario shoreline between Niagara-on-the-Lake and Pickering. The primary aim was to obtain sites where both bedrock and overlying surficial sediment were exposed, however, only four such sites were identified within the study area (Fig. 1-2). Other sites were selected where good exposures of either surficial glacial sediments or bedrock were observed (Fig. 1-2).

1.5 Methodology

At sites where glacial sediments were present, the section was cleaned and then logged using standard sedimentologic techniques (for example Eyles and Eyles, 1983). Average grain size was estimated in the field and represented by the width of the log column; diamict lithofacies were represented by the average matrix grain size. Additional information regarding sedimentary structures, nature of bed contacts and clast content was included using symbols on the logs. The deposit was also described objectively using the lithofacies code devised by Miall (1977, 1978), Eyles and Eyles (1983) and Eyles *et al.* (1983). Notes were taken recording face orientation (measured

with a compass) and clast shape, lithology and diameter (average and maximum). Several examples of sedimentologic logs are included within Chapter 3 (Figs. 3-3, 3-5, 3-6, 3-12, 3-18, 3-20). Bedrock sections were not logged in detail, but the section height was estimated or measured where possible, and the rock was described in terms of its colour, composition and any obvious sedimentary structures; the face orientation was also measured using a compass.

At all sites, vertical or near-vertical joints exposed along the section were described in detail. Joint characteristics such as geometry, length, frequency, orientation, staining, infilling and fracture width were noted in the field where appropriate.

Several articles have been written which pertain to the methodology of accurate **joint frequency measurement** in bedrock. The easiest method of determining joint frequency is by measuring the distance between adjacent joints along a scanline stretched across the face, parallel to the bedding planes. There is not an accepted scanline length for an accurate joint frequency measurement. Priest and Hudson (1976) suggest that a scanline at least fifty times the mean joint spacing distance is necessary for an accurate estimation of joint frequency. This contrasts strongly with standardized procedure proposed by the International Society of Rock Mechanics (ISRM, 1978), who suggest a scanline length of 3 metres is adequate, although the sampling length should preferably be longer than ten times the estimated joint spacing.

In this study, joint frequency was estimated at each site by counting the number of joints dissecting a three metre scanline along the outcrop. The results were then averaged to provide a joint frequency per metre. A horizontal scanline was used since the bedding was always horizontal or at a very low angle. The three metre scanline length was chosen to comply with the standards proposed by ISRM (1978), and could not be larger because of the limited exposures from which joints were measured.

Joint orientation measurement was concentrated on those joints which showed evidence of ground water movement either by oxidation along the joint faces or by crystalline infilling of the joints. However, other joints, lacking these features, were also measured if they showed a large vertical extent relative to the thickness of the bed, were essentially straight and appeared to continue into the face (and were not simply surface desiccation features). Care was taken avoid areas on the face where either natural or man-induced deformation was seen. In quarries, joint orientation measurements were taken as far away as possible from blast holes.

The number of joint orientation measurements required at any one site to define the regional joint sets is not generally agreed upon, although the ISRM (1978) suggest that 150 measurements is a reasonable number. Further, ISRM (1978) state that the number of joint orientation measurements necessary decreases the more consistent the orientations are. Unfortunately, in this study, 150 joint measurements could only be

approached at sites where bedrock was exposed. The exposures of unconsolidated glacial sediments are of very limited extent and as a result, fewer measurements were possible at each site (number of joint measurements per site range from 9 to 125 joints).

There are two published methods for joint orientation measurement, photoanalysis (Franklin and Maerz, 1988; Franklin *et al.*, 1988) and field measurement (ISRM, 1978). Research at the University of Waterloo is currently attempting to develop a method of remote joint orientation measurement in bedrock using photoanalysis (Franklin and Maerz, 1988; Franklin *et al.*, 1988). Unfortunately an attempt to use this method to analyze joints within unconsolidated sediments during the summer of 1989, found that the joints were too poorly defined for an accurate edge detection to be made. In addition, the inherent roughness of the surface of unconsolidated sediment exposures lead to difficulties in enhancing the face by computer analysis. Since this method could not be used with success for all sites, joint orientations were measured directly in the field.

Joint orientation and dip were measured directly on the section face using a Silva Ranger compass-clinometer. Joint orientation was measured by either placing the compass directly against the face of the joint (Fig. 1-3), or where this was not possible, by sighting the compass into the joint along the fracture plane and then reading the compass direction. Subsequent to the joint orientation measurement, the

FIGURE 1-3: Photograph showing method of joint orientation measurement.

dip of each joint was measured by rotating the compass face so that the clinometer could be read, placing the compass in a vertical position parallel to the face of the joint and then reading the dip measurement on the clinometer (Fig. 1-4). This method of field measurement is suggested by ISRM (1978). Care was taken to represent all joint sets by measuring joints on several differently oriented faces at each site (where possible) or by measuring joints on exposed bedding plane surfaces. In this way, it was hoped that joints lying at a low angle to the face would not be undersampled and the data would not be biased by face orientation (Terzaghi, 1965).

Brief notes were made on the **characteristics** of each joint measured. The nature and colour of any staining on the joint surface was noted as well as a subjective description of the joint as high or low quality. The evaluation of a joint's quality was based upon its vertical and apparent horizontal extent and the presence of staining or other evidence of ground water activity. Where possible, only those joints which could be classified as high quality were measured. However, when only a limited number of joints were present on the face, low quality joints were also measured in an attempt to provide a greater statistical reliability to the joint orientation measurements. Orientation data from the high and low quality joints were kept separate. Care was taken to complete all joint orientation measurements before analysis of the data began so that the field selection of joints to be measured was not biased.

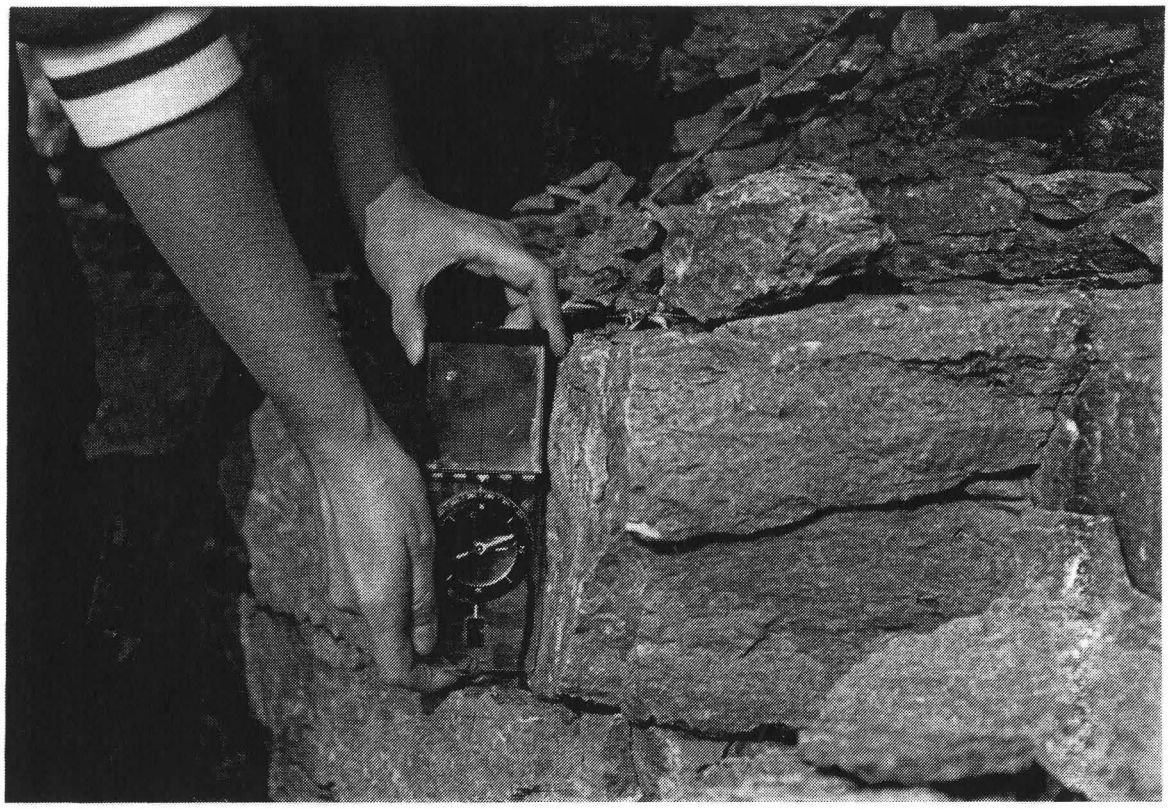


FIGURE 1-4: Photograph showing method of joint dip measurement.

1.6 Data Analysis

In order to identify the trends in the joint orientation data collected in the field, the data were firstly plotted on rose diagrams. Rose Diagrams show the relative frequency of joint orientation on a compass rose (Fig. 1-5). This method of display is preferred to equal-area stereonets or linear histograms, which could also have been used, since rose diagrams have more visual impact in terms of illustrating directional trends and variability (Dennison, 1968). Displaying the data on equal-area stereonets would not be appropriate for this study since the joints measured in the field had vertical or near-vertical dips. This would mean that all the data points would be plotted around the edge of the stereonet, making the directional trends difficult to identify. Histograms have the disadvantage of a linear abscissa which does not allow easy identification of bidirectional trends.

Joint orientation data collected from each site were plotted on several separate rose diagrams in order to determine whether the overall trend at the site was controlled by a single factor or a combination of several factors. At each site, individual rose diagrams were plotted for the high and low quality joint measurements within each bed, individual beds within each face, all measurements on each face and all measurements on all faces at each site (see for example Fig 3-11). It was hoped that by differentiating these various categories of joint measurement, the influence of face orientation, type of material or quality of joint on the overall jointing pattern identified for each sites could be determined. In addition, at sites where joint measurements

were taken from both the glacial sediments and bedrock, additional rose diagrams were plotted combining the joint orientation measurements taken in both the bedrock and glacial materials on each face, and from the entire site, in order to identify any relationship between the joint orientation within the glacial sediments and underlying bedrock.

Rose diagrams illustrating the joint orientation data (for example Figure 1-5) were constructed on a microcomputer using public domain software produced by COGS ("Rose Diagram", Computer Oriented Geological Society). With this program, the user has a choice of the number of segments the 360° plot was divided into. A class interval of 15° (24 segments) was chosen. This is consistent with the choice of Penner (1986) who found that an interval of 15° enabled the general joint orientation trend to be determined and yet filter out any minor variations in orientation.

The dominant joint sets for each site were determined from a visual inspection of each site's summary diagram. A comparison of the frequency of joints within each 15° interval on the rose diagram indicated which intervals and groups of intervals were preferred. For example, within Figure 1-5, there are three high frequency intervals oriented north/south, east-northeast/west-southwest and northwest/southeast respectively; these probably represent the dominant, secondary and tertiary joint sets.

Although rose diagrams provide the best display method for visual analysis of directional data, statistical analysis of the joint orientation measurements was also

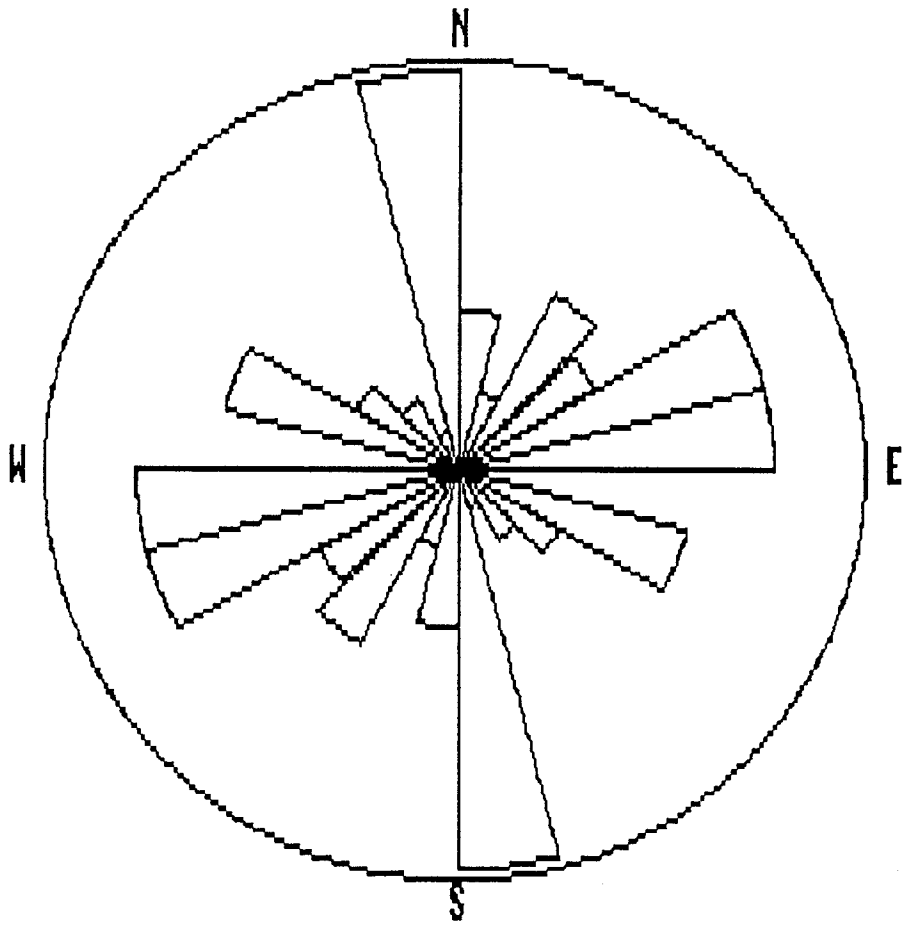


FIGURE 1-5: Example of a rose diagram. (note that three joint sets, oriented north/south, east-northeast/west-southwest and northwest/southeast can be identified.

attempted. No public domain software is available for this purpose. As a result, analysis of joint measurements was carried out using a statistical package developed by Dr. G.V. Middleton (Department of Geology, McMaster University) for analysis of directional paleocurrent data. This program is based upon equations summarized in Potter and Pettijohn (1963) and identifies the vector mean (theta), vector magnitude (R), consistency (L) and Raleigh test values. The results of the statistical analysis are discussed within Chapter 4.

1.7 Organization of Thesis

This thesis has been organized into seven chapters. Chapter 1 provides an introduction to the thesis. In Chapter 2 the geologic setting of southern Ontario is discussed with particular emphasis placed upon the bedrock and glacial sediments exposed within the study area. Chapter 3 includes a general description of each study site as well as descriptions of the specific joint characteristics at the site. Chapter 4 identifies the major jointing patterns within surficial glacial sediments and bedrock of south-central Ontario and compares the results of this study with published joint orientation data. In Chapter 5 an attempt is made to determine the origin of joints in glacial sediments as well as the regional joint pattern identified in Chapter 4. Chapter 6 discusses the local controls on joint orientation within both bedrock and glacial sediments. Final conclusions to the thesis are provided within Chapter 7 which summarizes the results of this thesis and introduces possible future research topics.

CHAPTER 2: GENERAL GEOLOGY

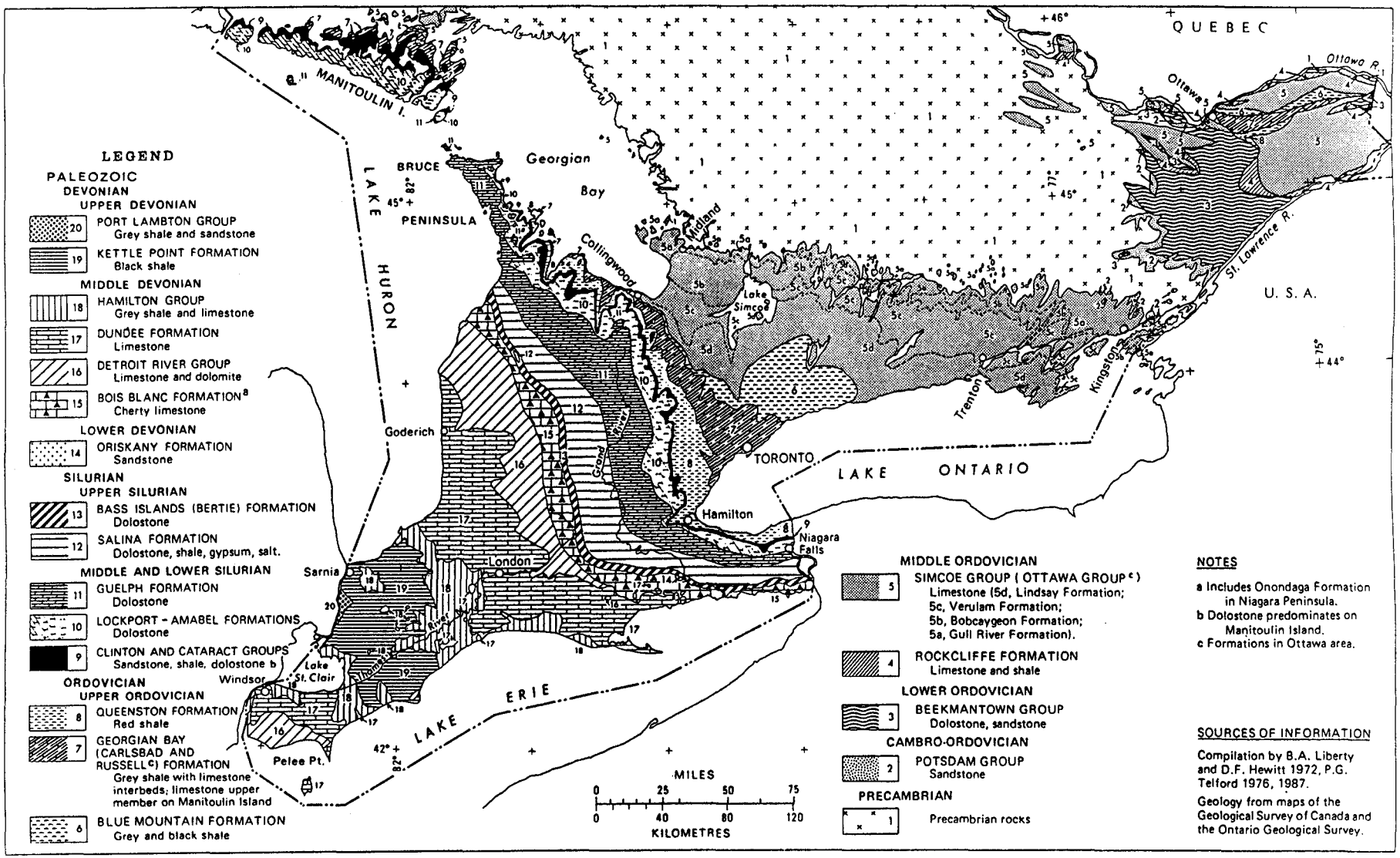
2.1 Introduction

The bedrock basement of south-central Ontario, consists of metamorphic and igneous rocks of the Grenville Province of the Precambrian Canadian Shield. Above the bedrock basement lies a cover of Palaeozoic sedimentary rocks, which range in age from Late Ordovician to Middle Silurian. At most locations, the Palaeozoic rocks are overlain unconformably by a variable thickness of Late Pleistocene glacial sediments. Geological aspects of both the Palaeozoic bedrock and glacial sediments will be treated within this chapter.

2.2 Bedrock Geology

The Canadian Shield rocks which compose the bedrock basement of south-central Ontario are deeply buried in the study area and can only be examined in cores or in outcrops which lie north and east of the study area (Fig. 2-1). As a result, the characteristics of the basement rocks will not be discussed within this thesis. However, the structural geology of the basement rocks will be considered below, since it controls some of the regional characteristics of the Palaeozoic and glacial geology of south-central Ontario. In particular, the structural geology of the Precambrian basement controls regional stress patterns which may be translated into jointing patterns evident

FIGURE 2-1: Bedrock Geology of southern Ontario (Geological Survey of Canada Map).


LEGEND
PALEOZOIC
DEVONIAN
UPPER DEVONIAN
20 PORT LAMBTON GROUP Grey shale and sandstone
19 KETTLE POINT FORMATION Black shale
MIDDLE DEVONIAN
18 HAMILTON GROUP Grey shale and limestone
17 DUNDEE FORMATION Limestone
16 DETROIT RIVER GROUP Limestone and dolomite
15 BOIS BLANC FORMATION[a] Cherty limestone
LOWER DEVONIAN
14 ORISKANY FORMATION Sandstone
SILURIAN
UPPER SILURIAN
13 BASS ISLANDS (BERTIE) FORMATION Dolostone
12 SALINA FORMATION Dolostone, shale, gypsum, salt.
MIDDLE AND LOWER SILURIAN
11 GUELPH FORMATION Dolostone
10 LOCKPORT - AMABEL FORMATIONS Dolostone
9 CLINTON AND CATARACT GROUPS Sandstone, shale, dolostone b
ORDOVICIAN
UPPER ORDOVICIAN
8 QUEENSTON FORMATION Red shale
7 GEORGIAN BAY (CARLSBAD AND RUSSELL[c]) FORMATION Grey shale with limestone interbeds; limestone upper member on Manitoulin Island
6 BLUE MOUNTAIN FORMATION Grey and black shale
MIDDLE ORDOVICIAN
5 SIMCOE GROUP (OTTAWA GROUP[c]) Limestone (5d, Lindsay Formation; 5c, Verulam Formation; 5b, Bobcaygeon Formation; 5a, Gull River Formation).
4 ROCKCLIFFE FORMATION Limestone and shale
LOWER ORDOVICIAN
3 BEEKMANTOWN GROUP Dolostone, sandstone
CAMBRO-ORDOVICIAN
2 POTSDAM GROUP Sandstone
PRECAMBRIAN
1 Precambrian rocks
NOTES
a Includes Onondaga Formation in Niagara Peninsula.
b Dolostone predominates on Manitoulin Island.
c Formations in Ottawa area.
SOURCES OF INFORMATION
Compilation by B.A. Liberty and D.F. Hewitt 1972, P.G. Telford 1976, 1987.
Geology from maps of the Geological Survey of Canada and the Ontario Geological Survey.
MILES
0 25 50 75
0 40 80 120
KILOMETRES
QUEBEC
U. S. A.
LAKE HURON
LAKE ONTARIO
LAKE ERIE
MANITOULIN I.
BRUCE PENINSULA
Georgian Bay
Collingwood
Midland
Lake Simcoe
Goderich
Sarnia
London
Windsor
Lake St. Clair
Pelee Pt.
Grand River
Thames River
TORONTO
Hamilton
Niagara Falls
Trenton
Kingston
Ottawa
Ottawa R.
St. Lawrence R.
82°
45°
42°
46°
44°
75°

within the overlying Palaeozoic and glacial materials.

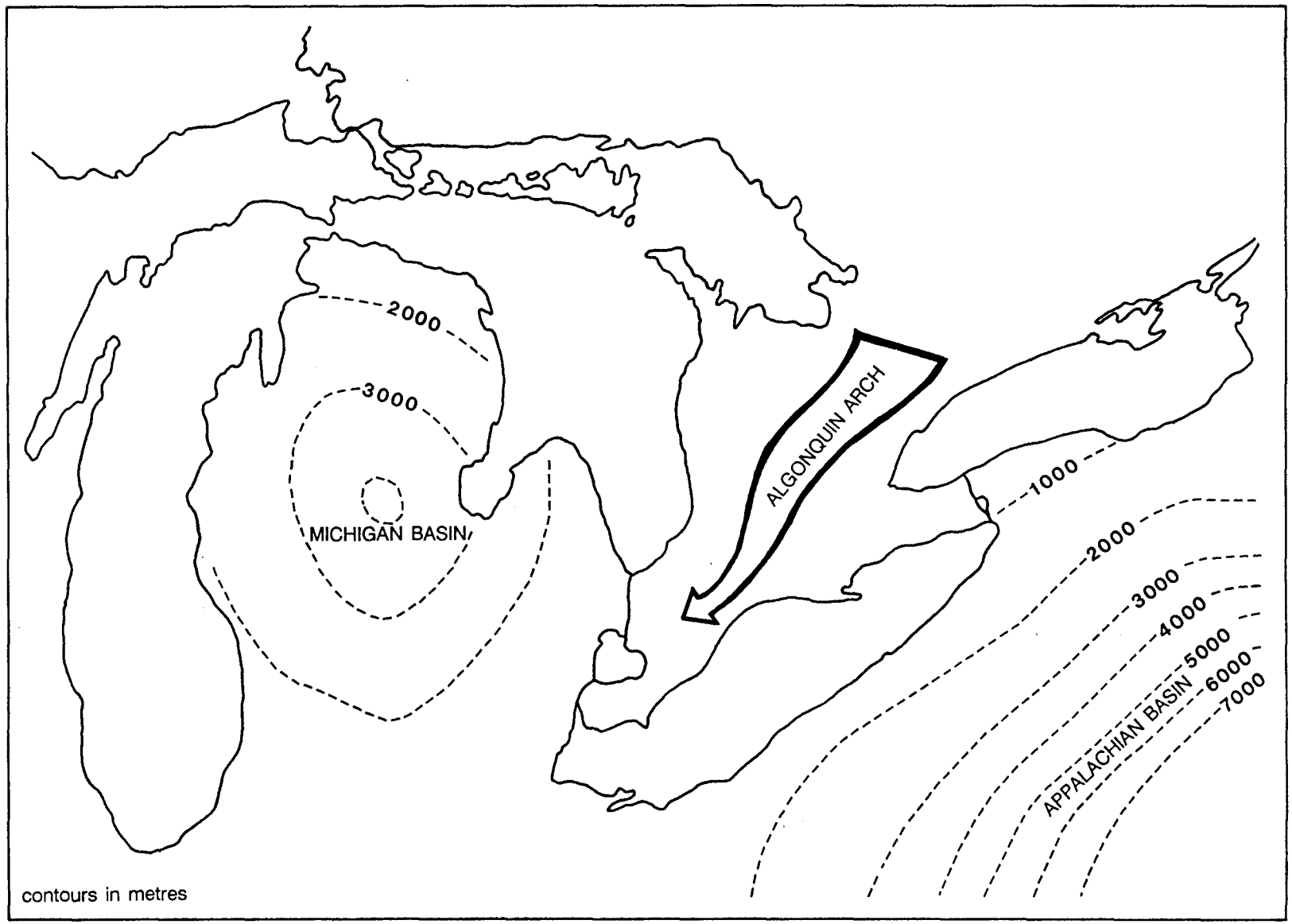
Palaeozoic sedimentary rocks are, in contrast to the basement rocks, well exposed within south-central Ontario, both in natural outcrops and roadcuts along the Niagara Escarpment and in numerous quarries within the region. Palaeozoic rocks form the immediate substrate to the surficial glacial deposits, or are themselves exposed at the surface, and may therefore be important in controlling the origin and pattern of jointing in south-central Ontario.

2.2.1 Palaeozoic Geologic History

During the Proterozoic, the Canadian Shield underwent varying amounts of crustal displacement which resulted in differential regional uplift and depression. These displacements are recorded in the present structure of the metamorphic and igneous rocks of the Canadian Shield. There are three major structural elements to the basement rocks of south-central Ontario, namely the Michigan Basin, Appalachian Basin and Algonquin Arch (Fig. 2-2).

The Michigan Basin is a roughly circular, deep (4200 m) sedimentary basin found at the margin of the Canadian Shield in northeastern Michigan and southwestern Ontario (Stearn *et al.* 1979). Subsidence at this location relative to the surrounding platform during the Cambrian, initiated a depression in the crust which, with continued subsidence, developed into the Michigan Basin (Cohee, 1948). This basin has

FIGURE 2-2: Structural elements of the Great Lakes Region (adapted from Freeman, 1978).


2000
3000
MICHIGAN BASIN
ALGONQUIN ARCH
1000
2000
3000
4000
5000
6000
7000
APPALACHIAN BASIN
contours in metres

subsequently been infilled by sedimentary rocks deposited during the Palaeozoic.

The Appalachian Basin is a large, elongate foreland basin located between the Appalachian Mountains (northeastern United States) and the Algonquin Arch (southern Ontario) (Fig. 2-2) (Stearn *et al.*, 1979). It developed as a result of crustal loading associated with the Taconic, Acadian and Alleghenian Orogenies from which the Appalachian Mountains formed (Tankard, 1986).

Separating the Michigan Basin in the west and Appalachian Basin in the south is the Algonquin Arch. The Algonquin Arch is a broad ridge in the crust which stretches from Chatham in the southwest to the Collingwood Upland in the northeast (Fig. 2-2) (Telford, 1978). It developed during the Cambrian in response to subsidence on either side of the arch, within the Michigan and Appalachian Basins (Brigham, 1971). The Algonquin Arch remained active until the Late Devonian (Freeman, 1978), and had a major impact on regional sedimentation patterns during the Palaeozoic when it acted as a open shallow water barrier or transition zone, separating the deep Michigan Basin from the shallow Appalachian Basin (Freeman, 1978). As a result of this barrier, several of the geologic formations within the study area thin toward the Algonquin Arch (Brigham, 1971).

Episodic subsidence of the crust during the Ordovician and Silurian, allowed repeated marine transgressions and the development of shallow inland seas within the

interior of North America (Stearn *et al.*, 1979). Sediments deposited in the Michigan Basin record deep water marine environments: shallow water near-shore beaches and tidal flats characterize the Appalachian Basin (Freeman, 1978). The very different depositional environments of the Michigan and Appalachian Basins interfinger on top of the Algonquin Arch and are recorded by the Palaeozoic rocks which blanket south-central Ontario. Characteristics of the various Palaeozoic formations exposed within south-central Ontario will be discussed in detail below.

2.2.2 Palaeozoic Stratigraphy

The Palaeozoic sedimentary rocks of south-central Ontario range in age from Upper Ordovician to Middle Silurian (Fig. 2-1). Within the study area, the Upper Ordovician strata consist essentially of shale interbedded with limestone. These rocks are represented by the Whitby Formation east of Markham, the Queenston Formation, east of the Niagara Escarpment and west of Streetsville and the Georgian Bay Formation which outcrops between Streetsville and Markham. The Lower and Middle Silurian formations, namely the Guelph Formation, Lockport-Amabel Formations and Clinton and Cataract Groups, are exposed primarily along the face of the Niagara Escarpment, and are composed primarily of sandstone and shales in the lower portions (Clinton and Cataract Groups) and limestone or dolomite in the upper part (Lockport, Amabel and Guelph Formations). Each of these formations show extensive jointing in outcrop and will therefore be described in some detail below.

Whitby Formation

The Whitby Formation is approximately 88 metres thick near Lake Ontario but thins northward to approximately 52 metres at Nottawasaga Bay as it onlaps the Algonquin Arch (Liberty, 1969). Within the study area, the Whitby Formation is exposed along the Rouge River and Little Rouge Creek at the Scarborough and Pickering Township Boundaries. It consists of grey to black, thinly bedded, fissile marine shale. At several locations the colour varies through dark, rusty brown to olive-yellow and is interbedded with arenaceous, bituminous and pyrite bands (Hewitt, 1969).

Georgian Bay Formation

The Georgian Bay Formation has a wide regional extent as a result of its deposition in a near-shore, shallow water environment onlapping the Algonquin Arch (Freeman, 1978). It extends from Pickering in the east, to Oakville in the southwest where it is approximately 250m thick and thins northwestward toward the Algonquin Arch (Fig. 2-2). The best exposures within the study area along the Lake Ontario shoreline and in a number of its tributaries including Etobicoke Creek, Credit River and the Humber River. The Georgian Bay Formation is composed of thin- to medium-bedded blue-grey shale interlayered with 10cm to 20cm thick beds of limestone or calcareous sandstone. The formation becomes increasingly calcareous and arenaceous towards the top where it grades into the Queenston Formation (Caley, 1940; Hewitt, 1969).

Queenston Formation

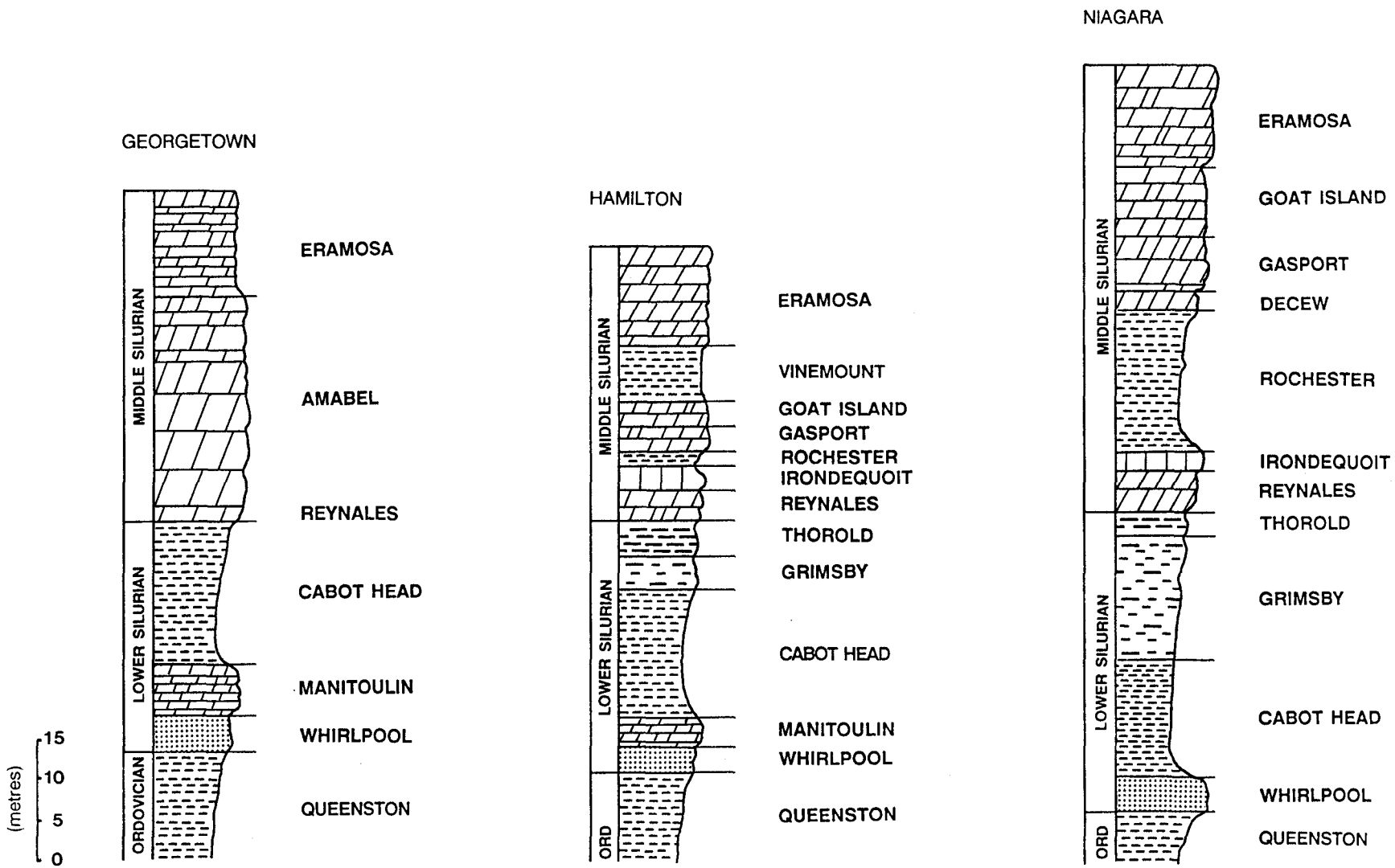
The Queenston Formation is composed of easily recognized red argillaceous and

arenaceous shale interbedded with green siltstone. The Queenston Formation represents a wide variety of depositional environments varying from nonmarine alluvial, through marginal marine deltaic, to marine basin conditions (Freeman, 1978). It outcrops in a wide band extending from Queenston on the Niagara River to Tobermory on the Bruce Peninsula (Fig. 2-1). The thickness of the formation varies from 244 metres at St. Catharines to 49 metres at Tobermory where a facies change occurs, and the Queenston Formation is replaced by an upper member of the Georgian Bay Formation (Liberty and Bolton, 1971). Although the Queenston Formation is well exposed at the base of the Niagara Escarpment near Milton, the best exposures within the study area are found along the Niagara Gorge, Sixteen Mile Creek and Bronte Creek.

Cataract Group

The Cataract Group consists of a series of Silurian formations of limited thickness which represent deltaic and shallow marine environments (Martini, 1972). The formations composing the Cataract Group vary with location, according to where the original sediment was deposited in relation to the regional structure (Fig. 2-3). In the southern portion of the study area, the Cataract Group consists of the Whirlpool Formation (light grey, high energy, shallow water, quartzose sandstone), Power Glen Formation (shallow water, grey shale and limited amounts of red sandstone) and Grimsby Formation (red shale and sandstone formed in deltaic channels)(Hewitt, 1972; Freeman, 1978; Telford, 1978; Karrow, 1987). Further north, the Whirlpool Formation (very shallow water sandstone), Manitoulin Formation (blue-grey to buff, deep-water, crystalline dolomite)

FIGURE 2-3: Variations in the palaeozoic stratigraphy along the Niagara Escarpment (adapted from Telford, 1978).


GEORGETOWN
MIDDLE SILURIAN
LOWER SILURIAN
ORDOVICIAN
ERAMOSA
AMABEL
REYNALES
CABOT HEAD
MANITOULIN
WHIRLPOOL
QUEENSTON
(metres)
15
10
5
0
HAMILTON
MIDDLE SILURIAN
LOWER SILURIAN
ORD
ERAMOSA
VINEMOUNT
GOAT ISLAND
GASPORT
ROCHESTER
IRONDEQUOIT
REYNALES
THOROLD
GRIMSBY
CABOT HEAD
MANITOULIN
WHIRLPOOL
QUEENSTON
NIAGARA
MIDDLE SILURIAN
LOWER SILURIAN
ORD
ERAMOSA
GOAT ISLAND
GASPORT
DECEW
ROCHESTER
IRONDEQUOIT
REYNALES
THOROLD
GRIMSBY
CABOT HEAD
WHIRLPOOL
QUEENSTON

and Cabot Head Formation (prodeltaic, shallow water, red to grey shale, containing dolomite, sandstone and limestone interbeds) comprise the Cataract Group (Caley, 1940; Bolton, 1957; Freeman, 1978).

Clinton Group

The Clinton Group consists of a series of formations which were deposited in the Clinton Sea. Within the study area, the Thorold Formation (grey shallow water sandstone) constitutes the base of the Clinton Group. Above it may be found the thin Neahga Formation (dark grey to green platy shale deposited in quiet shallow bays), Reynales Formation (grey deep marine dolomite), Irondequoit Formation (white crinoidal limestone), Rochester Formation (grey to black argillaceous shale) and the DeCew Formation (dark grey dolomitic limestone) (Bolton, 1957; Telford, 1975; Karrow, 1987). The DeCew Formation has also been assigned as the basal member of the Lockport Formation (Williams, 1914 and Cummings, 1939; as found in Bolton, 1957). The Clinton Group illustrates the characteristics of sediments deposited in a prodeltaic or marine environment (Telford, 1978).

Lockport and Amabel Formations

The Lockport Formation forms the thick (approximately 30 metres) cap for the Niagara Escarpment south of Waterdown (Karrow, 1987). It is composed of three members: Gasport Member (light grey crinoidal limestone), Goat Island Member (medium grey to brown argillaceous dolomite with chert nodules) and Eramosa Member (brown

bituminous dolomite deposited in quiet lagoons) (Bolton,1957; Telford, 1975; Telford, 1978). At Waterdown, the Lockport Formation grades into the Amabel Formation (Karrow, 1987). As a result, the Amabel Formation between Waterdown and Georgetown has a wide variety of characteristics. Generally, the Amabel Formation is a light grey to buff, crystalline, massive to irregularly bedded, reefy dolomite (Hewitt and Yundt, 1971).

Guelph Formation

At the most western reaches of the study area, the Guelph Formation is seen in outcrop. It may be found within a narrow, ten kilometre wide band which parallels the Niagara Escarpment (Fig. 2-1). The Guelph Formation is composed of irregularly bedded, buff-coloured reefal and interreefal dolomite (Hewitt and Vos, 1972; Telford, 1978). In the subsurface, the Guelph Formation reaches 78 metres thickness although the entire thickness is never seen in outcrop (Caley, 1940).

2.3 Pre-Quaternary Geology

Following the deposition of the Palaeozoic rocks described above, the bedrock surface of south-central Ontario was exposed for a considerable length of time during which it was altered by natural weathering and erosion processes. There is evidence to suggest that towards the end of the Tertiary period, an extensive river network termed the Laurentian Channel System, existed within the Great Lakes Region (Spencer, 1881 in Karrow, 1973; Hough, 1958; Karrow, 1973; Calkin and Brett, 1978). Within south-central Ontario, three large preglacial rivers formed part of the Laurentian

River System. One of these rivers flowed southward out of the present-day Georgian Bay area into the Toronto area (Karrow, 1967; White and Karrow, 1971; Karrow, 1973; Eyles, 1987); a second may have formed the reentrant at Dundas as it flowed between either the Lake Ontario and Lake Erie basins (Spencer, 1881 in Hough, 1958) or alternately, the Lake Huron and Lake Ontario basins (Karrow, 1973). There is also evidence of a third preglacial river in the Erigan Valley near St. Catharines which would have connected the Lake Ontario and Lake Erie basins (Karrow, 1973; Flint and Lolcama, 1985). All three of these preglacial river valleys have since been buried by a thick cover of glacial sediments and their presence can only be established using drill cores or geophysical studies (Karrow, 1973).

There is no depositional record for the period following the development of the Laurentian River System from the Middle Silurian to Late Pleistocene in south-central Ontario.

2.4 Quaternary Geology

The physiography of south-central Ontario was altered considerably by the sequence of glacial and interglacial episodes that occurred during the Quaternary. The glacial history of south-central Ontario is complex and has been discussed by many authors (for example Hough, 1958, Karrow, 1967, 1987; Chapman and Putnam, 1966, 1984; Dreimanis and Goldthwait, 1973; White, 1975; Freeman, 1978; Karrow *et al.*, 1982; Karrow and Calkin, 1985; Barnett and Kelly, 1987). The sediments of south-central

Ontario provide evidence for three distinct Quaternary climatic stages (Table 1): the Illinoian glacial stage (130-180,000 years B.P.), Sangamonian interglacial stage (110-130,000 years B.P.) and the Wisconsinan glacial stage (110-10,000 years B.P.) (Karrow *et al.*, 1982). The Illinoian glacial stage is recorded in south-central Ontario by the York Till, a grey, shale-rich till which is exposed at only two sites within the study area, namely the Don Valley Brickyards and the Woodbridge Cut (Karrow, 1967; Eyles and Clark, 1988a). The Sangamonian interglacial stage is represented by the deltaic sands of the Don Formation which are also visible at the Don Valley Brickyard (Karrow *et al.*, 1982; Eyles and Clark, 1988a). These deposits will not be discussed further within this thesis since they have a very limited exposure. Further information regarding these deposits may be found in Karrow (1967), White (1975), Poplawski and Karrow (1981), Hann and Karrow (1984), Eyles and Clark (1988a).

Wisconsinan glacial deposits are the dominant surficial material in south-central Ontario and will be discussed in detail. The extensive till deposits laid down by the Late Wisconsinan ice advance (Halton and Wentworth Tills) and postglacial lacustrine deposits associated with Lake Iroquois and Lake Peel will be emphasized since these deposits form the majority of the fine-grained surficial cover of south-central Ontario and commonly exhibit jointing (Fig. 2-4).

2.4.1 Wisconsinan History and Deposits

The Scarborough Formation is the oldest Wisconsinan deposit in south-

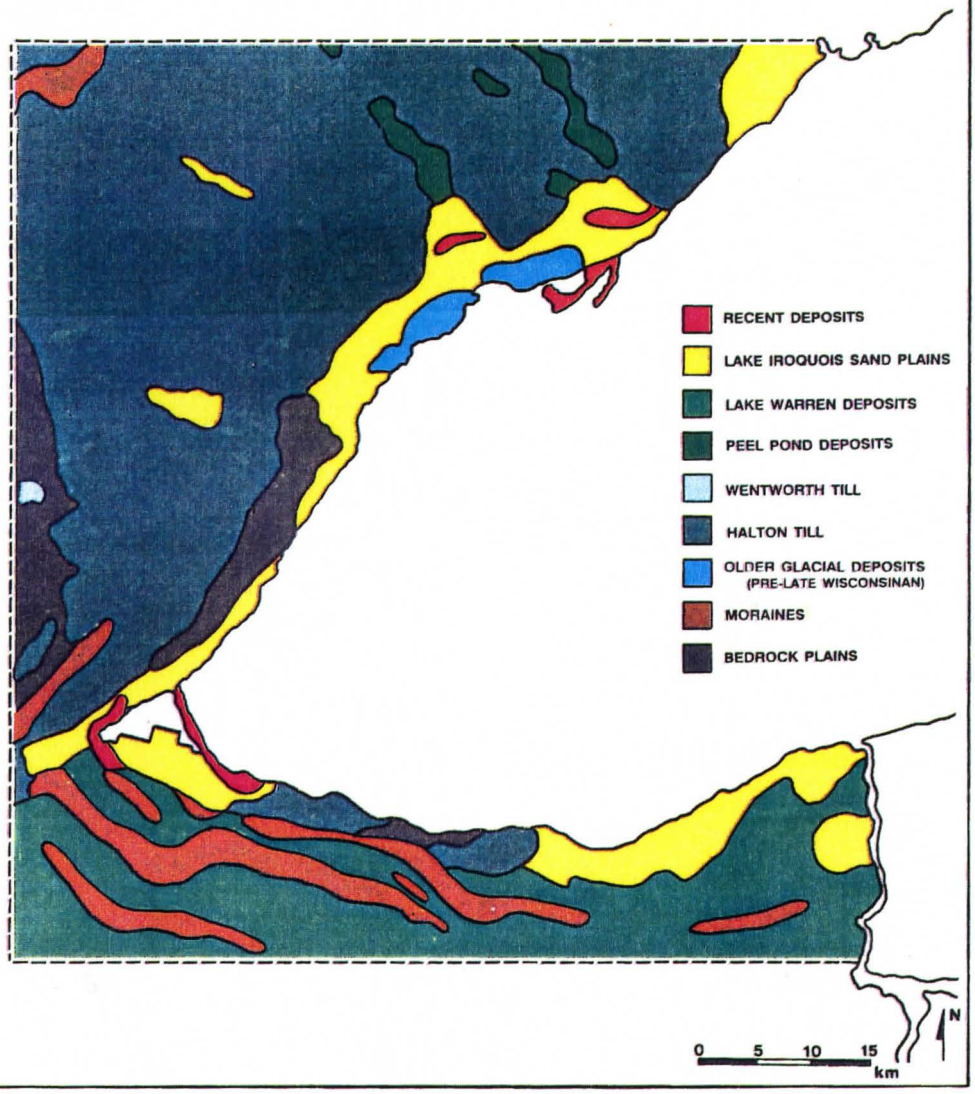
AGE YRS (BP)	CHRONOSTRATIGRAPHIC UNITS	ASSOCIATED DEPOSITS (ONTARIO LOBE)
< 10 000	POSTGLACIAL (LACUSTRINE)	PEEL POND DEPOSITS LAKE IROQUOIS DEPOSITS
< 30 000	LATE WISCONSIN (GLACIAL)	WENTWORTH TILL HALTON TILL
< 66 000	MIDDLE WISCONSIN (LACUSTRINE AND GLACIO-LACUSTRINE)	UPPER THORNCLIFFE FORMATION MEADOWCLIFFE TILL MIDDLE THORNCLIFFE FORMATION SEMINARY TILL LOWER THORNCLIFFE FORMATION
< 110 000	EARLY WISCONSIN (GLACIOLACUSTRINE)	SUNNYBROOK DIAMICT SCARBOROUGH FORMATION
< 130 000	SANGAMONIAN (LACUSTRINE)	DON FORMATION
< 180 000	ILLINOIAN (GLACIAL)	YORK TILL

SOURCES IN TEXT SEE SECTION 2.4

TABLE 1: Chronostratigraphy of south-central Ontario.

FIGURE 2-4: Surficial geology of south-central Ontario (compiled and generalized from, Watt 1955, 1968; Chapman and Putnam 1966; Feenstra 1972, 1975; Sharpe, 1980; Karrow, 1987).

SURFICIAL GEOLOGY



central Ontario and is associated with the Early Wisconsinan Substage (Table 1). The Scarborough Formation shows a general coarsening upward sequence from clay and silt rhythmites, through irregularly bedded silt and sand to cross-bedded sands, and has been interpreted as deltaic in origin. This delta formed at the mouth of a large, southward flowing river as it entered Lake Scarborough, a high level Early Wisconsinan glacial lake (Coleman, 1941; Karrow, 1967; Freeman, 1978; Kelly and Martini, 1986; Barnett and Kelly, 1987; Eyles and Clark, 1988b). High lake levels in the Ontario Basin may have been caused by blockage of the St. Lawrence valley by ice, postglacial isostatic rebound of the lake or loading of the lake basin by increased sediment or water inputs (Karrow, 1967; Eyles and Clark, 1988b).

Following the deposition of the Scarborough Delta, the Sunnybrook diamict, an extensive fine-grained diamict, was deposited. The Sunnybrook diamict is probably of Early Wisconsinan age (50,000 to 65,000 years B.P., White, 1975; 72,000 years B.P., Freeman, 1978; 66,000 +/- 7,000 years B.P., Berger, 1984). There are two general schools of thought with regard to the origin of the Sunnybrook diamict. One suggests that the Sunnybrook diamict was deposited below an extensive grounded ice sheet, while the other suggests that the diamict accumulated in a glaciolacustrine environment. Karrow (1967, 1984) suggests that the Sunnybrook is a lodgement till composed of reworked lake sediments and records a substantial Early Wisconsinan ice advance in south-central Ontario. Based upon clast fabric analysis and palaeomagnetic evidence, Gravenor and Wong (1987) conclude that there is currently insufficient evidence to be

completely certain of the Sunnybrook diamict's origin, although they suggest that the Sunnybrook diamict is likely a combination of a lodgement till and an undermelt till. Hicock and Dreimanis (1989) propose that the Sunnybrook diamict is a lodgement and/or deformation till composed of reworked glaciolacustrine muds.

This first theory of deposition of the Sunnybrook by a grounded ice sheet contrasts sharply with that of Eyles and Eyles (1983), who propose that the Sunnybrook diamict developed through a combination of rain-out of suspended sediment from the water column and debris from floating ice in a proglacial lake containing minimal ice volumes. The glaciolacustrine theory is substantiated by fossil evidence. Westgate *et al.* (1987) suggest that the ostracode fauna found within the Sunnybrook diamict were deposited within a large, deep and cold lake, consistent with the idea of Eyles and Eyles (1983). Further, because of their fragility, these valves would not have survived the reworking suggested by Karrow (1967, 1984).

The Sunnybrook diamict is overlain by the Thorncliffe Formation, a younger, Middle Wisconsinan deltaic unit which consists predominantly of interbedded sands and silty sands and includes two diamict units, the Seminary and Meadowcliffe diamicts (Table 1). Karrow (1967) suggests that the complex Middle Wisconsinan stratigraphy is associated with two minor glacial advances (Seminary and Meadowcliffe Tills), separated by deltaic sands (Thorncliffe Formation) deposited in interstadial glacial lakes. Eyles and Eyles (1983) propose that the entire Middle Wisconsinan sequence represents a series

of prograding deltas in ice-contact lakes and further, that the Seminary and Meadowcliffe units are not specifically tills but glaciolacustrine diamicts.

The most extensive Wisconsinan glacial advance occurred during the Late Wisconsinan (after 30,000 years B.P.) as glaciers spread over south-central Ontario out of the Lake Ontario basin, eroding pre-existing sediments and depositing an extensive diamict unit, the Halton Till (formerly Leaside Till in the Toronto area; Karrow, 1967, 1984), over much of south-central Ontario (Eyles, 1987). The Halton Till varies considerably in texture from 10 to 55% sand, 34 to 70% silt and 7 to 46% clay (White, 1975). The diamict is found either directly overlying bedrock or demonstrating an erosional contact with sediments below. It is the primary constituent of many surficial glacial landforms within the study area including several end moraines (Fig. 2-4) and flutes and drumlins found on the extensive till plains (Karrow, 1967, 1987; Chapman and Putnam, 1984). This suggests that the diamict was deposited directly by glaciers perhaps as a lodgement or deformation till (Karrow, 1987; Eyles, 1987).

Within the southwestern part of the study area, isolated pockets of Wentworth Till are found. This diamict is thought to have been deposited prior to the Halton Till at approximately 14,000 years B.P. although its origin is not completely understood (Table 1) (Barnett, 1979; Dreimanis and Goldthwait, 1973). Differences between the garnet ratios contained within the two till sheets have been used to suggest a reorientation of ice flow between the deposition of the Wentworth and Halton

Tills and that ice retreat and readvance may separate the two units (Karrow, 1987). However, it has also been suggested that the Halton and Wentworth Tills may be different facies of the same till sheet (White, 1975; Karrow, 1987). Textural data suggest that the two tills grade together near their margins although they show quite different characteristics at distal locations (Karrow, 1987).

2.4.2 Postglacial Lacustrine Deposits

As the Late Wisconsinan ice retreated from southern Ontario, much of the study area became covered by a series of proglacial lakes which developed in response to extremely high volumes of meltwater production, isostatic depression and the blockage of major spillways (Karrow and Calkin, 1985). In south-central Ontario, the most extensive and best defined postglacial lake deposits are associated with glacial Lake Iroquois. Lake Iroquois developed proximal to the Ontario Lobe as it retreated eastward out of the Ontario Basin (after 12,000 years B.P.; Eyles, 1987). The shoreline associated with Lake Iroquois was well-developed as the result of erosional processes and is readily identified at various locations around the margins of present day Lake Ontario. The Lake Iroquois shoreline varies in elevation considerably as the result of isostatic rebound. The shoreline is thirty metres higher in elevation at Toronto than at Hamilton where the shoreline is approximately 31 metres above present Lake Ontario (Freeman, 1978).

Lake Iroquois is commonly represented in the depositional record as stratified to massive clays, silts or sands, although the deposit's characteristics depends

upon how close the exposure is to the actual shoreline (Karrow, 1967, 1987; Feenstra, 1972, 1975). Where Lake Iroquois has eroded away pre-existing coarse-grained sediments (for example the Halton Till), a coarse lag of material may be present (Karrow, 1967). Remnant beaches, bars and spits of Lake Iroquois are also seen within the study area; an impressive landform associated with glacial Lake Iroquois is a set of gravel bars which presently separate Cootes Paradise from Hamilton Harbour (Fig. 2-4) (Karrow, 1987). Most other large deposits of Lake Iroquois gravels have been stripped for aggregate (Karrow, 1967).

Although Lake Iroquois is the major postglacial water body affecting south-central Ontario, there are also deposits associated with Lake Peel within the study area. Lake Peel was a comparatively small, proglacial lake which developed when meltwater became confined within the Trafalgar and Oak Ridges Moraines and the Niagara Escarpment (Chapman and Putnam, 1984) (Fig. 2-4). Only a thin veneer (approximately 1 metre) of sediments, consisting predominantly of sand and varved clay, were deposited within Lake Peel (Karrow, 1987). Isolated pockets of Lake Peel shallow- and deep-water deposits are found along several rivers within the study area including the Humber River, Don River, Etobicoke Creek and their tributaries (Sharpe, 1980).

This geologic history provides a basis from which the site descriptions contained within Chapter 3 may be understood.

CHAPTER 3: SITE DESCRIPTIONS

3.1 Introduction

This chapter contains descriptions of each site where data were collected. Thirty-seven sites in total were visited; at sixteen sites only surficial glacial materials were exposed, seventeen exposures displayed bedrock alone and at the remaining four sites, both bedrock and overlying surficial sediments could be observed. The location of each site is shown in Figure 3-1. The study area has been divided into three regions (Fig. 3-1); a southern zone which encompasses the Niagara Peninsula as far west as Stoney Creek: a central zone which stretches from Hamilton in the south, as far east as Oakville and north to Limehouse: and a northern zone which includes all sites east of the central zone, up to and including Pickering.

3.2 Site Descriptions

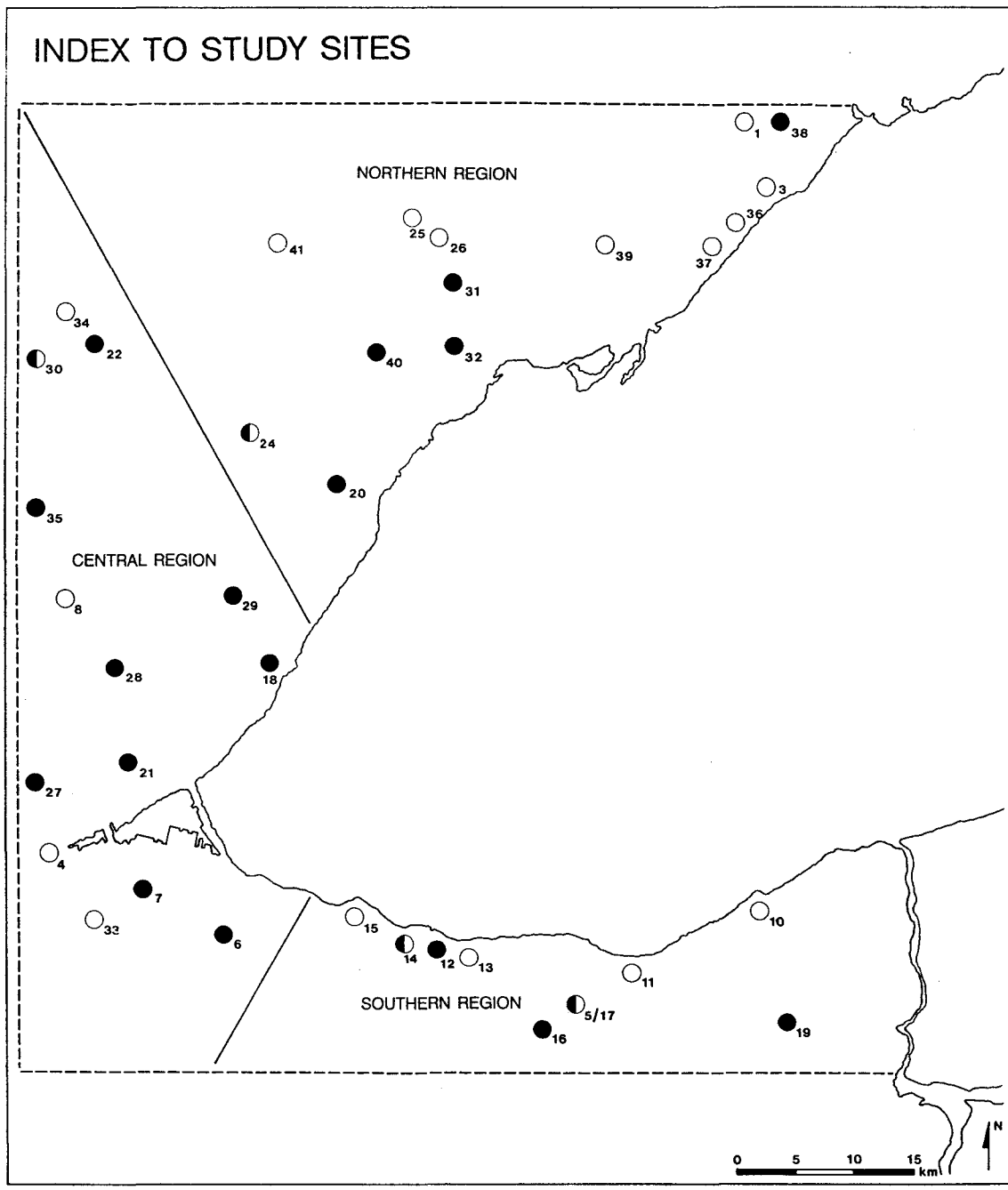
3.2.1 Southern Zone

Site 5/17: Vineland Quarries, south of Vineland (bedrock & glacial)

At Vineland Quarries (Fig. 3-1), joint measurements were taken in both the surficial glacial sediments and bedrock. The bedrock exposed at this site is part of the Lockport Formation, which is composed of well jointed (4 joints per metre) and thinly-bedded (20cm - 70cm) dolomite. The upper bedrock surface is very irregular with

FIGURE 3-1: Index to study sites located within the southern, central and northern regions of the study area (legend on Figure 1-2).

INDEX TO STUDY SITES



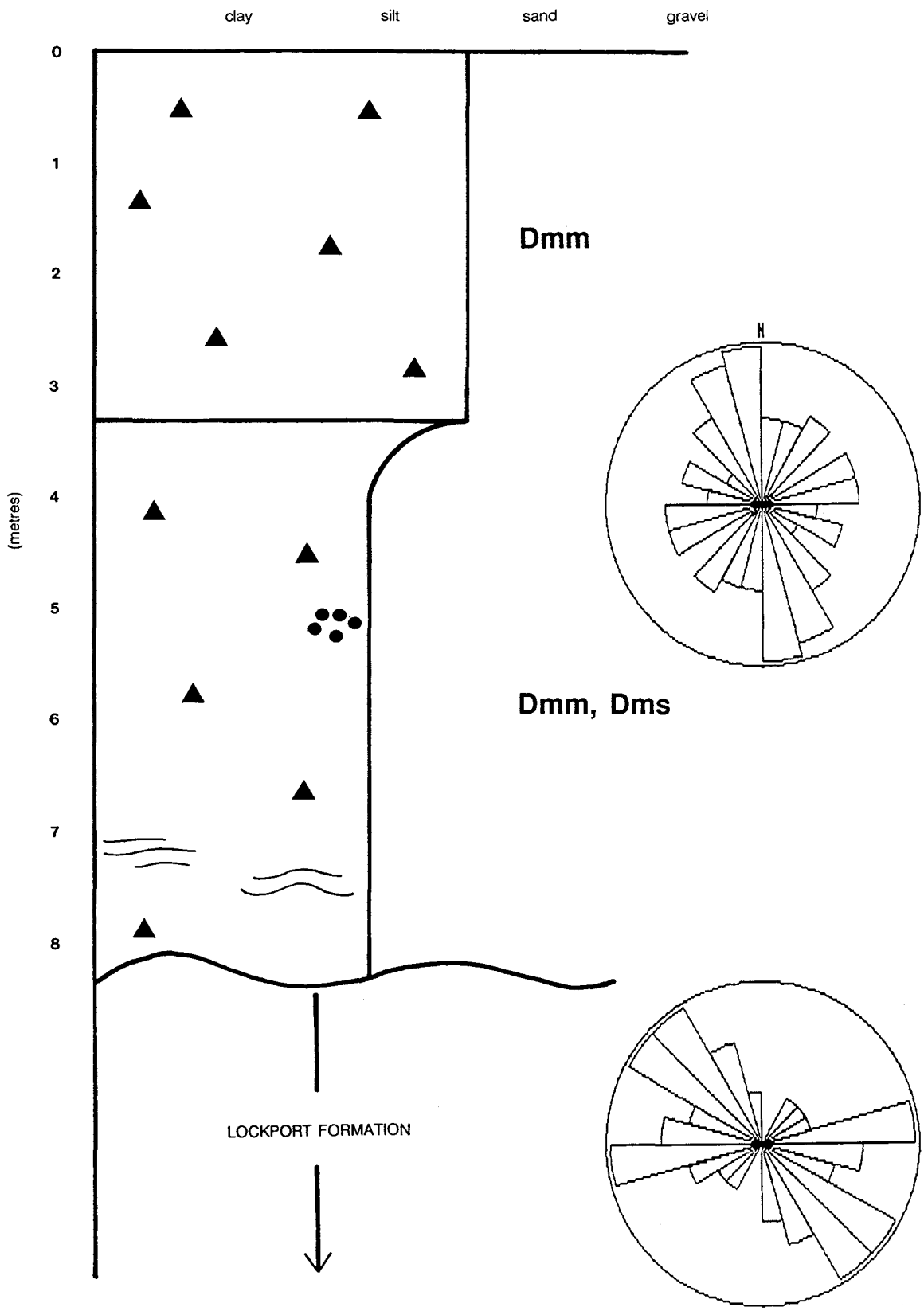
elongate undulations of up to 3 metres in amplitude caused by glacial erosion (Fig. 3-2). The streamlined features as well as striations present on the bedrock surface are oriented northeast/southwest at 40°. Joint measurements taken from both the upper plane surface and a vertical face show a dominant northwest/southeast trend (Fig. 3-3).

A mantle of up to 15 metres of fine grained diamict, mapped as Halton Till, overlies the bedrock (Feenstra, 1972). At the section where joints were measured, the diamict consisted of two distinct units; a 5 metre thick lower grey, clayey-silt diamict and a 3 metre thick, upper buff, silty diamict. The matrix texture of the lower diamict becomes coarser with height (clay to silty-sand), shows crude laminations at its base and contains rare small (<3 cm) clasts. Patches of silt-clast breccia including both angular and smeared clasts are present within the diamict; folded and contorted silt-clay laminations also occur (Fig. 3-3). This diamict may have formed in a glaciolacustrine environment by the settling out of fine-grained sediment from suspension together with some ice-rafted debris. Periodic downslope slumping of the accumulating sediment would account for the folded and brecciated silt beds within the diamict (Eyles and Eyles, 1983). Alternately, given the association of this fine-grained diamict with the overlying coarser-grained diamict, it may be interpreted as a glaciolacustrine deposit which has undergone post-depositional deformation and shearing by overriding glacier ice (and therefore may be considered to be a deformation till; Boulton and Hindmarsh, 1987). The overlying diamict is very hard, massive and

FIGURE 3-2: Photography showing streamline features at Vineland Quarries (Site 5/17) on top of the Lockport Formation (bar is approximately 3 metres in length).

FIGURE 3-3: Sedimentologic log showing the characteristics of the diamicts at Site 5/17. (black dots are silt clast breccia, wavy lines indicate contorted laminations).

Note strong north-northwesterly/south-southeasterly joint trends within the diamicts and strong northwest/southeast and west/east joint trends within the underlying Lockport Formation.


clay
silt
sand
gravel
0
1
2
3
4
5
6
7
8
(metres)
Dmm
N
Dmm, Dms
LOCKPORT FORMATION

overcompacted. This bed, like the one beneath, has a very low content of small (<4cm) clasts. The characteristics of the upper diamict suggests that it may be a lodgement till deposited over previously existing glaciolacustrine deposits.

Both diamict units are penetrated by joint systems which clearly show a north-northwesterly/south-southeasterly trend in orientation (Fig. 3-3). The joints within the upper and lower diamicts are readily seen, although fairly infrequent in occurrence (approximately 1 to 2 joints per metre). Unfortunately, due to face orientation and sediment slumping, it was not possible to see if any of the joints within the bedrock passed into lower diamict, or if any joints in the lower diamict extend into the upper diamict. Most joints within either the upper or lower diamict were well-defined and on average 1 to 2 metres in length.

Site 10: Lake Ontario shore, east of Port Weller, opposite Seaway Farms (glacial)

This site (Fig. 3-1) presents a complex stratigraphy of surficial sediments. At the base, a massive clay-rich diamict is exposed which contains horizontal silt partings, approximately 1 cm thick and 1 metre in length. The localized presence of red clay masses at the base of the lower diamict at several locations suggests that the Queenston Formation may be just below the base of the section. The upper part of this diamict is covered by slump material. Above the slump, lies a 2.75 metre thick bed of fine sand. The structures within the sand pass from convoluted bedding at the base of the unit upwards into ripples and finally into horizontal laminae. There are no clasts at

all within this sand unit. Above the laminated sands lies a 1 metre thick bed of convoluted sand which is mapped as Lake Iroquois deposits (Feenstra, 1972).

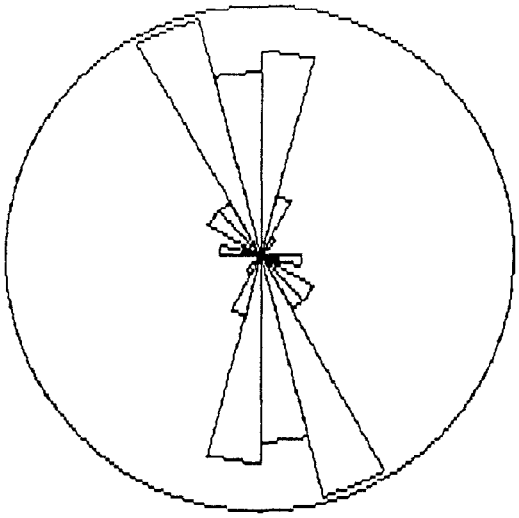
Joints were identified and measured only within the massive diamict at the base of the section. The joints were very well-defined, frequent (4 joints per metre) and several of these joints had been expanded by wave action to a width as large as 10 cm. The expanded joints could be seen to penetrate at least 0.5m into the face and extended the full height of the bed (1.75 metre). Overall, the joints at this site show a strong north-northwest/south-southeast trend in orientation (Fig. 3-4).

Site 11: Lake Ontario shoreline, west of Charles Daley Park (glacial)

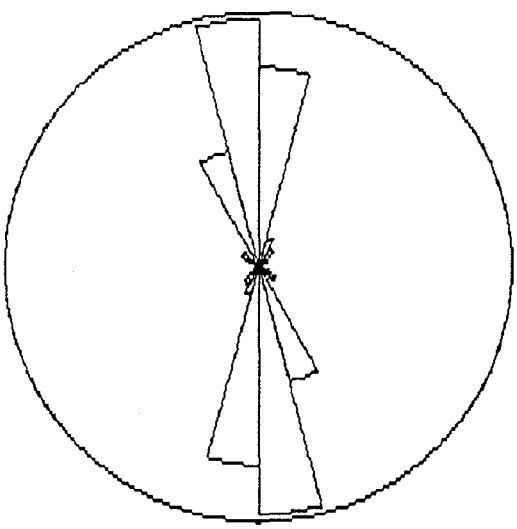
Three distinct beds are exposed at this site (Fig. 3-1). At the base of the section is a 2.5 metre thick bed of predominantly massive, clay-rich diamict, although both parallel laminations and soft sediment deformation structures are present in several places. Subrounded clasts are few and scattered within the diamict. Above this bed lies a 4 metre thick bed of massive silty-clay which is in turn overlain by a 2.5 metre thick bed of massive fine sand. Both of these upper beds contain only a rare clasts.

Joints were numerous within the lower clay-rich diamict (3 joints per metre) and many pass upward into the overlying massive silty-clay diamict although not into the bed of massive sand which caps the section. The joints ranged between 1 and 4 metres in length. Several smaller joints were also measured within the silty clay unit. The

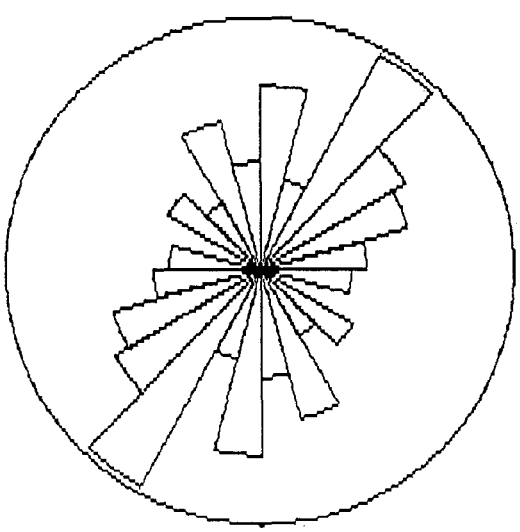
FIGURE 3-4: Rose diagrams for Sites 10, 11 and 12. Note strong north/south joint orientation trends at Site 10 and 11 as well as a strong northeast/southwest joint orientation trend at Site 12.



SITE 10



SITE 11



SITE 12

joints within all of these beds show a strong north-northwesterly/south-southeasterly trend as seen in Figure 3-4.

Site 12: Lake Ontario shoreline, west of Grimsby Harbour at Old Orchard Avenue (bedrock)

At this site (Fig. 3-1), approximately 2 metres of the Queenston Formation is exposed. The exposure consists of predominantly thin-bedded, red shale interbedded with green siltstone. The rocks are well jointed with 5 to 10 joints per metre as well as minor fissures almost every centimetre. The joints show a preferred northeast/southwest trend in orientation although a wide range in joint orientations were measured (Fig. 3-4).

Site 13: Lincoln Estates, Grimsby (glacial)

Two subsites were visited within the Lincoln Estates (Fig. 3-1). The first subsite was an excavation dug by a backhoe, approximately 25 square metres in area and 3 metres deep. The excavation exposed a thick bed of massive silty-clay diamict containing occasional red-clay lenses. Clast are rare, and those present are small (< 3cm); the average clast size is approximately 0.8 cm. The diamict is well-jointed (approximately 3 joints per metre) by fractures which continue vertically through the entire 3 metre thick bed.

The second subsite within Lincoln Estates, occurs stratigraphically above the first site (Fig. 3-5). The base of the section consists of a 1.5 metre thick bed of massive clay-rich diamict which contains clasts up to 25 cm in diameter. This bed likely correlates with the Halton Till. A coarse boulder lag separates this bed from the 1.25 metre thick bed of massive silty-sand above. This massive silty-sand is in turn overlain by a 1 metre thick bed of slightly coarser-grained silty-sand mapped as Lake Iroquois sands (Feenstra, 1975). The coarse lag which is present at the base of the middle bed, suggests an erosional contact associated with wave action on a Lake Iroquois beach.

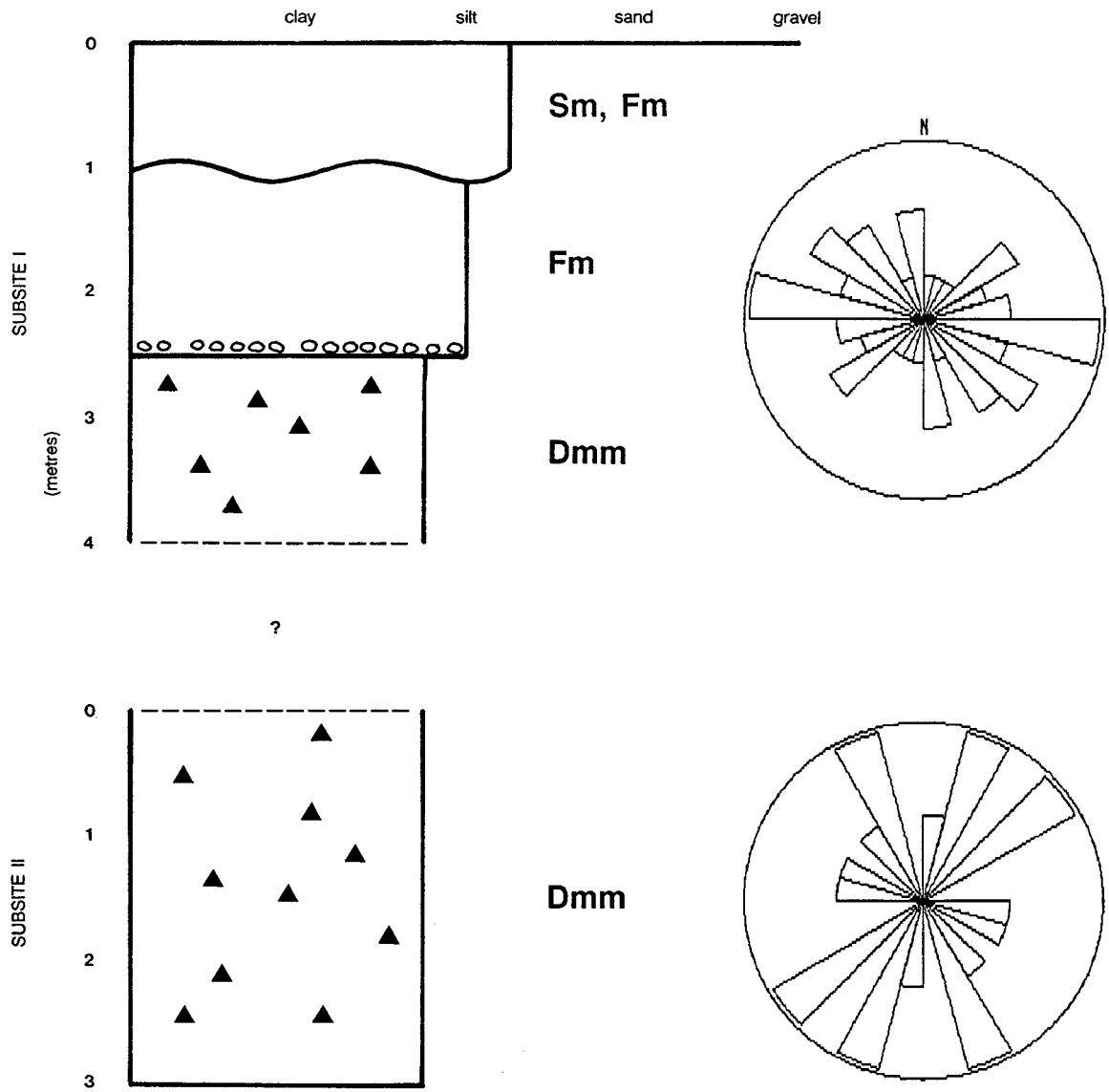
Joints were measured within the lower diamict and the massive silty-sand bed above it. Joints were sparse (<1 joint per metre) within both of these beds although those joints present were well-defined and exhibited iron-oxide staining. At both subsites within the Lincoln Estates, the joints show a wide range of orientations, although a preferred west/east trend can be identified for the entire site (Fig. 3-5).

Site 14: Lake Ontario shoreline, at Kerman Avenue, Grimsby (bedrock & glacial)

Measurements were taken within both the bedrock and overlying unconsolidated sediments at this site (Fig. 3-1). A 3 metre thick bed of Queenston Formation forms the base of the 5 metre thick section. There is a high frequency of joints within the Queenston shale: approximately 5 joints per metre. Above the Queenston shale, lies a 1.25 metre thick bed of silty-clay diamict, mapped as the Halton Till (Feenstra, 1975), which contains clasts of up to 20 cm in diameter. This unit is

FIGURE 3-5: Sedimentologic log showing the characteristics of the sediments at Site 13. The subsites appeared lie stratigraphically above each other, although they were approximately 50 metres apart. (small stones at the base of the Fm bed indicate a gravel lag).

Note the strong west/east joint orientation trend at Subsite I, and the north-northwest/south-southeast and northeast/southwest trends at Subsite II.


clay
silt
sand
gravel
0
1
2
3
4
(metres)
SUBSITE I
Sm, Fm
Fm
Dmm
N
?
SUBSITE II
Dmm

overlain by 1 metre of disturbed, slump material. The joints measured within the Halton Till are well-defined, infrequent (1 to 3 joints per metre) and do not extend the full thickness of the bed (<1 metre in length).

As Figure 3-6 shows, a preferred northeast/southwest orientation can be identified for the Queenston Formation and a preferred north-northeast/south-southwest trend may be identified within the Halton Till at this site although within the entire site there is considerable directional variability.

Site 15: Fifty Point Conservation Area, west of Grimsby (glacial)

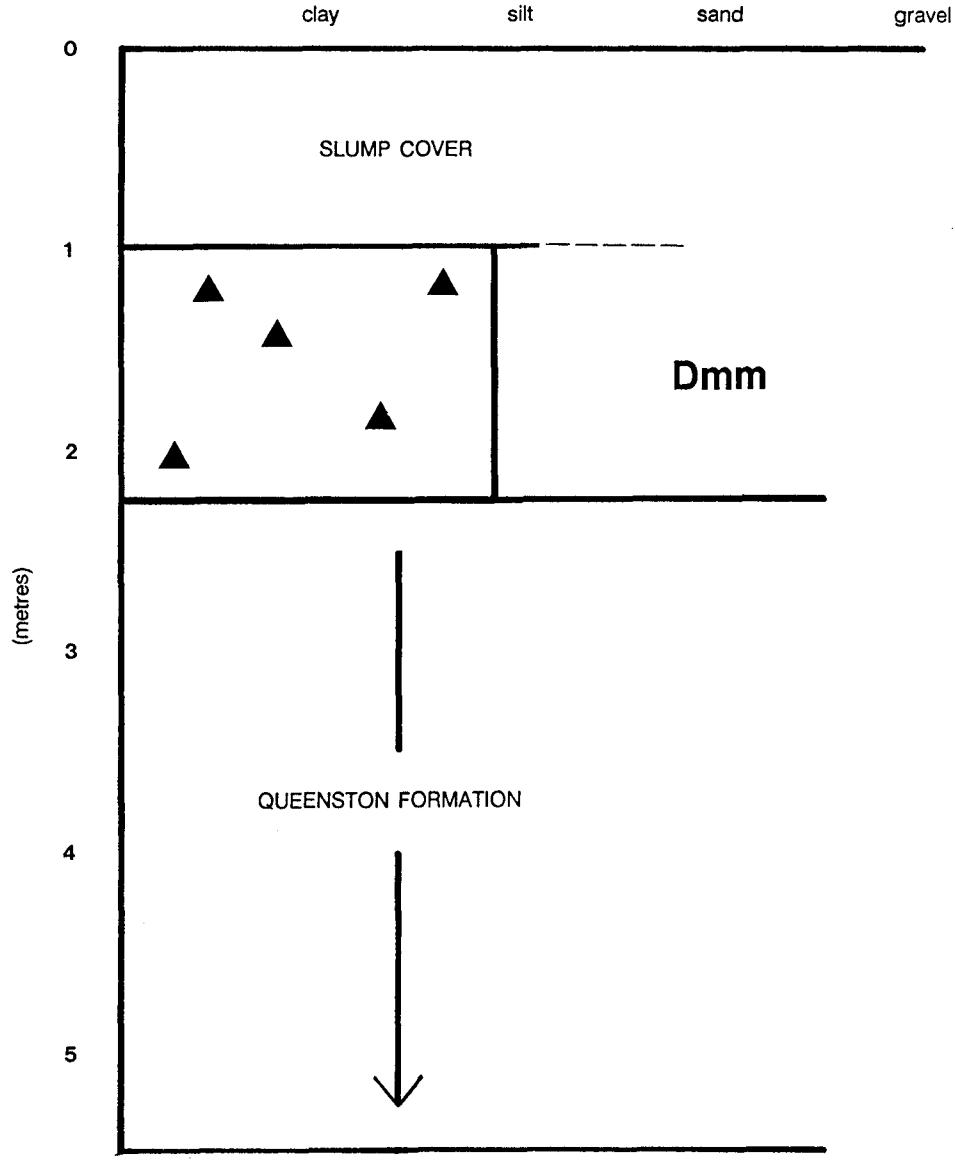
A three metre high face of massive, matrix-supported silty-clay diamict is exposed at Site 15 (Fig. 3-1). Clasts are common within the diamict and range up to 25cm in diameter. Jointing is intermittent, but at several locations within this site the joint frequency approached 4 joints per metre. The orientation of the joints within the diamict show a strong northeasterly/southwesterly trend (Fig. 3-7).

Site 16: Nelson Aggregates, Beamsville (bedrock)

At the Nelson Quarry (Fig. 3-1), the Lockport Formation is excavated at two levels forming an 9 metre high upper face and a lower 11 metre face. Both faces are well-jointed and contain joint frequencies of up to 5 joints per metre. The lower face shows gypsum filled vugs characteristic of the Eramosa member of the Lockport Formation (Caley, 1940). Joints measured within the Lockport Formation on both the

FIGURE 3-6: Sedimentologic log showing the characteristics at Site 14.

Note the strong preferred northeast/southwest joint orientation trend within the Queenston Formation. There is more variability within the overlying diamict but north-northwest/south-southeast and northeast/southwest trends may be identified.


clay
silt
sand
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0
1
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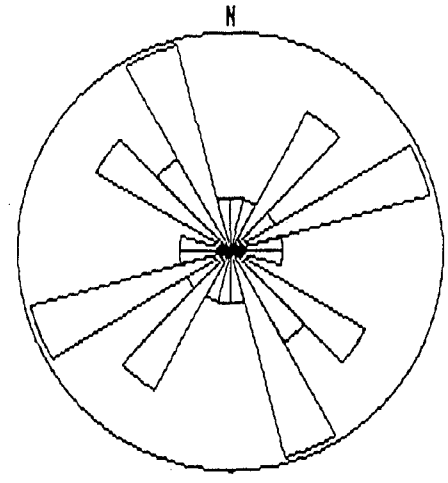
(metres)
SLUMP COVER
Dmm
QUEENSTON FORMATION


N

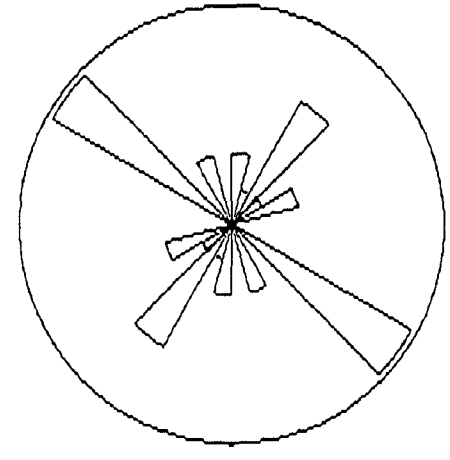
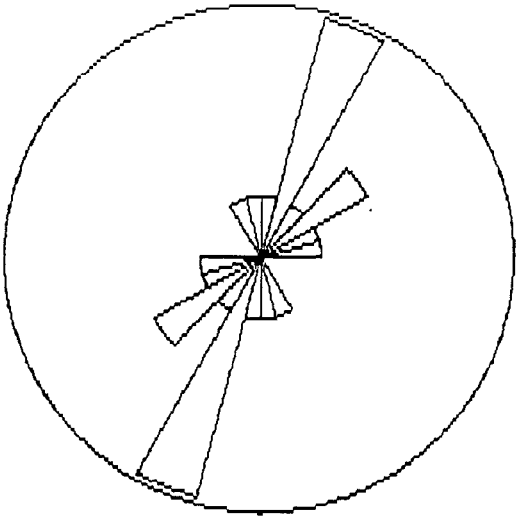
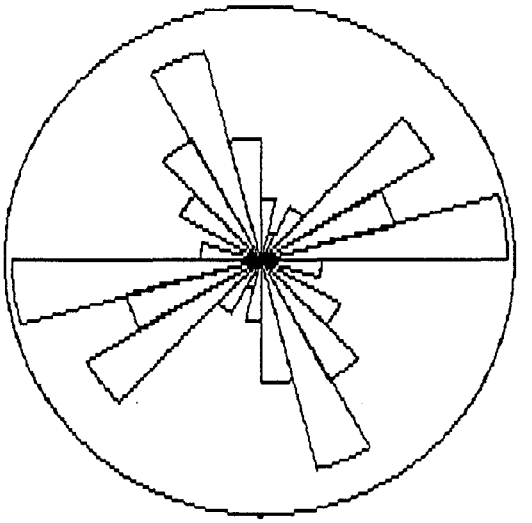


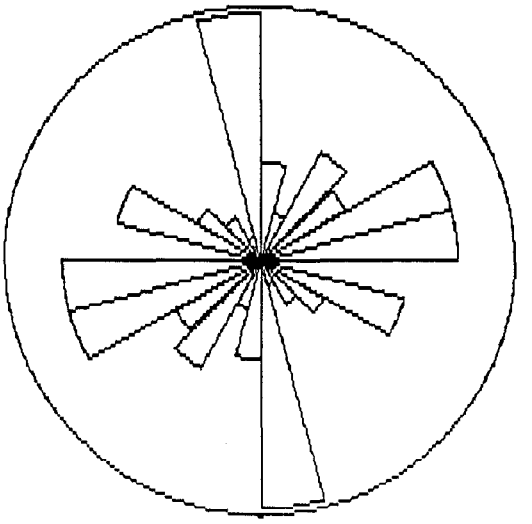
FIGURE 3-7: Rose diagrams for Sites 15, 16 and 19. Note the strong northeast/southwest joint orientation trend at site 15. Joint orientations are more variable at Sites 16 and 19, although respectively west/east, northwest/southeast and north/south, west/east trends may be identified.



SITE 15



SITE 16



SITE 19

upper and lower faces show preferred, east/west and north-northwest/south-southeast orientations (Fig. 3-7).

Site 19: Walker Bros. Quarry, Thorold (bedrock)

The Lockport Formation is excavated to a depth of 10 metres at Walker Bros. Quarry (Hewitt and Vos, 1972) (Fig. 3-1). Joints are frequent within the Lockport Formation (2 to 3 joints per metre), and several extend the full height of the face (10 metres). The joints demonstrate preferred north/south and east-northeast/west-northwest orientations (Fig. 3-7).

3.2.2 Central Zone

Site 4: West Hill Construction Site, Dundas (glacial)

A 50 metre long, 3.5 metre high section of unconsolidated sediment was exposed during construction of a subdivision west of Dundas (Fig. 3-1). The section consists of a complex stratigraphy of gravel, sands and silty-clay diamict, and has been mapped as Halton Till (Karrow, 1987). However, only the bottom metre of the section contains a silty-clay diamict which is similar to the Halton Till type described elsewhere (Karrow, 1987). Above this diamict is 2.5 metres of massive to interbedded sands in which several gravel pods are found.

Joints were measured within the silty-clay diamict at the base of the section. The joints were infrequent in occurrence along the face (<one joint per metre), and

continued only a short distance vertically (<one metre), perhaps in response to the complex stratigraphy. The joints show a dominant north/south preferred orientation (Fig. 3-8).

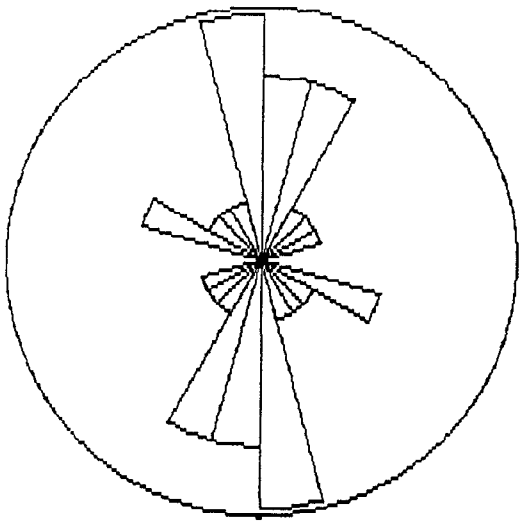
Site 6: Highway 20, south of Hamilton (bedrock)

A well studied, although partially overgrown, bedrock outcrop occurs on Highway 20, south of Hamilton (Bolton, 1957; Segall and Dunn, 1972) (Fig. 3-1). On both sides of Highway 20, the Goat Island and Gasport Members of the Lockport Formation are exposed in vertical sections. The Goat Island Member is also exposed on the horizontal surface above the vertical section west of Highway 20. This bedding plane surface displays glacial striations oriented at 49°. Jointing is present on both the vertical faces and the bedding plane exposure. Many of the joints along the bedding plane may be followed the entire width of the exposure (approximately 15 metres): others continue for several metres on the surface (Fig. 3-9). On the vertical faces, joints are frequent (approximately 3 joints per metre) and extend the full height of the section (4 metres). The joints in both the Goat Island and Gasport Members and on both the vertical and horizontal exposures, shows a strong east-west trend in orientation (Fig. 3-10).

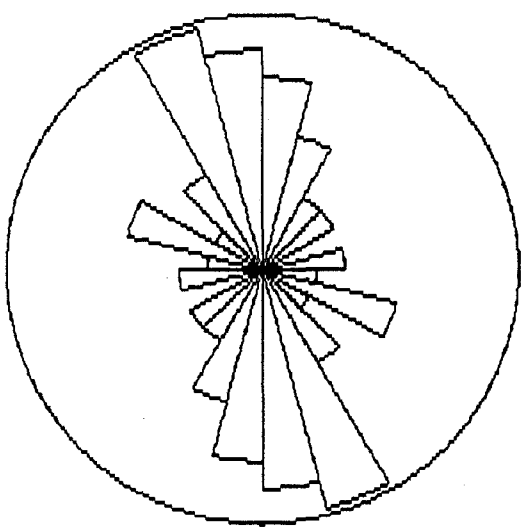
Site 7: Jolley Cut, Hamilton (bedrock)

The Jolley Cut (Fig. 3-1) exposes a lengthy bedrock sequence, passing upward from the Queenston Formation, through the Clinton and Cataract Groups to the

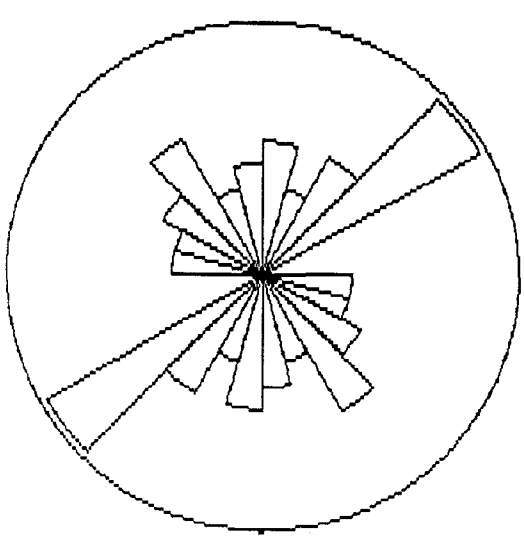
FIGURE 3-8: Rose diagrams for Sites 4, 18 and 21. Note strong north/south trends at Sites 4 and 18. A strong preferred northeast/southwest joint orientation is demonstrated in the rose diagram for Site 21.



SITE 4



SITE 18

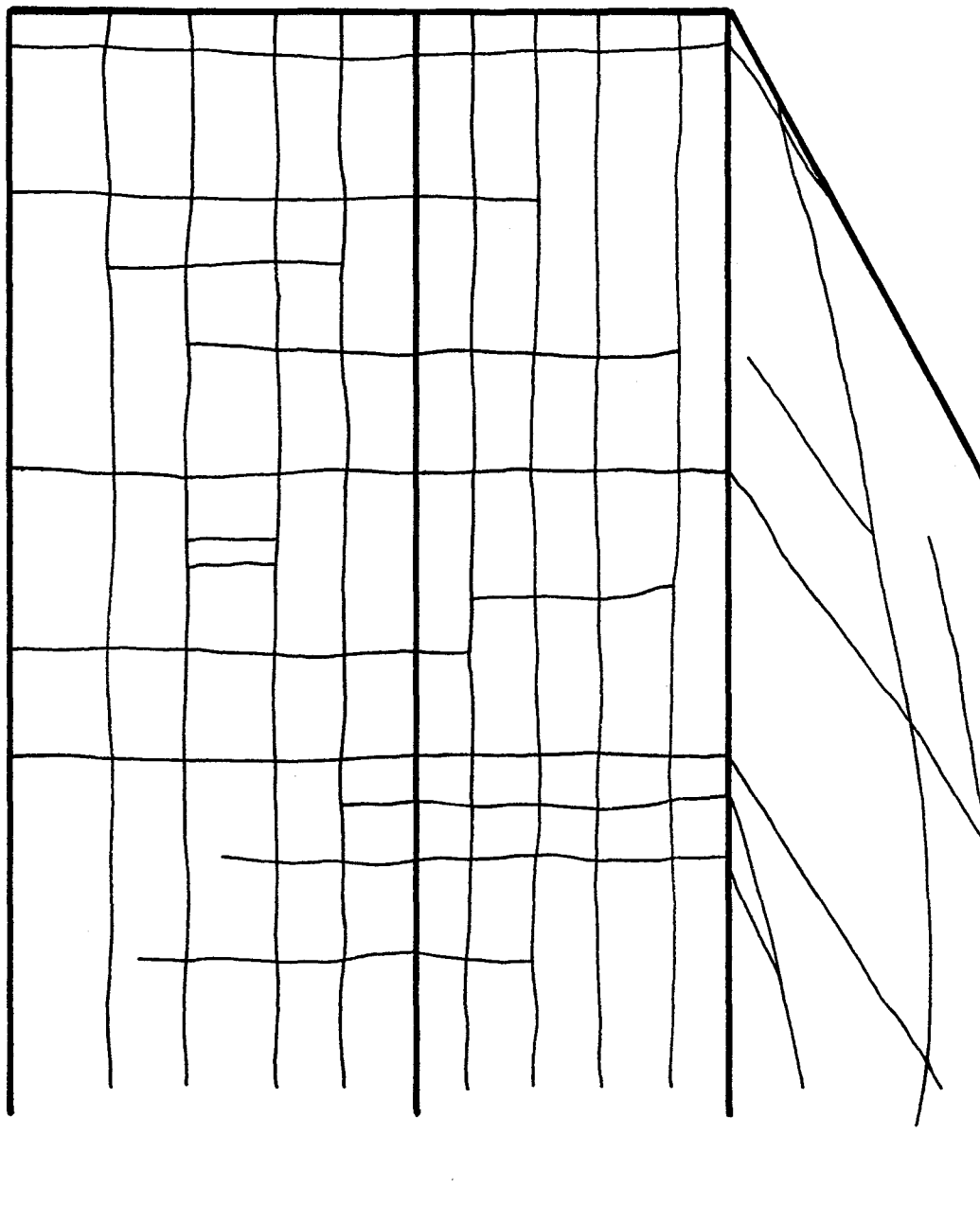


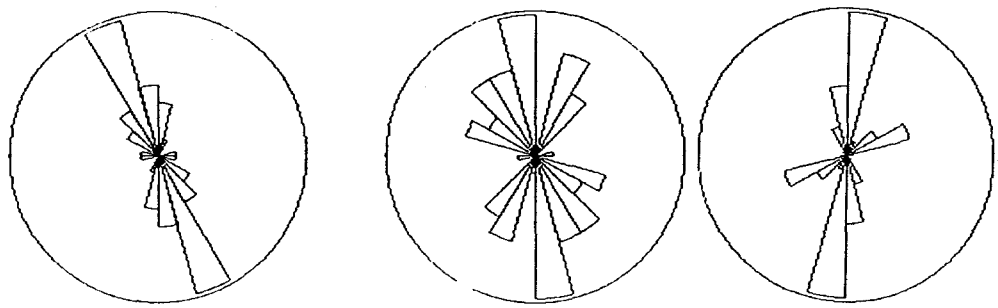
SITE 21

FIGURE 3-9: Photograph showing extent of jointing on the bedding plane surface of the Goat Island member at Site 6.

FIGURE 3-10: Comparison of bedrock lithology and joint orientation at Site 6. Note strong west/east trends within all joint orientation measurements.

GASPORT MEMBER GOAT ISLAND MEMBER





Lockport Formation, and is capped by the Goat Island Member (Fig. 3-11). Joint measurements were taken within the Thorold, Reynales and Irondequoit members of the Clinton Group and in Gasport member of the Lockport Formation. The distinctive ball and pillow structures within the Thorold sandstone were avoided when measuring joints since they disrupt the bedding. Joint frequency ranged from a low of 1 joint per metre in the Irondequoit member, to a high of 4 joints per metre in the Thorold member. The joints measured over the entire site show two dominant joint orientations trends: north/south and east/west (Fig. 3-11).

Site 8: Sherman Sand and Gravel, Milton (glacial)

Although the Sherman pit (Fig. 3-1) excavates primarily outwash gravel, joints were seen at one location within the pit within a bed of fine-grained material which separated units of very coarse sediment. At this location, there is a 1 metre thick bed of silty diamict separated by distinct undulatory boundaries from the stratified gravels and sands above and below (Fig. 3-12). The diamict has a variable clast content of subangular to subrounded clasts which are up to 8 cm diameter (average of 4 cm).

The relatively abundant (3 joints per metre) joints within the silty diamict are well-defined although small, and extend the entire height of the bed (one metre) but not beyond. The joint orientation data show a dominant north/south trend although other minor trends may also be identified (Fig. 3-12).

Figure 3-11: Comparison of joint orientation and bedrock lithology at Site 7. Note strong north/south and west/east trends within all beds (stratigraphy adapted from McCann, 1987).

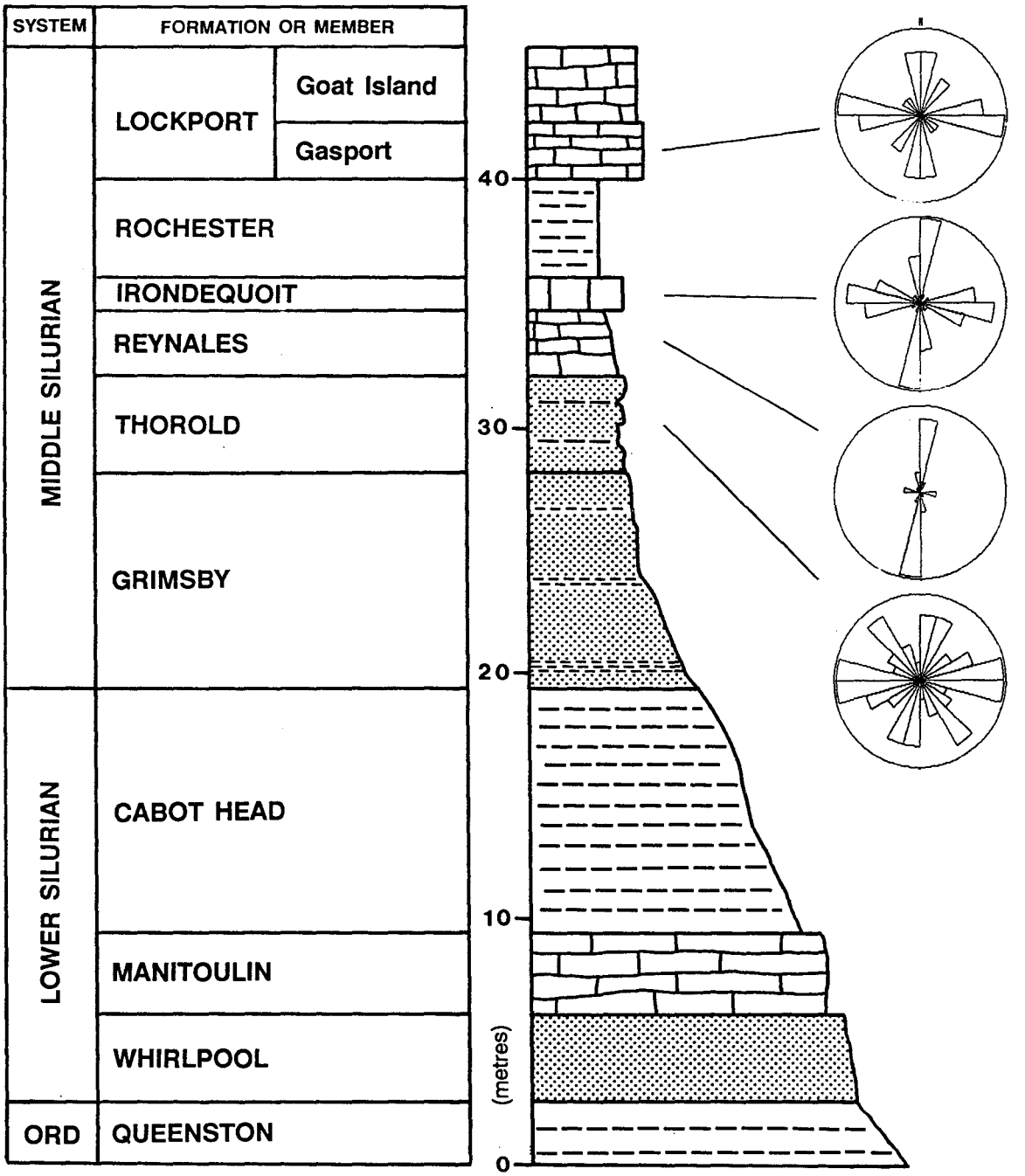
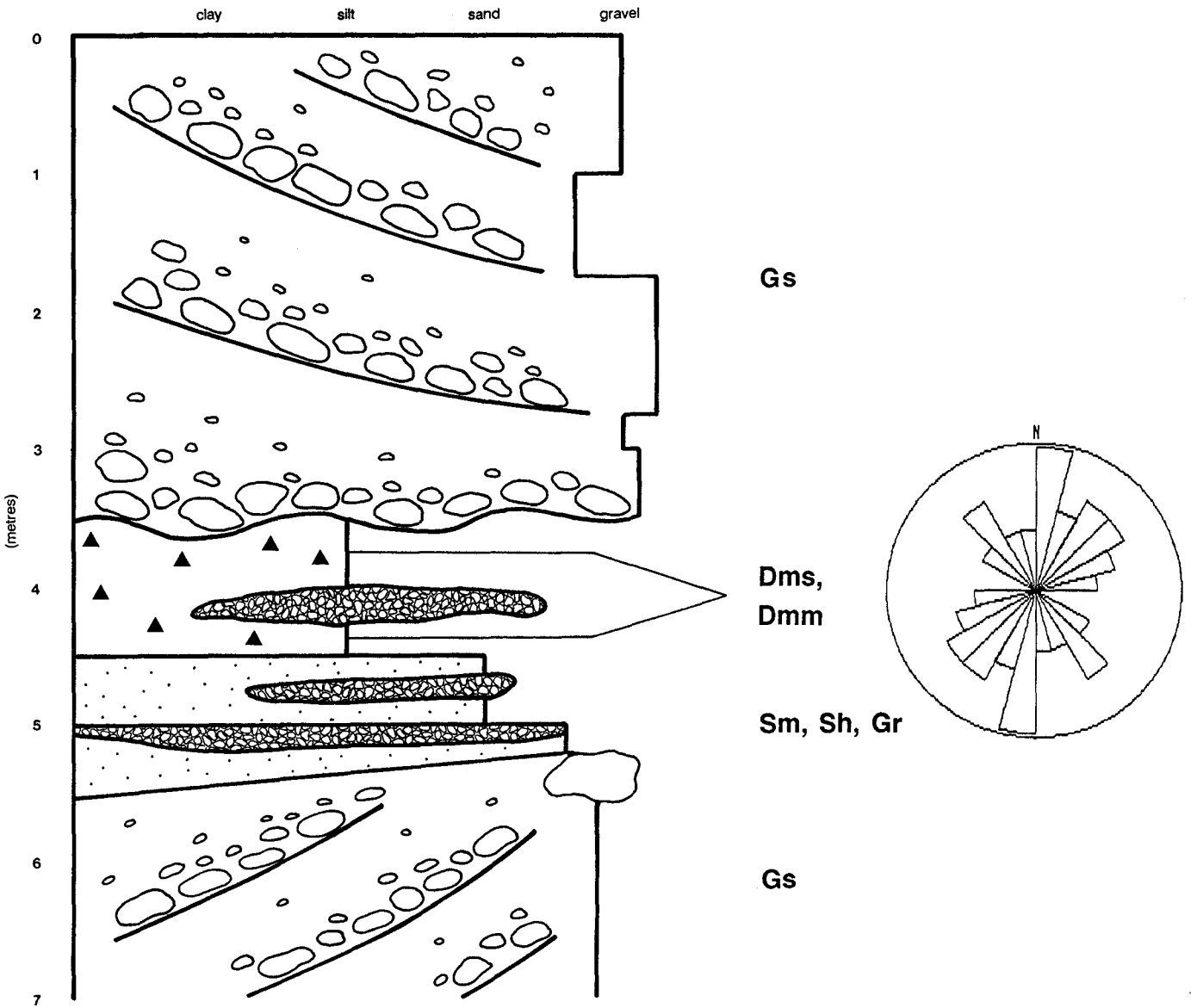

SYSTEM
FORMATION OR MEMBER
MIDDLE SILURIAN
LOWER SILURIAN
ORD
LOCKPORT
Goat Island
Gasport
ROCHESTER
IRONDEQUOIT
REYNALES
THOROLD
GRIMSBY
CABOT HEAD
MANITOULIN
WHIRLPOOL
QUEENSTON
40
30
20
10
0
(metres)

FIGURE 3-12: Sedimentologic log showing the complex stratigraphy at Site 8. Note the high variability within the rose diagram which may indicate the influence of the surrounding materials. A north/south joint orientation trend may also be identified.


clay
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(metres)
Gs
Dms,
Dmm
Sm, Sh, Gr
Gs
N

Site 18: Lake Ontario shoreline at Halton Pumping Station (bedrock)

A three metre thick exposure of the Queenston Formation occurs along the northern shore of Lake Ontario near the Burlington-Oakville boundary (Fig. 3-1). Although the Queenston shale is highly weathered at this site, the joints and their faces are very clear (Fig. 3-13). Joints are very common (10 joints per metre) within the Queenston Formation at this section and most can be traced for 1 metre up the face, although several joints extend the full height of the section face (3 metres). The joints measured at this site clearly show a north-northwest/south-southeast orientation although a wide range of orientations are also present (Fig. 3-8).

Site 21: Abandoned Quarry, Burlington (bedrock)

This site has been previously described by Telford (1978) in a regional description of the limestone quarries of southern Ontario. The quarry is situated on the edge of the Niagara Escarpment above Burlington (Fig. 3-1). Joint measurements were taken within the Irondequoit and Reynales members which are found near the base of the quarry face. Joint frequency ranges from 1 joint per metre in the Irondequoit to 3 joints per metre in the Reynales. Several joints may be traced through the entire 6 metre high face. Although a wide range of joint orientations were measured, a northeast/southwest trend does dominate (Fig. 3-8).

Site 22: Credit River at Georgetown (bedrock)

Three to five metres of Queenston Formation are exposed on cutbanks

FIGURE 3-13: Photograph showing how well defined joints are within the Queenston Formation at Site 18.

along the Credit River at Georgetown (Fig. 3-1). At this site, the Queenston Formation demonstrates its characteristic red colour, although weathering and leaching has caused green-grey mottles to develop on the surface. Joints within the formation are very well defined at this site (Fig. 3-14) and are frequent along the face (10 joints per metre). The joints show a strong preferred northwest/southeast orientation (Fig. 3-15).

Site 27: Flamborough Quarries, west of Waterdown (bedrock)

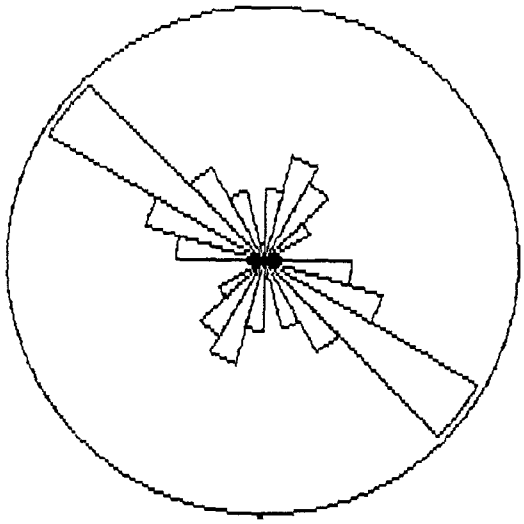
This is the only site within the study area where the Guelph Formation was exposed (Fig. 3-1). The limestone is thin-bedded (10 cm) and flat-lying. The five metre high face is very well jointed (4 joints per metre) and shows two dominant orientations, north-northeast/south-southwest and northwest/southeast (Fig. 3-15).

Site 28: Nelson Quarry, north of Burlington (bedrock)

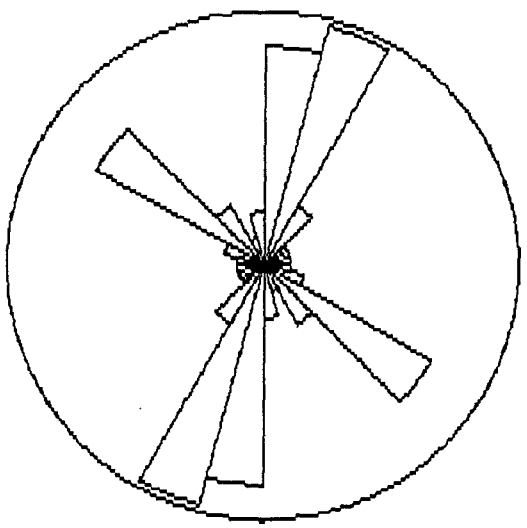
Nelson Crushed Stone (Fig. 3-1) operates one of the largest limestone quarries in Ontario, excavating dolomite from the Amabel Formation. The actual face height varies considerably (19-23 metre in height) because differential erosion of reef cores within the Amabel dolomite has caused an irregular upper surface (Fig. 3-16) (Karrow 1987). Joints within the Amabel Formation may be traced the entire height of the sections and occur frequently across the face (2 to 3 joints per metre). The joints within the Amabel Formation show two preferred orientations, north-northwest/south-southeast and east-northeast/west-northwest (Fig. 3-15).

FIGURE 3-14: Photograph showing the variations in the characteristics of the Queenston Formation within the study area (compare to Figure 3-13). Note again how well defined the joints may be within shales. (follow string to compass for scale)

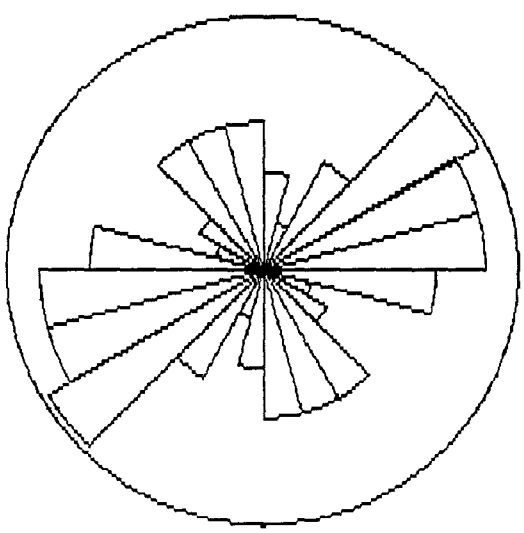
FIGURE 3-15: Rose diagrams for Sies 22, 27 and 28. Note the northwest/southeast joint orientation trend present at Sites 22, 27 and 28. At Sites 27 and 28, the northwest/southeast trend is ancillary to a north-northeast/south-southwest trend at Site 27 and northeast/southwest trend at Site 28.



SITE 22



SITE 27



SITE 28

FIGURE 3-16: Photograph showing the irregular upper surface of the Amabel Formation at Site 28. (field assistant for scale)

Site 29: Credit River, at Lions Park off Highway #5 (bedrock)

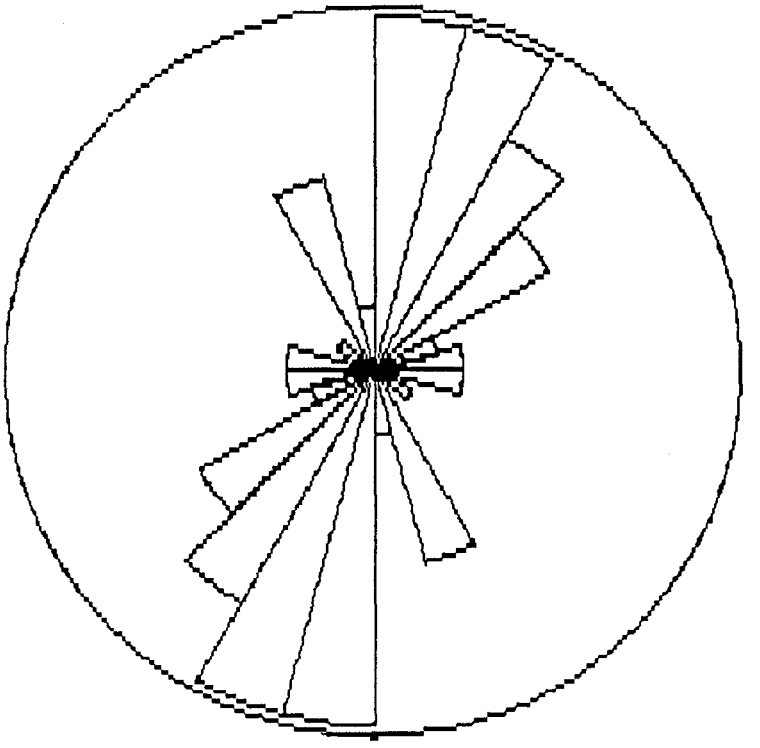
At the north end of Lions Park, the Credit River has cut a 10 metre high face within the Queenston Formation (Fig. 3-1). The face is very well jointed (6 joints per metre) and many of the joints extend for several metres up the face. There is a clear trend to the joint orientations at this site, with almost all of the joints trending north-northeasterly/south-southeasterly (Fig. 3-17).

Site 30: United Aggregates, Acton Quarry (bedrock & glacial)

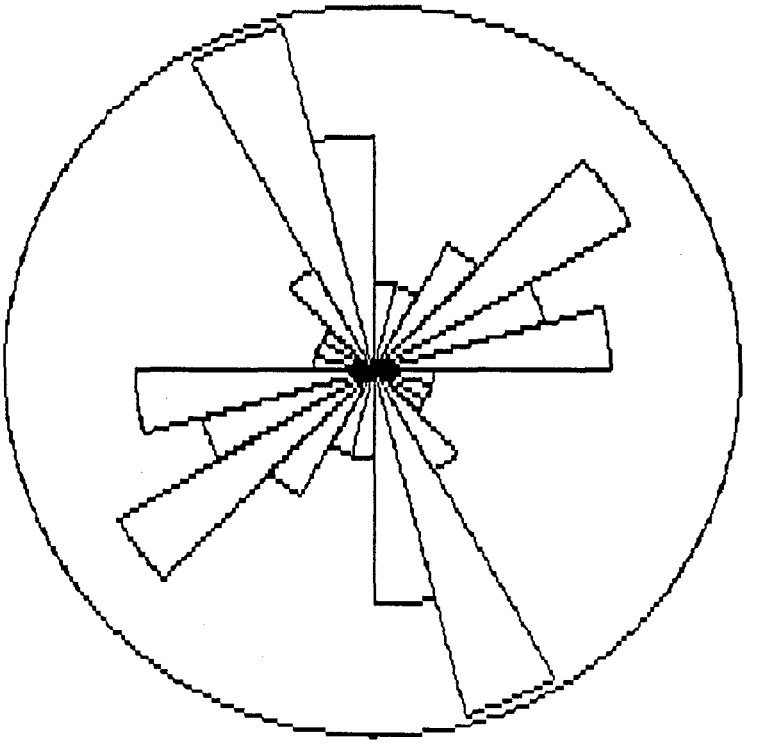
A 19 metre face of Amabel dolomite is mined at this quarry (Fig. 3-1). The upper bedding plane surface is very hummocky with up to 6 metres of relief although the beds are generally flat-lying. The irregular surface results from differential erosion of the more resistant reef cores and the less resistant surrounding dolomite. Joints within the Amabel Formation are less frequent at this site than at other bedrock quarries visited (<one joint per metre) but nearly all of the joints extend the full height of the face. The joints measured in the dolomite show a strong east/west trend (Fig. 3-18).

As a result of the irregular bedrock surface, the thickness of overlying sediment varies from 0 to 6 metres (Hewitt and Vos, 1972). At one location, 5 metres of laminated clay mantles the dolomite. The clay contains no clasts, although a small gravel pod was noted at one position. The clay is relatively well-jointed with approximately 2 joints per metre; these joints extend the full height of the sections exposed (1 to 2 metres). Joint orientation measurements show a north-northwest/south-southeast, and an east/west trend (Fig. 3-18).

FIGURE 3-17: Rose diagrams for Sites 29 and 33. Note the strong north-northeast-/south-southwest joint orientation trend at Site 29. At Site 33, northwest-/southeast and northeast/southwest trends may be identified.



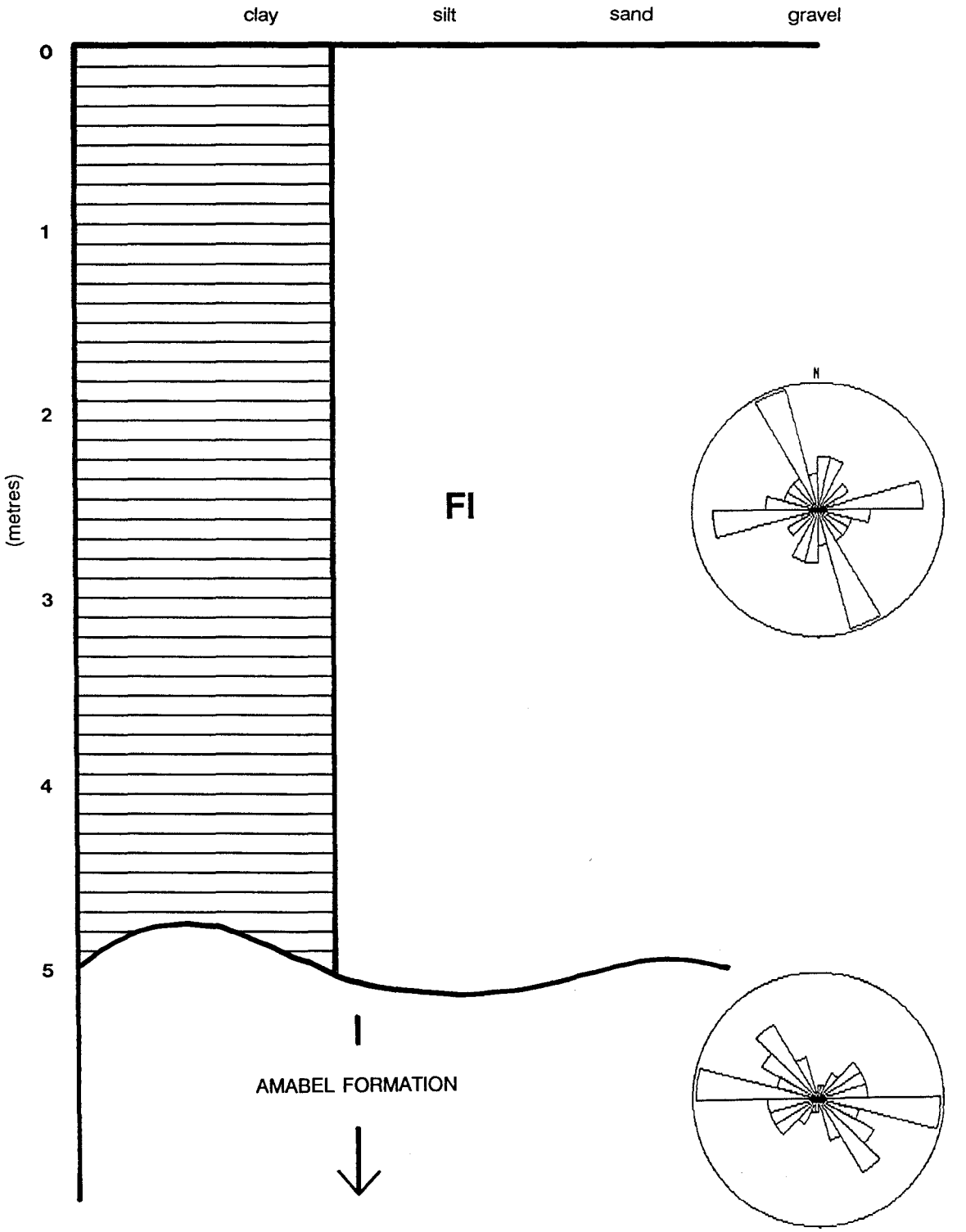
SITE 29



SITE 33

FIGURE 3-18: Sedimentologic log showing the characteristics at Site 30.

Note the northwest/southeast and west/east trends within the joint orientations of both the clay and underlying Amabel Formation.


clay
silt
sand
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0
1
2
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(metres)
Fl
N
AMABEL FORMATION

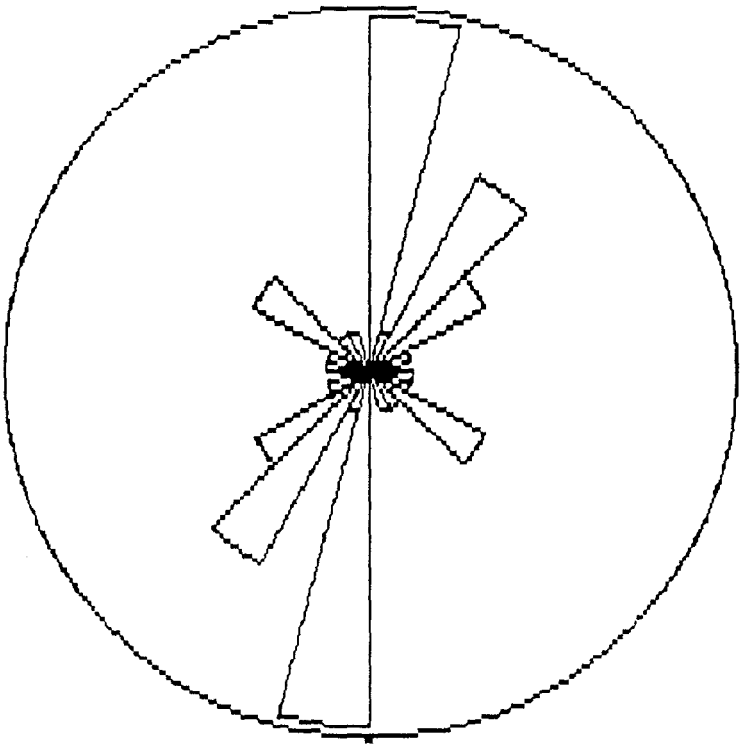
Site 33: Oakdale Homes excavation, Hamilton (glacial)

Within a house excavation at Oakdale Homes in south Hamilton (Fig. 3-1) several three metre high faces of unconsolidated sediment are exposed. The base of these exposed sections consists of massive clay (up to 1.25 metre thick bed) which shows fine parallel lamination in the upper 10 cm. A sharp boundary separates this bed from an overlying 0.75 metre thick bed of crudely stratified, fine sand. Joint measurements were taken within the well jointed (5 joints per metre) clay bed located at the base of the section. These joints extend the full bed thickness, and exhibit two strongly preferred orientations: northeast/southwest and north-northwest/south-southeast trend (Fig. 3-17).

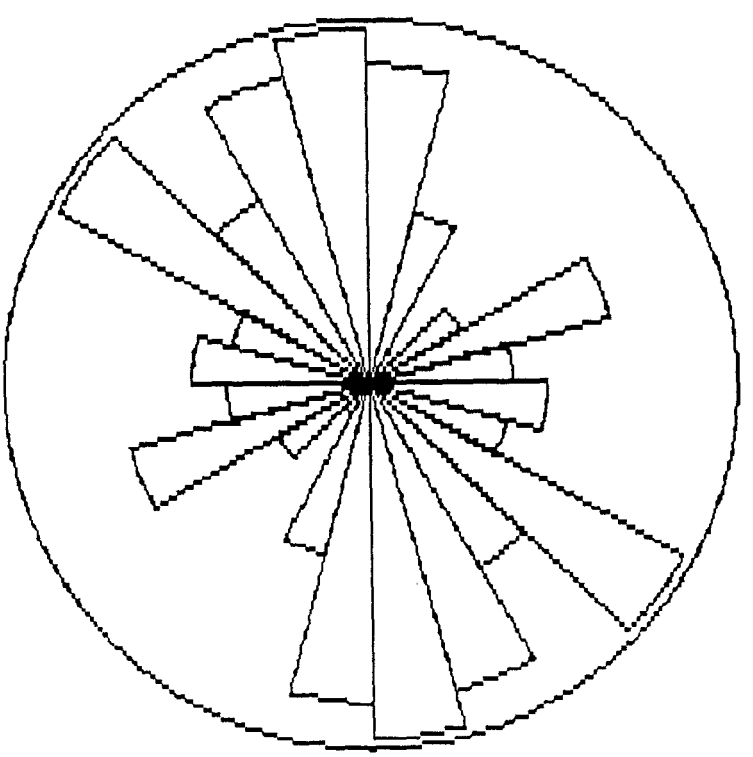
Site 34: Albion Sand & Gravel, Glen Williams (glacial)

Two sections were investigated at Albion Sand and Gravel: a 15 metre face of clay, silt and sand interbedded with laterally extensive gravel lenses, and an 8 metre face of interbedded massive sand, clay diamict, fine sand and gravel lenses. At the first section, joints at a frequency of 2 joints per metre were identified and measured within a 1.5 metre thick bed of stratified to massive silty-clay; this bed was underlain by a coarse gravel pod and overlain by massive fine sands. At the second section, joint measurements were taken from a 1.5 metre thick bed of massive, clayey-silt which showed a joint frequency of approximately 3 joints per metre. Rare, subangular to subrounded clasts (average of 2.5 cm in diameter) were present within this bed. A very strong, north/south joint orientation trend can be identified for this site although minor northeast/southwest, northeast/southwest trends can also be recognized (Fig. 3-18).

FIGURE 3-18: Rose diagrams for Sites 34 and 35. Note the strong north/south trend at Site 34. The joint orientations at 35 cover the entire compass although they appear to show a preferred northwest/southeast trend.



SITE 34



SITE 35

Site 35: Halton Crushed Stone, Milton (bedrock)

At Halton Crushed Stone (Fig. 3-1) the Amabel Formation is mined from a 27 metre high face (Hewitt, 1964). The upper bedding plane is highly irregular (up to 4 metre variations in surface elevation) as a result of differential erosion of the reefy Amabel dolomite. Joints are vertically extensive, frequent (2 to 3 joints per metre) and may be traced a minimum of several metres up the face. The general trend of the joint orientations measured at this site is north/south to northwest/southeast (Fig. 3-18).

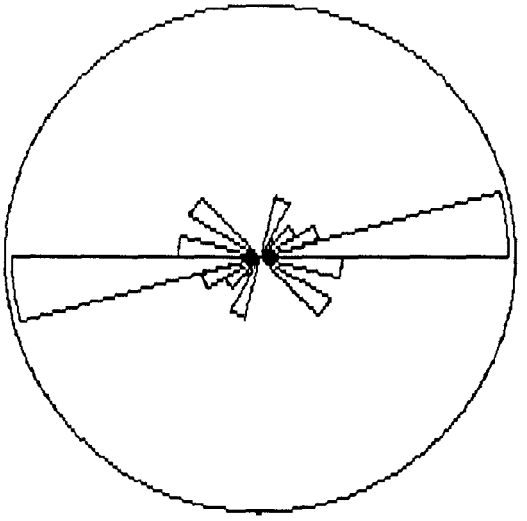
3.2.3 Northern Zone

Site 1: Bailley Bridge on the Rouge River, Pickering (glacial)

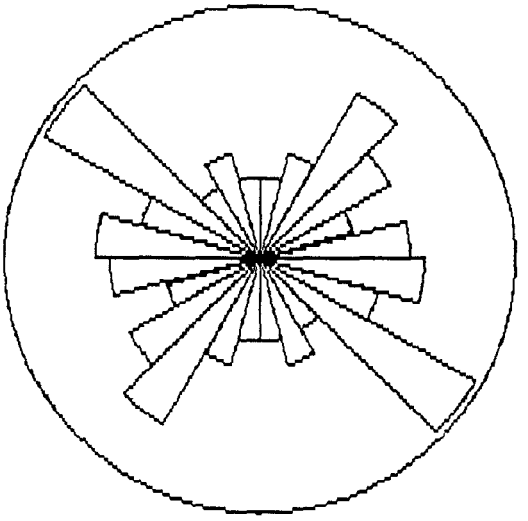
An eleven metre high cutbank of glacial sediment, previously studied by Karrow (1967) is exposed on the Rouge River (Fig. 3-1). Although the base of the section is partially covered by slump material, it appears to be composed of 20 cm to 1 m thick beds of interbedded clay and deformed sands of the Scarborough Formation. The Scarborough sands at this site show shear planes and deformed bedding with plumose structures. Joints are abundant within the sand beds: approximately 4 joints per metre were recorded. Care was taken to measure only those joints which did not appear in conjunction with any deformation structures. The joints within the Scarborough sands show a west/east trend (Fig. 3-19).

A sharp, undulatory boundary separates the Scarborough Formation sands from the overlying Halton Till which forms a 6 metre thick bed of massive, matrix

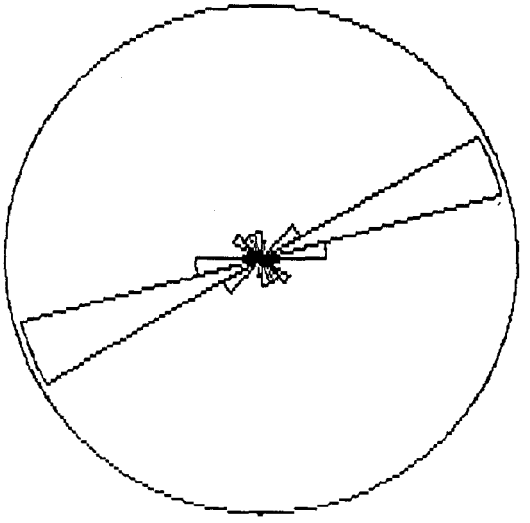
FIGURE 3-19: Rose diagrams for Sites 1, 3 and 20. Note the very strong joint orientation trends at Sites 1 and 20. Preferred west/east, northwest/southeast and northeast/southwest joint orientation trends may be identified for these sites.



SITE 1



SITE 3



SITE 20

supported diamict (Sharpe, 1980). Well-rounded to subangular clasts are common within the till and vary considerably in size, up to a maximum diameter of 80 cm. Two joint sets were evident, northeast/southwest and northwest/southeast within the Halton Till although the joints were infrequent in occurrence (one joint per metre). Two metres of massive Lake Iroquois sands cap the section.

Site 3: Scarborough Bluffs below Guild Inn, Scarborough (glacial)

Four sections were examined at this location on the Scarborough Bluffs (Fig. 3-1). The three sections east of Guild Inn Road show a similar stratigraphy: a 7 metre face of massive, matrix-supported, silty-clay diamict (the Sunnybrook Diamict; Eyles and Eyles, 1983) underlain by the Scarborough Formation. At the fourth section visited, to the west of Guild Inn Road, a 7 metre thick bed of massive to crudely stratified, matrix supported diamict is overlain by a 2.5 metres thick bed of laminated silts and clays. These beds are most likely different lithofacies of the massive Sunnybrook Diamict exposed at the three previous sections. The diamict contains sparse small clasts (<5 cm diameter). There are many (2 joints per metre), well-defined joints which can be traced through the entire thickness of the bed. In addition there are numerous (6 joints per metre) smaller fractures which are up to 2 metres in length. Within the four sections examined at Guild Inn, a preferred northwest/southeast trend may be identified although a wide range of joint orientations are present (Fig. 3-19).

Site 20: Credit River at Mississauga (bedrock)

Joint measurements were taken from a 5 metre high face of the Georgian

Bay Formation along the Credit River (Fig. 3-1). At this site, strongly fissured shale is interbedded with thin beds (maximum of 10 cm thick), of flat lying limestone approximately every 0.5 metres. The joint frequency within the limestone beds (2.5 joints per metre) is much lower than within the shale beds (7 joints per metre). A very strong east-northeast orientation is demonstrated by the joints within both the limestone and shale at this site (Fig. 3-19).

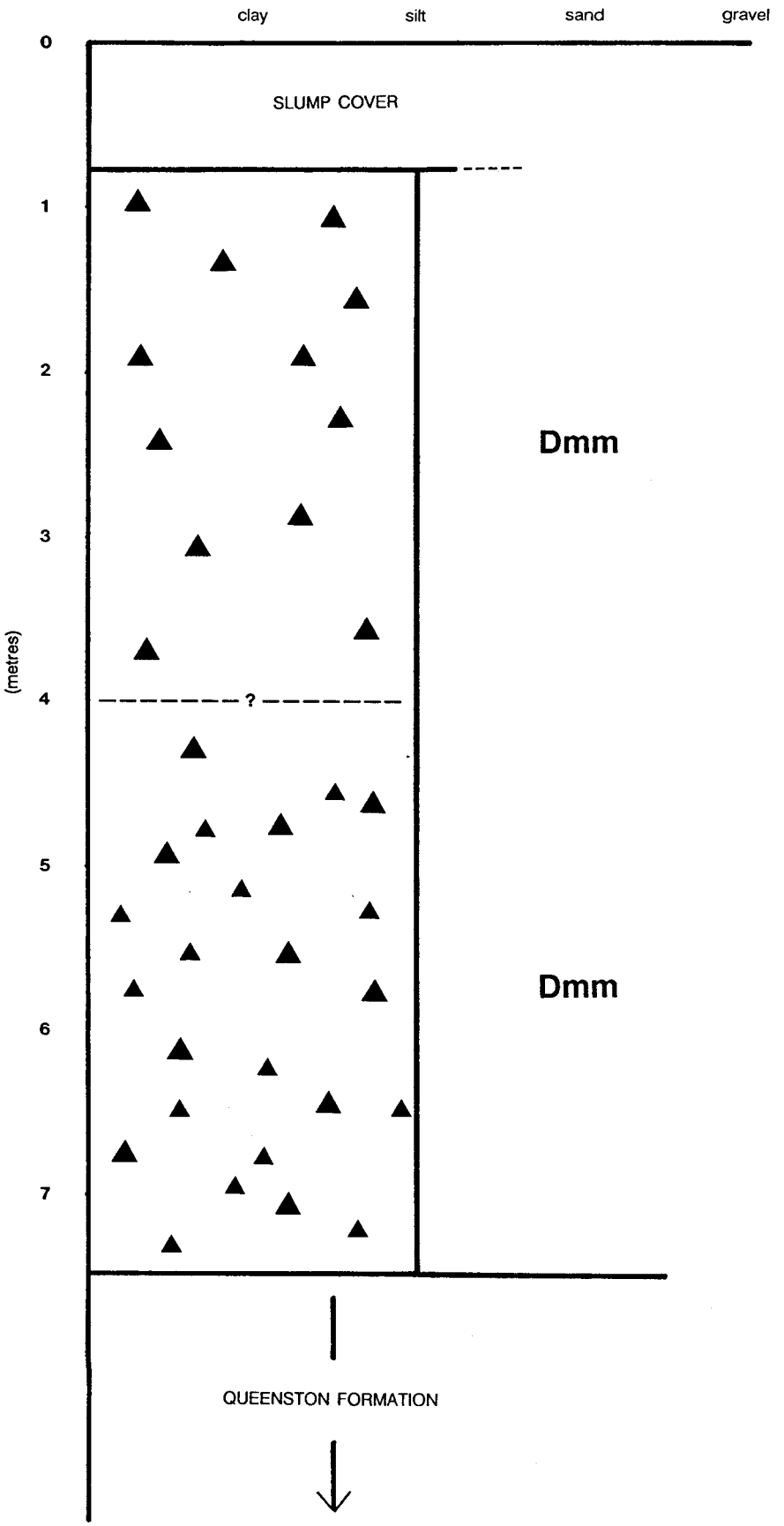
Site 24: Canada Brick Company, Streetsville (bedrock & glacial)

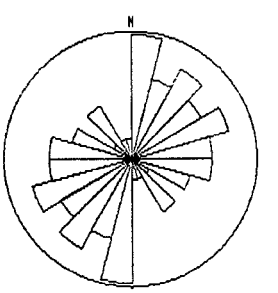
Site 24 is the easternmost site at which the Queenston Formation is exposed (Fig. 3-1). Above 8 to 10 meters of Queenston Formation shale lies 7.5 metres of unconsolidated sediments. The bottom 4.5 metres of sediment consist of massive, silty diamict containing numerous, small, (<2cm) angular to subrounded clasts. The joint frequency within the lower diamict is approximately 1 joint per metre. The lower diamict grades upward into a silty diamict of very similar characteristics, although with a much lower clast content. No joints were seen within the upper diamict.

Joints were measured within both the lower diamict and the Queenston Formation. Unfortunately, at no single face were both the till and bedrock exposed so that it was not possible to tell if any joints passed from the bedrock directly up into the till. As Figure 3-20 shows, the joints within the Queenston Formation show a clear, preferred west-northwest/east-southeast trend. Within the lower diamict, the joint orientations fall almost exclusively into the northwest/southeast quadrant (Fig. 3-20).

FIGURE 3-20: Sedimentologic log for Site 24. Uncertain whether one or two diamicts were exposed at this site.

Note the variable joint orientations at this site although overall northeast/southwest (diamict) and northwest/southeast (Queenston Formation) trends may be identified.


clay
silt
sand
gravel
0
1
2
3
4
5
6
7
(metres)
SLUMP COVER
Dmm
?
Dmm
QUEENSTON FORMATION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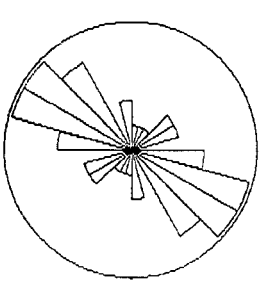


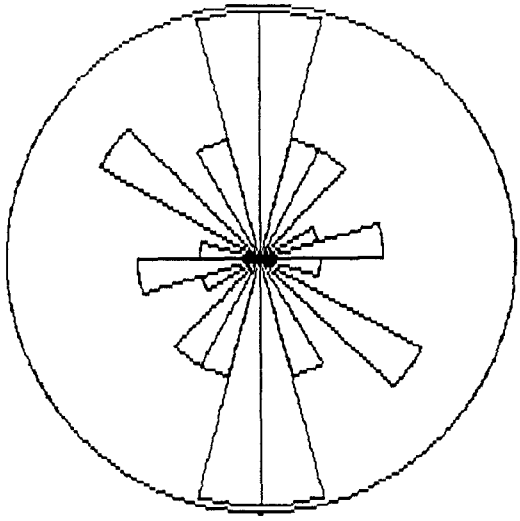
Site 25: East Humber River at Storer Crescent, Toronto (glacial)

A three metre high section of unconsolidated sediments is exposed at Storer Crescent along the East Humber River (Fig. 3-1). At the base of the section, 1 metre of well-jointed (4 joints per metre) laminated clay is exposed. This bed may be equivalent to a bed in the adjacent Township of North York map area which Watt (1955) describes as: "... varved clay, stratified silt. Deposited in glacial lakes and rivers in the intervals between substages of the Wisconsin glaciation." The joints are easily seen within this bed and show a preferred north/south orientation (Fig. 3-21). A bed of massive silty-sand floodplain deposit (Watt, 1968) overlies the clay.

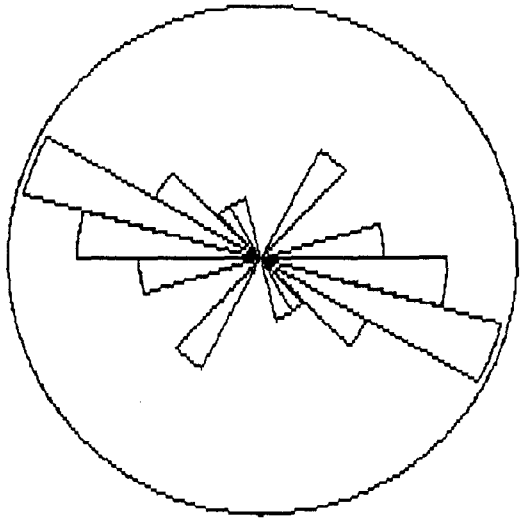
Site 26: East Humber River at Attercliffe Crescent, Toronto (glacial)

A cutbank along the East Humber River (Fig. 3-1) downstream from Site 25 exposes 5.5 metres of unconsolidated sediments. A large slump block obscures the middle two metres of the section from view. Both above and below the slump, a crudely stratified, silty-clay diamict containing small (average 2.5 cm in diameter), rounded to subangular clasts, is exposed. This diamict may be interpreted as either Peel pond deep water deposits (Sharpe, 1980), or the Halton Till (Watt, 1955). The former interpretation is more likely since the Halton Till is typically a lodgement till and would be unlikely to show any stratification. Deep, extensive joints (2 metres in length and continuous for at least 1 metre into the face) exposed along the face produce several sharp edged promontories. The joints within this bed shows a strong west-northwesterly/east-southeasterly orientation (Fig. 3-21).

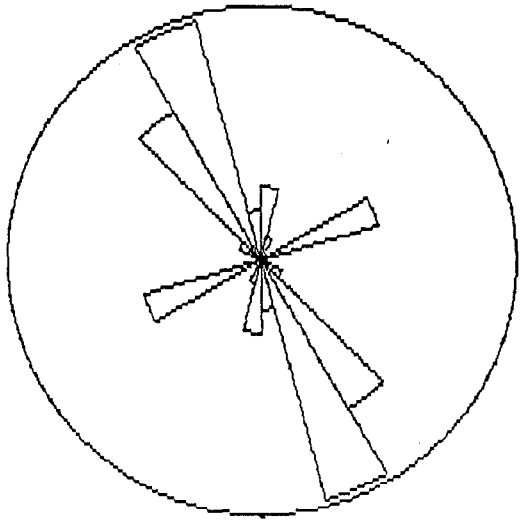
FIGURE 3-21: Rose diagrams for Sites 25, 26 and 31. Note the strong west-northwest/east-southeast, northwest/southeast joint orientation measurements at Sites 26 and 31. A north/south joint orientation trend may be identified for Site 25.



SITE 25



SITE 26



SITE 31

Site 31: Humber River at Weston Lions Park, Toronto (bedrock)

A 5 high metre section of interbedded limestone and shale of the Georgian Bay Formation occurs on the Humber River south of Weston Lions Park (Fig. 3-1). In addition, limestone of the Georgian Bay Formation forms the bed of the Humber River at this site. Three to five joints were seen every metre on a transect across the river bed. On the vertical section, joint frequency within the limestone varies considerably, but is approximately 4 joints per metre: within the shale, the frequency is higher, approximately 6 joints per metre. Joint measurements taken in both the limestone and shale beds on the section, and in the limestone as seen on the bottom of the river bed show a major north-northeasterly/south-southwesterly trend and a minor northeast/southwest trend in orientation (Fig. 3-21).

Site 32: Humber River at Etienne Brule Park, Toronto (bedrock)

The Georgian Bay Formation is exposed at several locations within the Etienne Brule Park (Fig. 3-1). At Site 32, the Humber River has cut a 6 metre high face, of which only 3.5 metres is visible: the entire base of the exposure is covered by vegetated, slump material. At the base of the exposed face, only the shale is present: further up the face, thick beds of limestone (up to 25 cm) appear, and near the top of the face, limestone beds dominate. Joints are abundant within the lower shale (5 joints per metre, less than 0.5 metres in length). Within the limestone beds near the top of the section, joint frequency varied from approximately 1 joint per metre to up to 6 joints per metre. The joints within the limestone varied from 10 cm to 2 metres in

length. Joint orientation measurements taken within the limestone and shale beds clearly demonstrate a preferred west-southwest/east-northeast trend (Fig. 3-22).

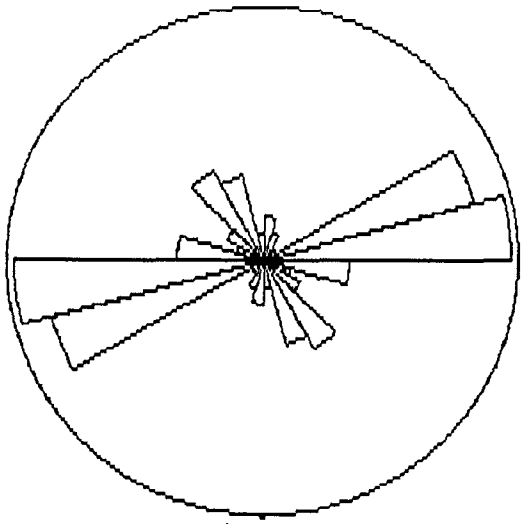
Site 36: Scarborough Bluffs, east of Bluffers Park (glacial)

A four metre thick bed of Sunnybrook Diamict is exposed along the Scarborough Bluffs approximately 30 metres above Bluffers Park (Fig. 3-1). This bed is sandwiched between the Scarborough Formation sands below and Thorncliffe Formation sands above. The diamict has a silty-clay matrix, is massive and strongly-jointed. Small (average diameter of 1 cm), subangular clasts are rare within the bed. Joints within the Sunnybrook diamict are extremely well-defined, consistently present at a frequency of 1 joint per metre, and can be seen to extend the full thickness of the bed (4 metres) (Fig. 3-23). The joints show an overall west-northwest/east-southeast trend although a wide range of orientations are present (Fig. 3-22).

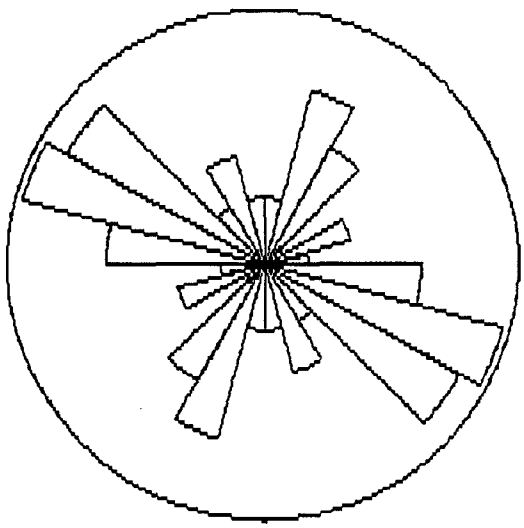
Site 37: Dutch Church, west of Bluffers Park (glacial)

The Dutch Church section of the Scarborough Bluffs at Bluffers Park, has been well described in the literature (Karrow, 1967; Eyles and Eyles, 1983). At this site (Fig. 3-1) approximately 30 metres of the Sunnybrook diamict consisting of massive to stratified silty-clay diamict and laminated silts and clays are exposed. These sediments infill a broad channel which has been cut into the Scarborough Formation sands below. The joints within the laminated silts and clays are very sharply defined, common (2 joints per metre) and continue for up to 7 metres up the face. A wide range of joint

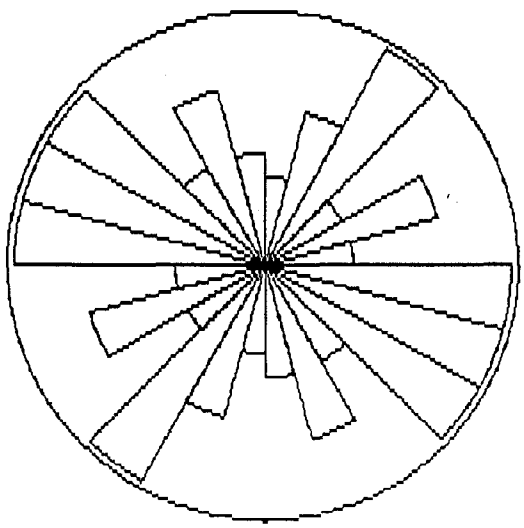
FIGURE 3-22: Rose diagrams for Sites 32, 36 and 37. Note the strong west-southwest/east-northeast joint orientation trend at Site 31. Preferred northwest/southeast and northeast/southwest trends may be identified for Sites 36 and 37.



SITE 32



SITE 36



SITE 37

FIGURE 3-23: Photograph showing the strong jointing pattern within the Sunnybrook diamict at Site 36. (note author for scale)

orientations were measured at this site although a west-northwest/east-southeast trend and a northeast/southwest trends are preferred (Fig. 3-22).

Site 38: Twyn Rivers, Pickering (bedrock)

Site 38 is the only site within the study area where the Whitby Formation is exposed (Fig. 3-1). At this site, a 1.5 metre high exposure of the Whitby Formation has been cut along the east bank of the Rouge River. Joints are well defined and abundant (12 joints per metre) within the shale on the face of the section (Fig. 3-24), and are also common on the bed of the stream (Fig. 3-25). Joints measured from both the stream bed and vertical face show a very strong, east/west preferred orientation (Fig. 3-26).

Site 39: Wilket Creek, Toronto (glacial)

A seven metre high face of laminated clay is exposed in a cutbank on the south bank of Wilket Creek (Fig. 3-1). The clay may be equivalent to Sangamon interglacial alluvial deposits (Watt, 1955). Although the joints are poorly defined within the clay, a frequency of approximately 4 joints per metre, across the 5 metre wide face was measured. The joint measurements within the laminated clay show a preferred north-northwest/south-southeast orientation (Fig. 3-26).

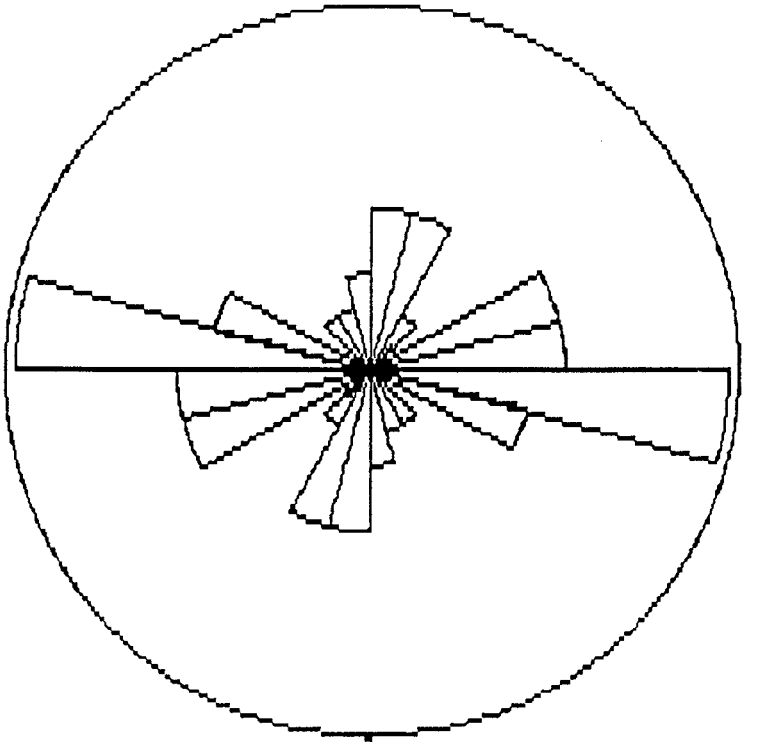
Site 40: Etobicoke Creek off Eglington Avenue, Toronto (bedrock)

The western most exposure of the Georgian Bay Formation within the study area is found along Etobicoke Creek, where a 12 metre high face is exposed

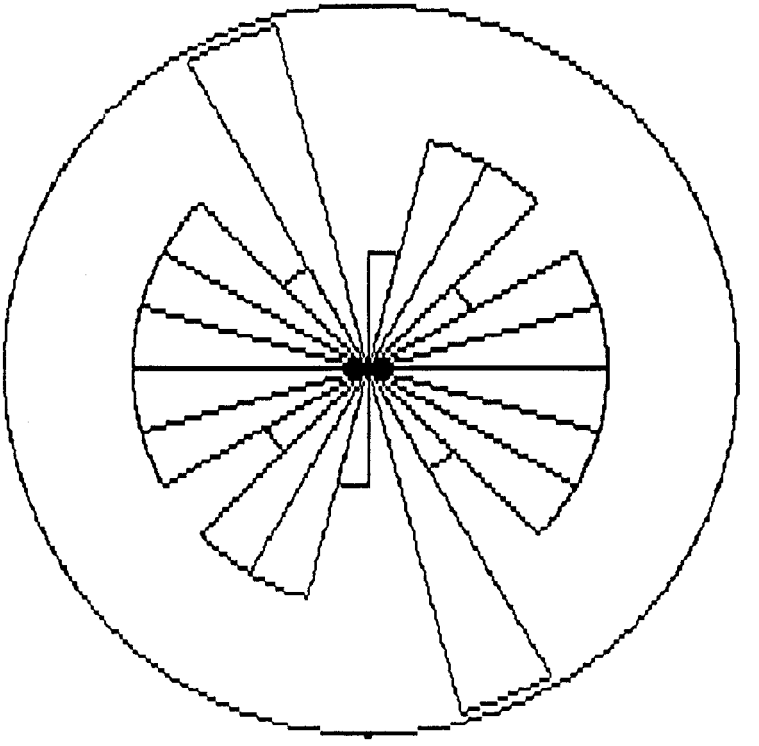
FIGURE 3-24: Photograph showing well-defined joints within the Whitby shales at Site 38.

FIGURE 3-25: Photograph showing joints within the Whitby shale which may be traced along the river bed (Site 38).

FIGURE 3-26: Rose diagrams for Sites 38 and 39. Note the strong west/east joint orientation trend at Site 38. A preferred northwest/southeast trend may be identified for Site 39.



SITE 38



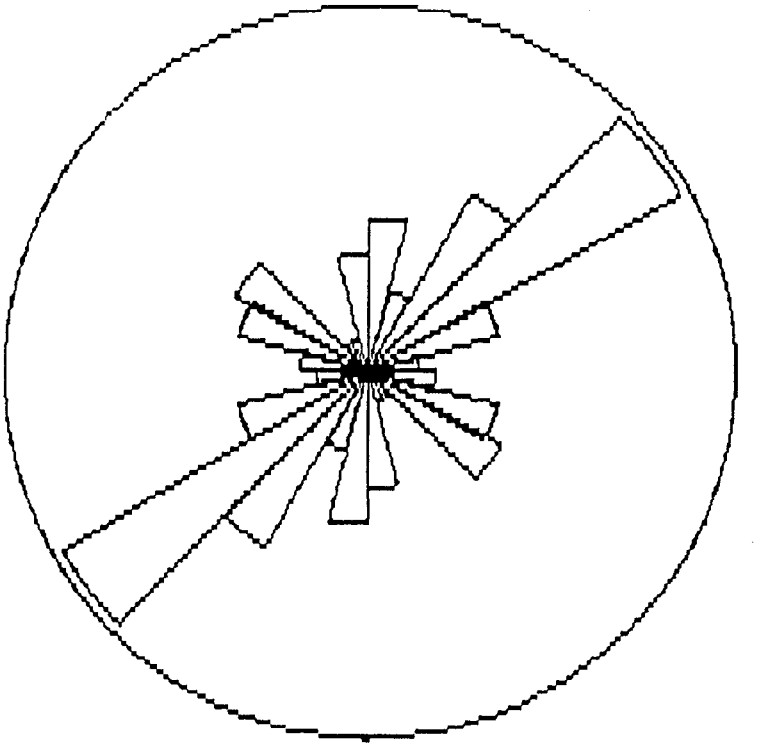
SITE 39

(Fig. 3-1). At this site, shale dominates although 10 cm thick interbeds of limestone are occasionally seen. Joints are abundant within the shale (5 joints per metre), although short in length (less than 0.5m). The frequency of joints within the limestone beds varied with height above the base of the section: joints were more frequent within the upper limestone beds (3 joints per metre) than in the lower limestone beds (less than 1 joint per metre). Joints were up to 1 metre in length and could be seen to pass upward from the limestone beds into the surrounding shale. Joint orientation measurements within both the shale and limestone beds show a clear, northeast/southwest trend (Fig. 3-27).

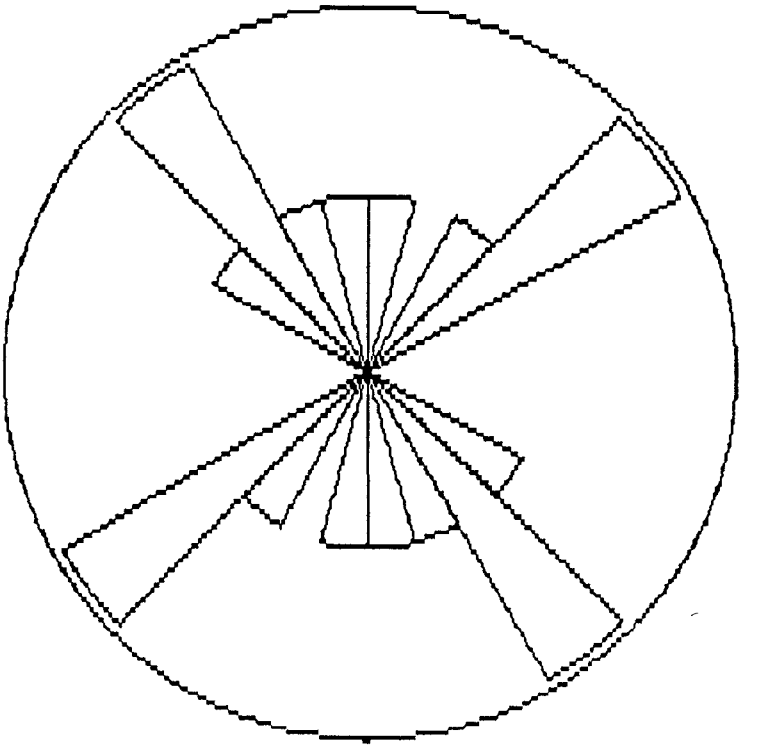
Site 41: Franceschini Bros., Brampton (glacial)

Franceschini Bros. have developed a sand and gravel pit to extract aggregate from the Brampton Esker (Fig. 3-1). The esker contains a variety of deposits including gravel, stratified sands as well as limited amounts of fines (Hewitt, 1969). Massive sands, gravel, fine rippled sands and lenses of silty-clay are present in the study section. Within the lenses of silty-clay (up to 0.5m thick), several joints were identified and measured. The joints were uncommon (only a total of 9 joints were present) although where present, the joints were clustered together at a frequency exceeding 3 joints per metre. The joints at this site showed a wide range of orientations, although two preferred trends may be identified: northeast/southwest and northwest/southeast (Fig. 3-27).

FIGURE 3-27: Rose diagrams for Sites 40 and 41. Preferred northeast/southwest joint orientation trends are present at both sites, although the trend is much stronger at Site 40.



SITE 40



SITE 41

The results of analysis of the joint measurements taken at each of these sites will be discussed within Chapter 4.

CHAPTER 4: RESULTS

4.1 Introduction

The primary goal of this thesis is to determine the preferred orientation of joints within bedrock or glacial sediments at selected sites within south-central Ontario and to identify any trends that might exist. This chapter discusses the results obtained from the analyses of raw field data and summarizes the joint orientation trends identified at each site to determine the pattern of jointing within the glacial sediments and bedrock of south-central Ontario (Tables 2 and 3). The methods of analyses are found within Chapter 1.

4.2 Statistical Results

Upon completion of the statistical analysis, it became apparent that certain of these measures were not appropriate for describing the data when more than one directional trend was present. At sites where there were two joint sets of equal strength perpendicular to each other, theta (vector mean) became the average of the these sets and as a result did not delineate either joint set. However, the consistency measure (L) was useful for describing the variability in joint orientation within the site. Where only one strong joint set was present, the value of L was high (for example within the glacial sediments at Site 11, L = 82.80; Table 3); at sites where there was a large directional

TABLE 2: Summary table for joint orientation measurements in bedrock.

JOINT ORIENTATION RESULTS FOR BEDROCK: BY REGION								
SITE NUMBER		# OF JOINTS	JOINT SETS IDENTIFIED			CONSIS TENCY	RALEIGH NUMBER	MAX. RADIAL
			DOMIN ANT	SECONDA RY	TERTIA RY			
SOUTHERN	5/17	38	NW	=W	-	39.13	0.997	6
	12	98	NE	N	NW	24.33	0.997	16
	14	18	NW	NE	-	10.64	0.184	6
	16	89	W	NW	NE	7.97	0.432	16
	19	53	N	ENE	NW	11.54	0.506	10
CENTRAL	6	134	W	NW	-	47.10	1.000	33
	7	197	N	W	-	20.95	1.000	65
	18	51	N	NW	-	33.97	0.997	9
	21	57	NE	NW	N	15.50	0.746	11
	22	56	NW	NE	-	28.13	0.988	14
	27	75	NNE	NW	-	32.66	1.000	18
	28	68	NE	W	NW	19.30	0.921	10
	29	80	NNE	NNW	-	45.24	1.000	16
	30	80	W	NW	NE	33.82	1.000	17
	35	73	N	=NW	W	19.57	0.939	10
NORTHERN	20	81	ENE	-	-	50.24	1.000	38
	24	26	N	NE	=W	35.38	0.961	5
	31	27	NW	ENE	N	56.90	1.000	10
	32	64	ENE	NW	-	36.34	1.000	17
	38	48	W	N	-	23.89	0.935	11
	40	90	NE	NW	=N	26.32	0.998	21

TABLE 3: Summary table for joint orientation measurements in glacial sediments.

JOINT ORIENTATION RESULTS FOR GLACIAL SEDIMENTS: BY REGION								
SITE NUMBER		# OF JOINTS	JOINT SETS IDENTIFIED			CONSIS TENCY	RALEIGH NUMBER	MAX. RADIAL
			DOMIN ANT	SECONDA RY	TERTIA RY			
SOUTHERN	5/17	75	NNW	ENE	NE	15.14	0.821	6
	10	44	N	NW	-	68.75	1.000	12
	11	67	N	-	-	82.80	1.000	25
	13	58	W	NE	NW	15.33	0.744	9
	14	23	NW	NE	-	4.93	0.054	4
	15	12	NNE	NE	-	61.53	0.989	4
CENTRAL	4	18	N	NW	-	40.62	0.949	4
	8	42	N	NW	=NE	28.84	0.970	7
	30	33	NNW	W	NNE	18.22	0.666	7
	33	64	NNW	NE	ENE	14.33	0.731	12
	34	26	N	NE	NW	38.89	0.980	8
NORTHERN	1	29	W	NW	=NE	59.54	1.000	12
	3	115	NW	NE	W	12.76	0.846	18
	24	41	NW	N	=NE	27.94	0.959	6
	25	21	N	NW	W	32.96	0.898	4
	26	15	WNW	NE	-	55.35	0.990	4
	36	63	NNW	NE	NW	17.69	0.861	11
	37	90	WNW	=NE	NNW	11.76	0.712	11
	39	20	NNW	NW	W	12.77	0.278	3
	41	9	NW	=NE	-	29.92	0.553	2

variability in joint orientation, the value for L was much lower (for example within the bedrock at Site 14, L =10.64; Table 2).

The Raleigh number provided a useful indicator of the strength of the trend within the individual sites. At twenty of the thirty-seven sites, there is a 95% probability that the trends identified at the site are not simply the result of a normal distribution. At twenty-four of the sites, the probability is greater than 90%. Although these statistical analyses may be used to help interpret the joint orientations, they are not ideal; a statistical package needs to be developed specifically for the analysis of joint orientation data, in particular, to help objectively identify individual joint sets that may exist.

4.3 Results from Visual Inspection

In absence of any statistical analyses to help identify particular joint orientation trends, the dominant joint sets for each site were determined from a visual inspection of each site's summary rose diagram using the methods described in Chapter 1. The regional joint orientation trend was determined by tabulating the joint sets identified for each site and then determining the strongest trends.

Tables 2 and 3 include a summary listing of the number of joints measured, maximum radial (maximum number of joints within a 15° segment), type of material present and number and orientation of joint sets for each site. The preferred joint orientation trend for each site along with a summary rose diagram is presented in

Chapter 3 together with the individual site descriptions. These rose diagrams are compiled in Figures 4-1 and 4-2 to show the regional distribution of joint orientation in bedrock and glacial sediments within the study area.

4.3.1 Regional Orientation Trends

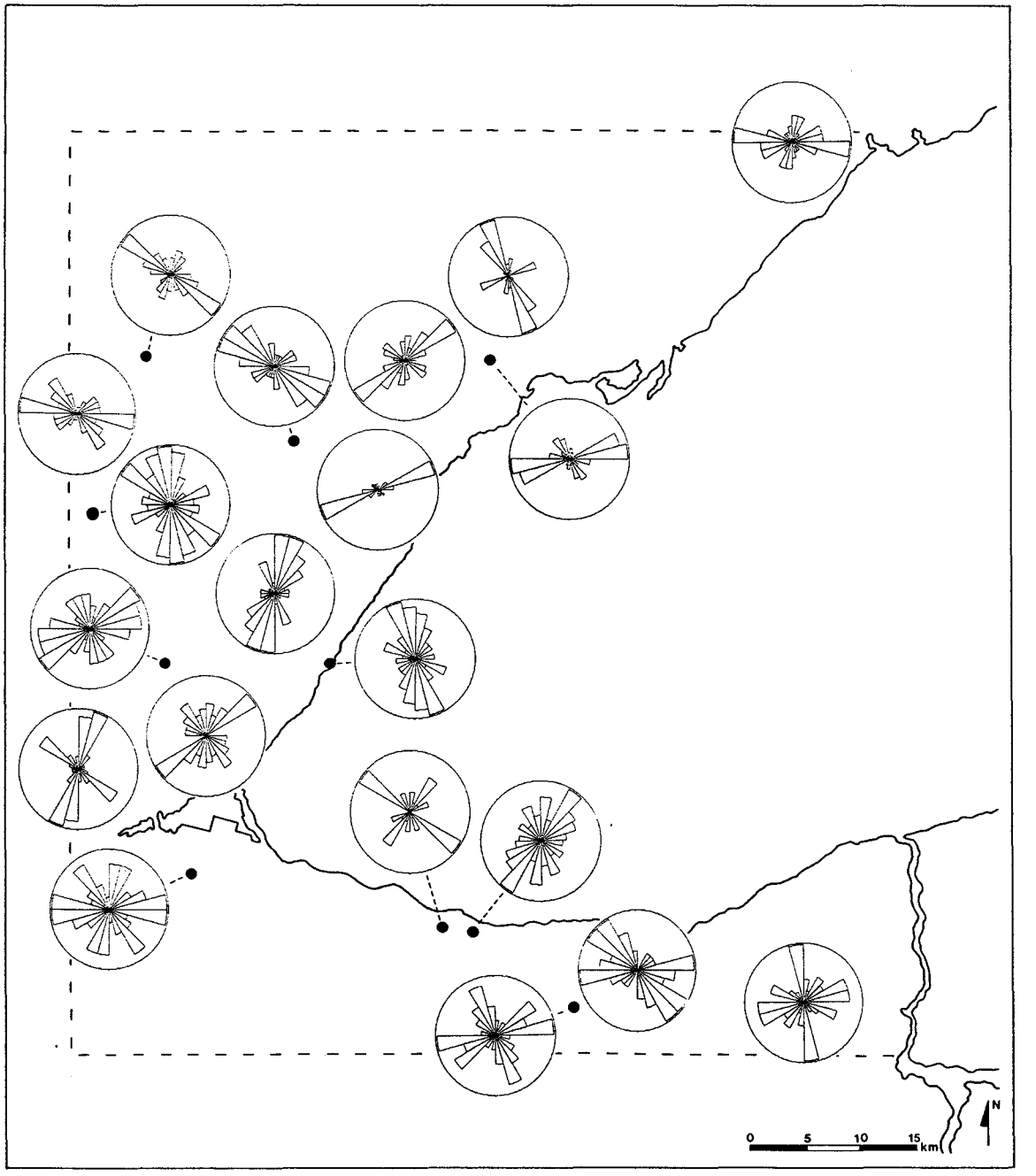
Bedrock

On a regional scale, several trends may be identified within the joint orientations measured in bedrock during this study (Table 2 and Fig. 4-1). Within the southern region of the study area, two regional joint sets may be identified. The dominant joint set, oriented **northwest/southeast** is demonstrated at all of the sites within this region (5 of 5). A secondary northeast/southwest trend may also be identified at 4 of the 5 sites.

One dominant and three ancillary regional joint sets may be identified within the central region of south-central Ontario. The best represented joint set (8 of 10 sites) is oriented **northwest/southeast**. However, west/east, northeast/southwest and north/south oriented joint sets are also present (at respectively 5, 4 and 4 of the 10 sites within this region.

Within the northern region of the study area, the dominant joint orientation trend oriented **north/south**, is present at four of the six sites. However, only slightly less well represented are the east-northeast/west-southwest and northwest/southeast joint sets each demonstrated at three of the six sites.

FIGURE 4-1: Compilation of all of the summary rose diagrams for each site within the study area where joints were measured in bedrock.


0
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15
km
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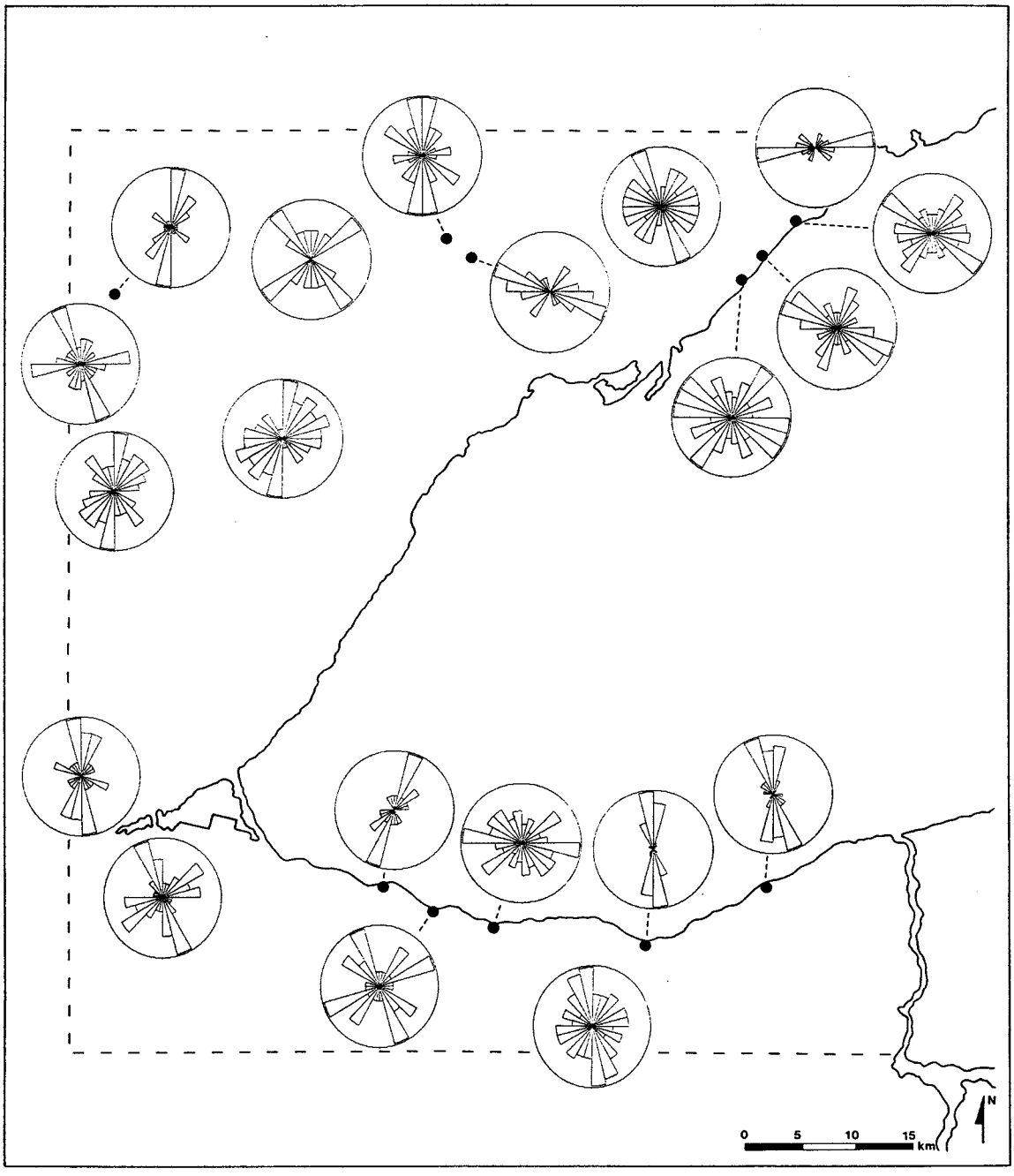
FIGURE 4-2: Compilation of all of the summary rose diagrams for each site within the study area where joints were measured in glacial sediments.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km
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Within the entire study area, a **northwest/southeast** oriented joint set is consistently present (Fig. 4-1). Sixteen of twenty-one sites within the study area contain a northwest/southeast oriented joint set. Of the sites which demonstrate this trend, a high percentage (81%) demonstrate the northwest/southeast oriented joint set as either the strongest or second strongest preferred orientation (Table 2).

Although the northwest/southeast trending joint set is dominant in the bedrock of south-central Ontario, there are two other significant joint orientation trends, a northeast/southwest trend and a north/south trend (Fig. 4-1). The northeast/southwest joint set is present at 9 out of 21 sites and is most often (78% occurrence) one of the two strongest joint sets present at the site. A north/south trend is displayed at nearly one half of all the bedrock sites (10 of 21 sites).

Glacial Sediments

The pattern of jointing measured within the glacial sediments of south-central Ontario is illustrated in Figure 4-2. It should be noted that although there appears to be a regional joint orientation trend within the glacial sediments of south-central Ontario, the pattern is not as clear as that measured within the bedrock (Fig. 4-1). This may be the result of fewer joint measurements being taken within the glacial sediments or a function of the origin of joints.

Within the southern region of the study area, a **northeast/southwest** oriented joint set dominates and is demonstrated at four of the six sites. However, a

secondary northwest/southeast and tertiary north/south oriented joint set may be identified at respectively three and two sites within the region.

There are three joint sets of equal strength within the central region of the study area. **North/south, northwest/southeast** and **northeast/southwest** oriented joint sets are presented at three of the five sites within this the central region.

Two joint sets dominate the joint orientation trends within the northern region of south-central Ontario. **Northeast/southwest** and **northwest/southeast** oriented joint sets are demonstrated at respectively seven and six of the nine sites within the region.

Within the entire study area, there are two well represented regional joint sets within the glacial sediments, a **northwest/southeast** oriented set which is present at twelve of the twenty glacial sites, and a **northeast/southwest** joint set displayed at fourteen sites (Table 3). At these sites, the northwest/southeast trend is commonly the strongest joint orientation trend present (46%), while the northeast/southwest joint trend is most commonly the second strongest preferred orientation measured (57%). In addition to these trends, there is also a more poorly defined north/south trend in joint orientation (north-northwest/south-southeast to north-northeast/south-southwest) which might be classified as the third regional joint set. Within south-central Ontario, there does not appear to be any regional variation in the strength of the joint orientation trends or any correlation between the location within the study area and the dominant joint sets present.

Comparison of Bedrock and Glacial Orientation Trends

At the regional level, there appears to be a good correlation between the jointing pattern in the glacial sediments and underlying bedrock. As noted earlier, a **northwest/southeast** joint set dominates the bedrock and glacial sediments of south-central Ontario although a strong northeast/southwest joint set is also present. A weaker, less well defined north-northeast/south-southwest, north/south, north-northwest/south-southeast oriented joint set may also be identified within both the bedrock and glacial sediments.

This regional trend may be supplemented by the joint orientation results at four sites within the study area where both bedrock and glacial sediments were exposed (Sites 5/17, 14, 24, 30). At two of the four sites where joint measurements were taken within both the bedrock and surficial glacial sediments (Sites 14 and 30) there is a good correlation between the joint orientations in bedrock and overlying glacial materials. However, at the other two sites (Sites 5/17 and 24), there appears to be little agreement between the joint orientation in bedrock and in the overlying glacial materials. The correlation at Sites 14 and 30 suggests that the joints within the glacial materials may have propagated up from the underlying bedrock.

4.3.2 Other Regional Trends

As might be expected, variations in joint frequency and length in bedrock appeared to be related to the bedrock lithology, limestones and dolomites showed a

lower frequency and longer joints than shales. In general, joints within the more massive rocks (limestone and dolomite) were better defined than within the finely bedded shales.

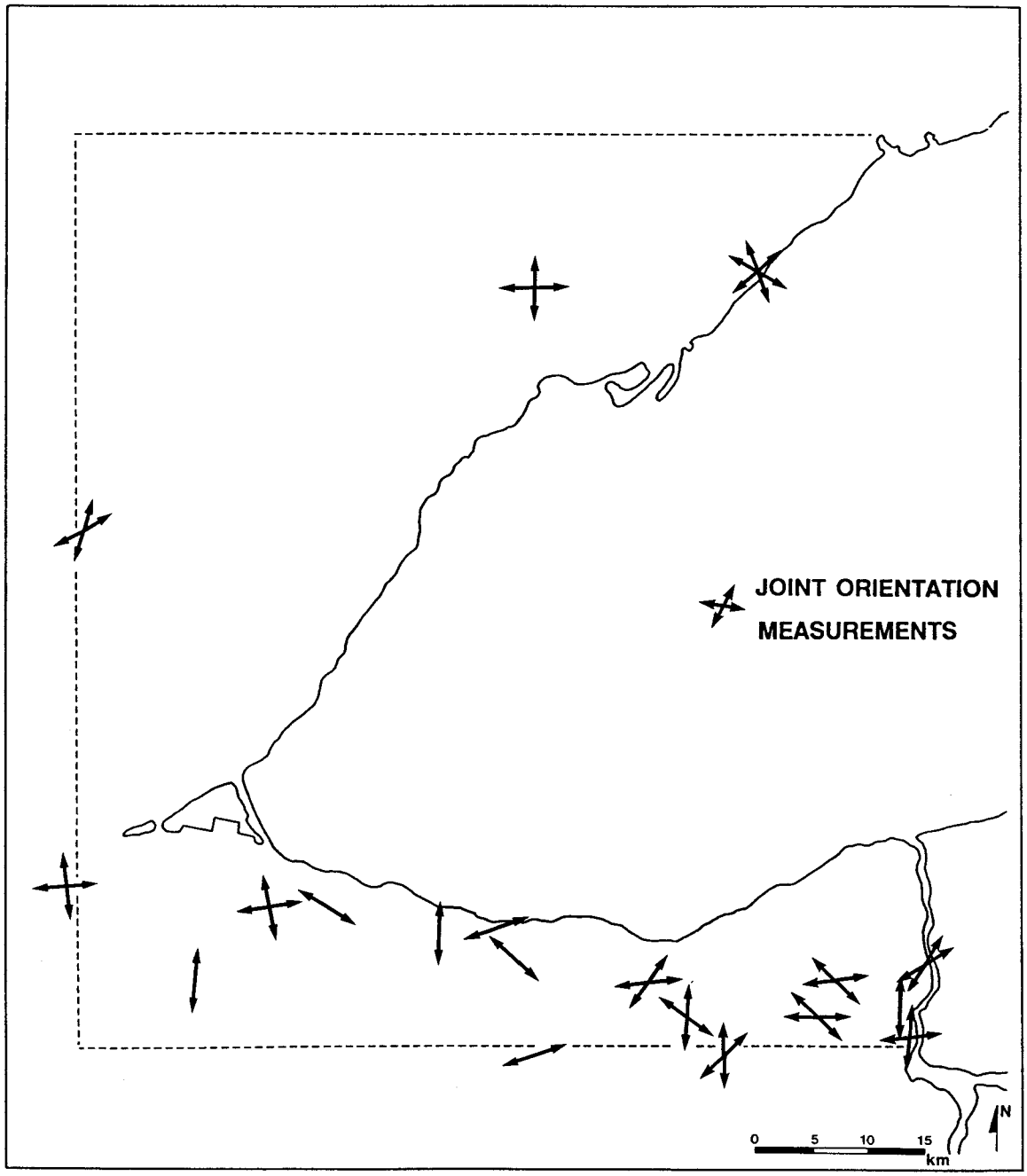
Within the glacial sediments analyzed, generally, clay-rich glaciolacustrine diamicts contained the best defined and longest joints, followed by tills and finally coarser materials. There was no correlation between joint frequency and sediment type. The joint frequency appeared to be a site dependant feature.

4.4 Published Joint Orientation Data

There is very little published joint orientation data for south-central Ontario. The lack of data on bedrock jointing may partly be the result of a thick glacial cover which only allows joint measurement at a limited number of natural or man-made cuts and quarries. The lack of information regarding the jointing pattern within the glacial sediments of the region is consistent with the lack of information on jointing in unconsolidated materials elsewhere in the world. Two studies have been published which describe jointing within the bedrock of south-central Ontario, Scheidegger (1977) and Williams *et al.* (1985). The results of these studies are collected in Figure 4-3.

Scheidegger (1977) collected joint orientation data from three locations within south-central Ontario, at Niagara Falls (115 joints measured), Hamilton (34 joints measured) and Toronto (71 joints measured); he extrapolated from these few sites to define the jointing pattern of all of south-central Ontario. However, his joint grid does

FIGURE 4-3: Compilation of all published joint orientation data for south-central Ontario (compiled from White *et al.*, 1973; Scheidegger, 1977; Eyles *et al.*, 1985; Williams *et al.*, 1985). Only the uppermost right joint system are measurements in glacial sediments.


JOINT ORIENTATION
MEASUREMENTS
0
5
10
15
km
N

not agree with the pattern of jointing determined in this study (Section 4.3.1). There may be two causes for this lack of agreement. First, his extrapolation from only three sites to determine the jointing pattern over a large region seems suspect. Secondly, the sites he has chosen may not accurately reflect the pattern of jointing within south-central Ontario, since the joint orientation trends at nearby sites from this study (Sites 7, and 19) are similarly inconsistent when compared to the pattern of jointing demonstrated by the majority of the sites within south-central Ontario (Fig. 4-1). In addition, the joint orientations determined by Scheidegger (1977) along the Humber River at Toronto, do not correlate well with data from two nearby sites examined in this study (Site 31 and 32). The preferred joint orientations determined by Scheidegger (1977) at the Humber River (north/south and west-southwest/east-northeast) are only minor trends at Sites 31 and 32 where a strong northwest/southeast joint set dominates (Fig. 4-1).

A study by Williams *et al.* (1985) analyzed jointing at thirty sites on the Niagara Peninsula and concluded that there are four joint sets represented in the region, which are oriented north-northeast/south-southwest (5°), northeast/southwest (45°), east-northeast/west-southwest (85°) and northwest/southeast (135°). The trends determined by Williams *et al.* (1985) (Fig. 4-3) are consistent with the findings of this study (Fig. 4-1) although the northeast/southwest joint set of this study is poorly represented in their study. Their methodology, which entailed taking an average orientation of only six joints which fit into expected joint sets at each site, does not comply with standards set by ISRM (1978) and may have placed too much subjectivity

on the measurement. This disagreement in methodology may explain the difference in results between this study and Williams *et al.* (1985).

There are no published data pertaining to the overall pattern of jointing within glacial sediments of south-central Ontario with which to compare the results of this study. Of the brief mentions of jointing in glacial sediments mentioned earlier in Section 1.3 only Eyles *et al.* (1985) provide actual joint orientation data. The joint sets identified by Eyles *et al.* (1985) within the Sunnybrook diamict below South Marine Drive on the Scarborough Bluffs, are exactly the same joint sets identified in this study at other sites on the Scarborough Bluffs (Sites 3, 36 and 37).

The origin of the regional joint orientation patterns identified within this chapter will be discussed in Chapter 5.

CHAPTER 5: ORIGIN OF REGIONAL JOINTS

5.1 Introduction

The compilation of orientation data within Chapter 4 suggests that the controls on joint orientation may be at two scales, local and regional. Regional controls are those factors which cause joint orientation trends to be consistent over a large area, while local controls explain the directional variability amongst sites which are otherwise similar.

As stated earlier (Section 1.3), there is a great wealth of literature on the origin of joints in bedrock which suggests that the most important control over joint orientation in bedrock is the regional stress field (Uemura and Mizutani, 1984; Engelder and Geiser, 1980; Engelder, 1982; Hancock and Engelder, 1989). However, there is very little research into the origin of jointing in glacial sediments. For this reason, the origin of jointing in glacial material will be considered in detail below.

5.2 Origin of Joints in Glacial Sediment

Connell (1984) as well as Nickelson and Hough (1967) have suggested that joints in glacial sediments are polygenetic in nature. Their origin is complex and results from a variety of processes which can rarely be differentiated in the field. Vertical

fractures may form as the result of subglacial deformation (Broster and Clague, 1987; Aber *et al.*, 1989), propagation from underlying bedrock (Grisak and Cherry, 1975; Burford and Dixon, 1978; Eyles *et al.*, 1985), synaeresis (Kazi and Knill, 1973; Connell, 1984), physical and chemical weathering (Babcock, 1977; Connell, 1984), and stress relief (Vonhof, 1970). This section will provide a review of the possible causes of jointing in glacial sediments and will examine how well each theory might explain the pattern of jointing identified in Chapter 4 for the glacial sediments of south-central Ontario.

Physical and Chemical Weathering

Joints may be created or reactivated as the result of volume changes associated with desiccation, water table fluctuation, freeze/thaw, chemical alteration or other types of weathering. Joints associated with physical weathering may be subvertical although they are commonly horizontal and tend to form a close polygonal or random network (Boulton and Paul, 1976; Bullock, 1978 as found in Connell, 1984). Chemical weathering may cause vertical joints to form as the result of volume losses associated with leaching or alterations in the clay mineralogy which may increase the swell potential of the sediments and therefore increase the opportunity for jointing (Connell, 1984; Quigley and Ogunbadejo, 1976). Joints associated with physical and chemical weathering are randomly oriented and therefore, do not show a regional pattern (Connell, 1984). Weathering may however, account for some of the directional variability at individual sites.

Synaeresis

Synaeresis is a process whereby the mutual attraction of clay particles within a fine-grained sediment such as a glaciolacustrine deposit, causes aggregates to form separated by fissures (Connell, 1984). The joints resulting from this process are by nature small and random in orientation. Although at sites where Lake Peel or Lake Iroquois deposits were exposed (Sites 10, 11, 13, 25 and 26), synaeresis might cause small joints to develop, it would not produce the regional joint sets identified in Chapter 4, although it may account for some slight local variability.

Subglacial Deformation

Subglacial deformation is a broad category of physical processes which includes any deformation of a pre-existing substratum by glacial ice. Subglacial deformation occurs when the stress imparted onto the substrate exceeds the strength of the stressed material. If the sediment deforms in a brittle fashion, joints may result. The physical result of the vertical and horizontal stresses caused by the weight (glacistatic) and movement (glacitectonic) of glacial ice can not usually be visually differentiated (Aber *et al.*, 1989), although glacistatic joints tend to be horizontal (unlike those of this study) and glacitectonic joints are commonly vertical (Connell, 1984). The joints associated with glacitectonic deformation tend to have a consistent preferred orientation over a large area, perpendicular to the direction of ice flow (Broster *et al.*, 1979).

Within south-central Ontario, the Ontario Lobe of the Wisconsinan ice sheet flowed out of the Lake Ontario basin, radiating to the northwest in the northern part of the study area, west in the central region and to the southwest in the southern region (Straw, 1968; Chapman and Putnam, 1984; Barnett and Kelly, 1987). If the regional joint orientation pattern within the bedrock and glacial sediments of south-central Ontario identified in Chapter 4 is controlled by the direction of glacier flow, the dominant joint orientations should rotate around the west end of Lake Ontario, from west/east in the northern zone, through north/south in the central zone to west/east in the southern zone. However, this is not the case. Similar joint orientations are seen within all three regions of the study area (Section 4.3.1) and as a result, do not show any systematic variation which may be associated with the direction of ice flow (Figs. 4-1, 4-2).

Stress Relief

Jointing may result from expansion associated with stress relief and unloading. When surrounding bedrock and/or surficial materials are removed by erosion, or excavation there is a sudden decrease in the confining pressure, which may cause a deformation of the remaining material (Kazi and Knill, 1973). Joints produced this way are aligned parallel to the unloaded surface (Connell, 1984). Therefore, vertical joints will result from the removal of lateral support and horizontal joints develop from release of a vertical confining pressure. Formation of joints by lateral stress release is well-documented in quarries where one joint set is often parallel to the quarry face. However, joints lying parallel to the face are likely to be undersampled in any

investigation of joint orientation trends and therefore are unlikely to form an important component of the documented trend. Although stress relief is an important method of joint formation, it acts only on a local level and does not have an effect on the regional jointing pattern.

Glacioisostatic Rebound

Glacioisostatic rebound is the resultant crustal expansion associated with the retreat of glaciers or glacial meltwater and the removal of a large vertical confining pressure. Removal of the confining pressure imparts stress to the substrate and has been found to be important to the development of vertical and horizontal joints in both glacial sediments and bedrock at several locations (for example: Manitoba, Grisak and Cherry, 1975; Greenland, Dawson, 1983) although horizontal joints tend to dominate (Grisak and Cherry, 1975). Although all of southern Ontario is currently rebounding from the weight of Late Wisconsinan ice, south-central Ontario is rising at a lesser rate than the surrounding region and as a result, may act as if it were subsiding (Moore, 1948; Price, 1954; McGinnis, 1968; Barosh, 1986). This suggests that although crustal rebound may be important to the formation of joints in other areas of southern Ontario, its importance may be limited to being only a local control within the study area.

Tectonic Stress

Perhaps the theory which has been the most neglected by authors in search of the origin of joints in glacial sediments is tectonic stress. Tectonic stresses are those

stresses which result from earth movements most commonly associated with the movement and interaction of the crustal plates which compose the lithosphere. Although tectonic stress is greatest at the plate boundaries where the interaction occurs, there is growing evidence to suggest that there is considerable intraplate tectonic stress (Sbar and Sykes, 1973). Tectonic stress causes bedrock to flex and fracture; these fractures may in turn be propagated into the overlying sediments of which there is evidence for in south-central Ontario (Section 4.3.1). The recent published literature suggests that the regional pattern of jointing in bedrock is related to the contemporary regional stress field (Grisak and Cherry, 1975; Burford and Dixon, 1978; Uemura and Mizutani, 1984; Engelder and Geiser, 1980; Engelder, 1982; Hancock and Engelder, 1989), which in a non-glaciated area is the result of tectonic stress (Sbar and Sykes, 1973). In a recently glaciated area such as south-central Ontario, the stress field is more complex and may be affected by glacioisostatic as well as recent or neotectonic stresses (White and Russell, 1982). A comparison between the regional stress field and the jointing pattern of south-central Ontario identified in Chapter 4, may determine whether the regional jointing pattern is controlled by neotectonic stresses.

5.3 Regional Stress Field

The regional stress field may be identified by an examination of oriented stress related features: pop-ups, faults, lineaments and river valleys, other stress related features: earthquake epicentres and rock squeeze, and *in situ* stress measurements. Of these features, pop-ups, faults and rock squeeze phenomena are specifically stress

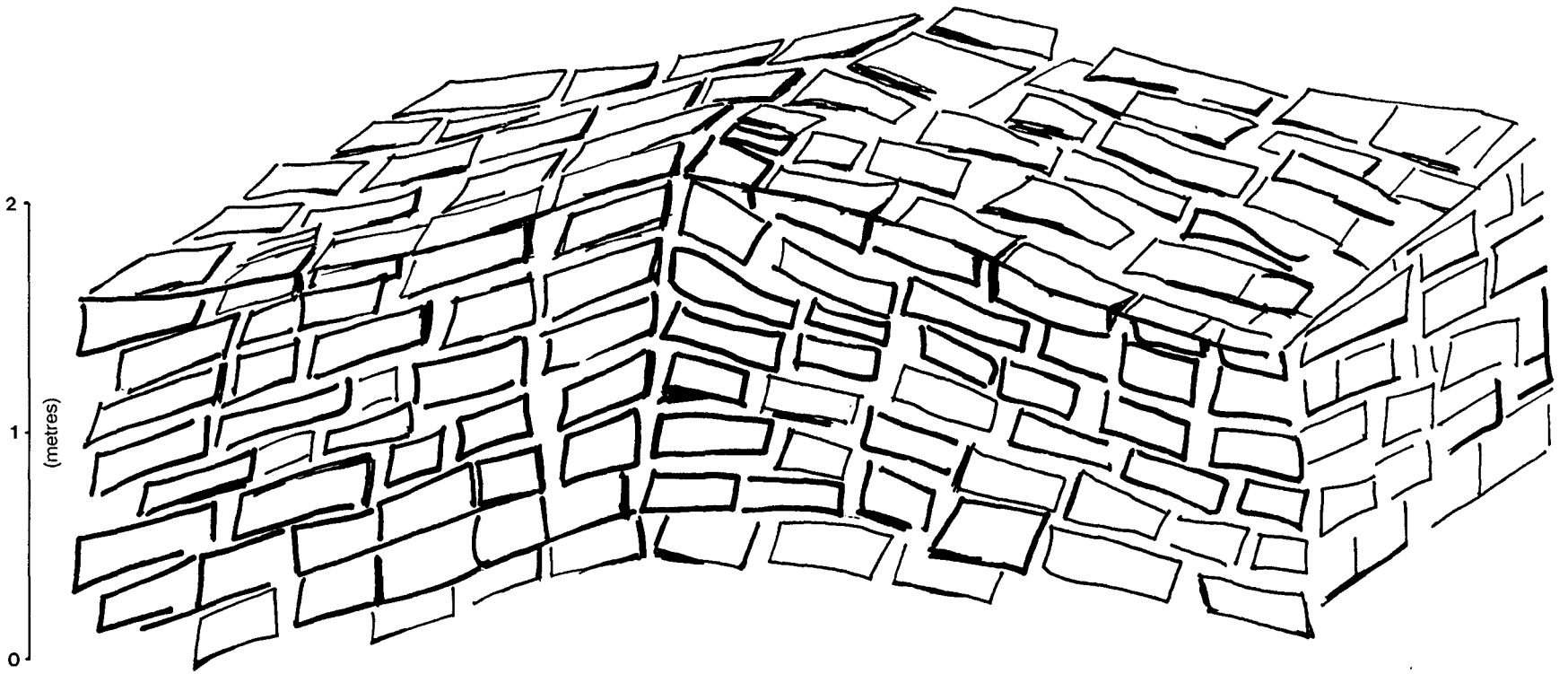
release structures. They develop as the result of a disequilibrium between the strength of the material and the stresses imparted to it. When the strength of the material is exceeded, failure occurs and the stress is released. Lineaments, river valleys and earthquake epicentres are indirect measures of the regional stress field. Lineaments mimic deep-seated faults and fractures (Barosh, 1986), river valleys have been shown to have an orientation consistent with the regional stress field (Scheidegger, 1980; Scheidegger and Ai, 1986) and earthquake epicentres provide evidence of neotectonic activity (Sbar and Sykes, 1977).

5.3.1 Oriented Stress Related Structures

Pop-ups

Pop-ups are elongate anticlinal forms which develop in bedrock (Fig. 5-1), and have been seen to propagate upwards deforming the overlying glacial sediments (White *et al.*, 1973). High, surface or near-surface horizontal compressive stress causes the bedrock to buckle, releasing stored elastic-strain energy as the rock 'pops up'. If the compressive stress is large enough, the rock may become faulted rather than simply folded. Pop-ups commonly form in the base of quarries (where they are termed quarry heaves) or other deep excavations in response to unloading. When overlying bedrock and/or surficial materials are stripped, there is a sudden decrease in the vertical confining pressure which releases the horizontal compressive stress and causes an upward deformation of the rock (Lo, 1978).

FIGURE 5-1: Sketch of a pop-up. Note the similarity between this sketch and folds and faults.

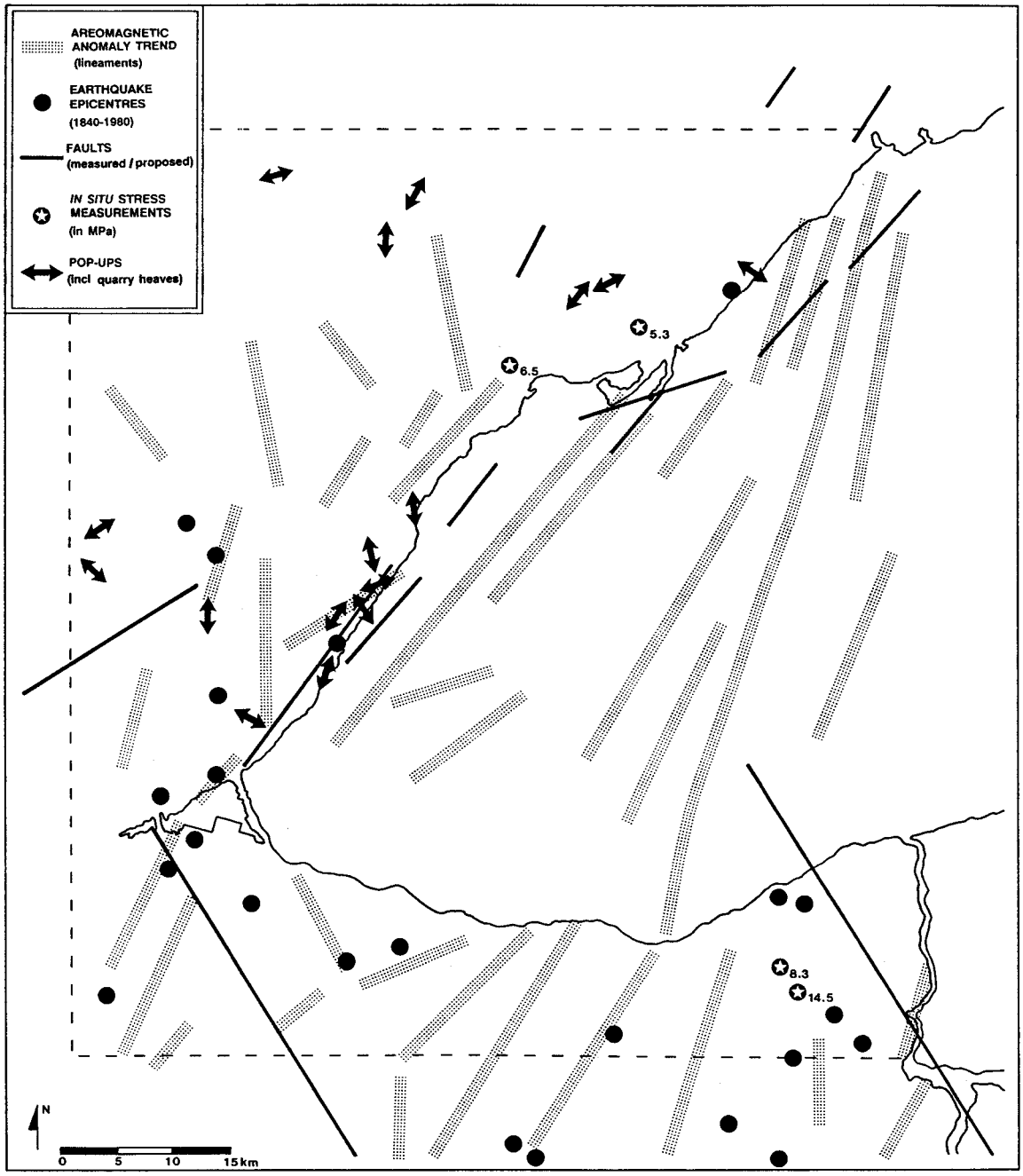

2
1
0
(metres)

Within south-central Ontario, pop-up structures have a variety of orientations although preferred **northeast/southwest** and **northwest/southeast** trends may be identified (Fig. 5-2). This northwest/southeast trend in pop-up orientation in southern Ontario was also identified by White and Russell (1982). Since pop-ups are essentially compressive features, the long axes of pop-ups are oriented perpendicular to the dominant stress field (Williams *et al.*, 1985). Where the axes do not follow this convention, it may be the result of either a complicated regional stress field or intensive localized stresses (Chagnon and Wallach, 1988). The orientation of pop-ups within south-central Ontario suggests either a northwest/southeast oriented stress field (by 8 of 17 pop-ups) or a northeast/southwest oriented stress field (6 of 17 pop-ups).

Major Faults

Faults are fractures along which displacement occurs relative to the fracture surface. There are three common causes of faulting in bedrock in a glaciated area: local rock expansion due to unloading (natural or man-induced), fracturing in response to regional flexure and glacioisostatic uplift, and neotectonic forces unrelated to ice unloading (Adams, 1981). Only nine major faults have been documented within the study area (Fig. 5-2) (Barosh, 1986; Kenny, 1988). Seven of the faults identified were oriented **northeast/southwest**, the other two faults are oriented northwest/southeast (Fig. 5-2). Faults are generally oriented parallel to the principal compressive stress (Adams, 1981; Scheidegger, 1981). Thus, the general trend of most major faults within south-central Ontario, indicate a regional stress field that is oriented northeast/southwest.

FIGURE 5-2: Compilation of all oriented stress related data as well as the locations of earthquake epicentres and *in situ* stress measurements (compiled from, Palmer and Lo 1976; Lo 1978; White and Russel 1982; Nottis 1983; Barosh 1986; Geological Survey of Canada 1987; Kenny 1988, 1990; Trow and Lo 1989).


AREOMAGNETIC ANOMALY TREND (lineaments)
EARTHQUAKE EPICENTRES (1840-1980)
FAULTS (measured / proposed)
IN SITU STRESS MEASUREMENTS (in MPa)
POP-UPS (incl quarry heaves)
5.3
6.5
8.3
14.5
N
0
5
10
15km

Lineaments

Large (Fig. 5-2) geologically controlled linear features which occur at the earth's surface but are visible only by remote sensing, are termed lineaments. They are commonly identified from aerial photographs, radar imagery and aeromagnetic anomaly maps. Lineaments are the surficial expression of deep-seated, large-scale geologic features, most commonly faults which could otherwise not be detected (Barosh, 1986). Preliminary data from the Ontario Centre for Remote Sensing indicates that no major lineaments can be identified within south-central Ontario using Landsat MSS and TM images (Kenny, 1990). This may be the result of a combination of the thick surficial cover of glacial sediments, agricultural practices or an intensely urbanized landscape. However, aeromagnetic anomaly maps of the study area indicate a strong **northeast/southwest** trend in lineament orientation (18 of 29 lineaments), together with weak north/south (4 of 29 lineaments) and northwest/southeast (3 of 29 lineaments) trends. These trends are consistent with the lineaments defined by Kenny (1990) from Landsat imagery outside of the study area. The strong northeast/southwest trend in lineament orientation suggests that the regional stress field is oriented northeast/southwest.

River Valleys

Scheidegger (1980) analyzed the direction of major river valley trends within Ontario and found that there was pattern to their orientation. In order to determine the orientation of each river valley, rectified river segments were delineated by connecting

(with a straight line), the head of the river with the node where another water body was met. Within south-central Ontario five rectified river segments were identified, the orientations of which were generally within the **northwest/southeast** quadrant (Scheidegger, 1980). Scheidegger (1981) suggests this trend in orientations indicates a tectonic control on river valley development and identifies a principal compressive stress oriented northeast/southwest. In addition, Scheidegger (1980) and Flint and Lolcama (1985) noticed a correlation between joint orientation in the bedrock of south-central Ontario and the orientation of nearby river valleys. This suggests that their orientation may be controlled by the same process.

Summary of Orientation Trends

There appears to be a preferred orientation shown by the stress related features described above. As Table 4 shows, the stress related features are oriented either to the northeast or the northwest. The dominant inferred stress is therefore oriented **northeast/southwest**. However, a northwest/southeast oriented stress is also supported by the data.

TABLE 4: SUMMARY OF ORIENTATION TRENDS FOR STRESS RELATED STRUCTURES

FEATURES	PRIMARY TREND	INFERRED STRESS	SECONDARY TREND	INFERRED STRESS
POP-UPS	NE/SW	NW/SE	NW/SE	NE/SW
FAULTS	NE/SW	NE/SW	NW/SE	NW/SE
LINEAMENTS	NE/SW	NE/SW	NNW/SSE	NNW/SSE
RIVER VALLEYS	NW/SE	NE/SW	-	-

5.3.2 Other Stress Related Features

Rock Squeeze

The inward deformation of rock within underground structures is known as rock squeeze. The excavation of tunnels or other underground structures removes the lateral confining pressure and allows high horizontal compressive stress to deform the rock inwards as a form of stress relief. Rock squeeze has been reported at several locations within south-central Ontario, and gives evidence for the presence of high horizontal compressive stress. In the Niagara area, rock squeeze has been identified within a wheel pit of the Canadian Niagara Power Company (Lo *et al.*, 1975), the Thorold Tunnel (Bowen *et al.*, 1976) and tunnel No. 1 of the Sir Adam Beck Niagara Generating Station Number 2 (Coates, 1964; Lo *et al.*, 1975). At Hamilton, rock squeeze was identified as the cause of damage to the concrete lining of the Hamilton Mountain Trunk Sewer (Roegiers and Thompson, 1977). In the Toronto area, rock squeeze has been noted during the construction of several major projects including the Scotia Plaza (Trow and Lo, 1989) and the relocation of the John Street Pumping Station (Lo *et al.*, 1987), whose designs were altered to compensate for high horizontal compressive stress. In addition, rock squeeze forced the closing, and later replacement of a section of a storm sewer tunnel in Mississauga (Lo *et al.*, 1987). Although many of these studies indicate the strength of the stresses involved (and are included within direct *in situ* stress measurements), they do not state an orientation. Therefore, although rock squeeze can not be used to determine the orientation of the regional stress field, it does provide additional evidence of high horizontal compressive stress.

Earthquake Epicentres

Earthquakes often occur as the result of sudden deep-seated movement within the earth's crust and most commonly occur at the boundaries between lithospheric plates. Since earthquakes result from earth movements resulting from the release of built up strain, the location of earthquake epicentres may correlate well with regions of neotectonic activity (Sbar and Sykes, 1977). As is evident from Figure 5-3, there is a cluster of earthquake epicentres around western Lake Ontario. Although there is no regional trend or belt of epicentres within the study area, the epicentres are contained within a region of high seismic frequency which includes south-central Ontario and much of northwestern New York state (Fig. 5-2) (Barosh, 1986). The clustering of earthquake epicentres around western Lake Ontario provides evidence of recent tectonic activity within the study area and suggests high regional *in situ* stress (Sbar and Sykes, 1977).

5.3.3 *In situ* Stress Measurements

Stress measurement at several locations within south-central Ontario (Fig. 5-2) provides direct evidence of high *in situ* stress. *In situ* stress is commonly determined within deep holes by either overcoring stress relief methods or hydrofracturing. In a standard open-hole hydrofracturing procedure, the section of interest for stress measurement is isolated from the rest of the hole and then a fluid is injected. As the pumping of fluid continues, the fluid pressure is measured. The pressure within the isolated section will reach a maximum value at which time the

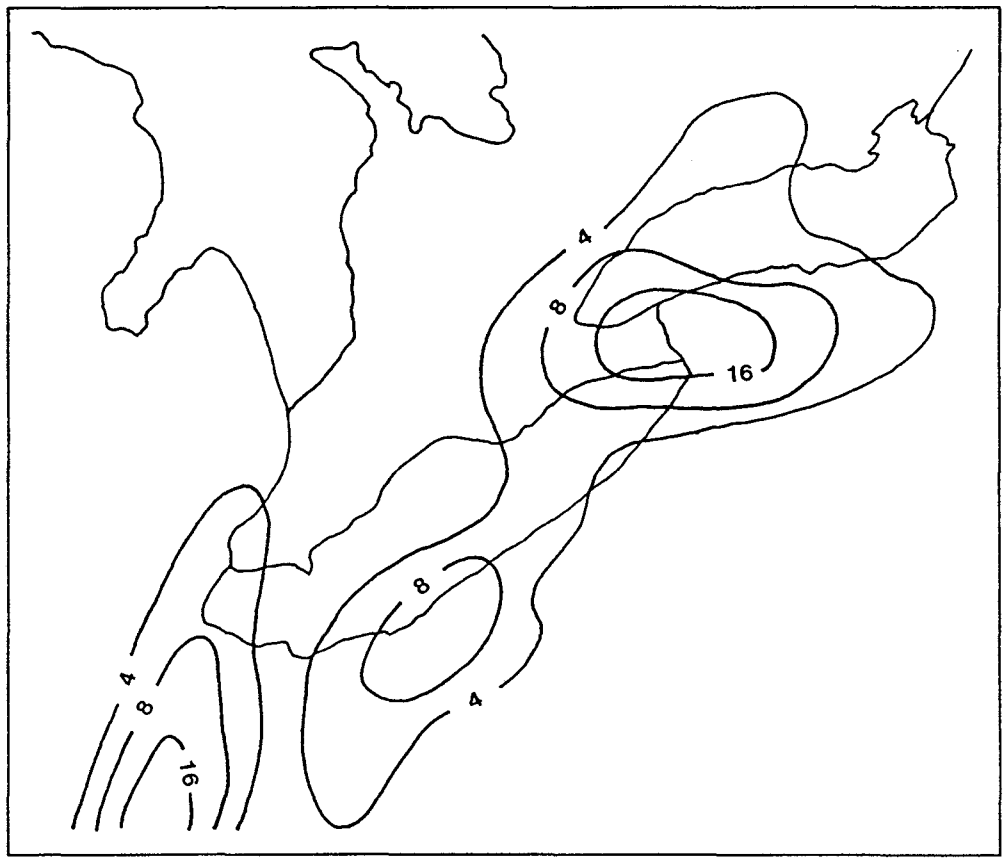


FIGURE 5-3: Seismic frequency map for the Great Lakes Region, modified Mercalli III or greater (after Barosh, 1986).

material surrounding the hole fractures. Upon fracturing, the fluid pressure will immediately decrease and eventually level off to a constant value if pumping is continued. Measurement of the fluid pressures at the fracture point and at the constant value, as well as the stabilization pressure after the fluid is released, allows the stress distribution to be modelled (Kehle, 1964).

Overcoring is generally the chosen method of *in situ* stress determination since it is easier and less expensive than other methods including hydrofracturing (De la Cruz and Raleigh, 1972). The basic technique of overcoring involves the overcoring of a small instrumented hole by a larger concentric hole. If the direct strain-gauge method is used, the pilot hole is instrumented by means of electric resistance strain gauges attached directly to the surrounding rock. These gauges give a direct measure of the principal stresses as well as information necessary to calculate the stress orientation (De la Cruz and Raleigh, 1972).

Both of these techniques, as well as direct measurement in open excavations were used to produce the measurements of *in situ* stress for south-central Ontario found in Figure 5-2. The maximum horizontal compressive stress identified by *in situ* stress measurements shows a preferred **northeast/southwest** orientation. These findings are consistent the findings of Lee (1981 In: White and Russell, 1982) who found that approximately two thirds of the *in situ* stress measurements taken in southern

Ontario fall within the northeast/southwest quadrant. These stress field orientations are consistent with the inferred stress deduced from the stress release and stress related features discussed in Section 5.3. Only the pop-up trends do not show a dominant inferred northeast/southwest stress. Within the pop-up data, the northeast/southwest inferred stress is second to a slightly better represented northwest/southeast trend.

A **northeast/southwest** oriented stress field is consistent with the regional stress condition in southern Ontario and northeastern United States (Zoback and Zoback, 1980, 1981). South-central Ontario is located within a mid-continent belt of northeast/southwest trending horizontal compressive stress (Sbar and Sykes, 1973; Haimson, 1978; Zoback and Zoback, 1981). This agreement in stress orientation over such a large area, part of which was not glaciated during the Pleistocene, suggests that the stress is deep-seated and tectonic in origin (Sbar and Sykes, 1973; Lo, 1978; White and Russell, 1982) and could not be the result of glacioisostatic rebound as suggested by White *et al.* (1973). Further, the tectonic stresses must be of recent origin (ie. neotectonic). If the joint orientations determined within this study are consistent with the regional stress field, then the regional joint pattern is likely to be neotectonic in origin.

5.4 Comparison of the Jointing Pattern and Regional Stress Field

The regional jointing pattern identified within Chapter 4 correlates well with the regional stress field as determined from the orientation of pop-ups, faults, lineaments, river valleys and direct *in situ* stress measurements (Section 5.3). Within the

glacial sediments and bedrock of south-central Ontario. Three regional joint sets were identified within this study: strong **northwest/southeast** and slightly weaker **northeast/southwest** oriented joint sets are present, along with a less well defined north/south (north-northeast/south-southwest to north/south to north-northwest/south-southeast) oriented joint set. As stated in Section 1.2 regional joints are ideally represented by three joint sets, longitudinal joints whose orientation is parallel to the maximum stress, transverse joints oriented perpendicular to the maximum stress and oblique joints which cut across the other two sets (Uemura and Mizutani, 1984). Within south-central Ontario, where the maximum *in situ* stress is oriented northeast/southwest (Section 5.3), the longitudinal joint set should be oriented northeast/southwest, the transverse joint set oriented northwest/southeast, and the oblique joint set should be oriented either north/south or east/west. The regional jointing pattern identified within Chapter 4 conforms to this pattern. Specifically, the northwest/southeast joint set, may represent transverse joints, the slightly weaker northeast/southwest joint set could correlate with longitudinal joints, and the third trend identified, north-northwest/south-southeast to north-northeast/south-southwest may represent oblique joints (Uemura and Mizutani, 1984).

Three regional joint sets may be identified within the bedrock and surficial glacial sediments of south-central Ontario. A comparison amongst stress related structures, direct *in situ* stress measurements and the regional joint sets determined in this study

suggest that the regional jointing pattern is controlled by the regional stress field. This should allow the prediction of jointing characteristics at proposed landfill sites within the study area. However, there are a number of local factors which add variability to the regional jointing pattern and may complicate the prediction of jointing. These local factors will be considered within Chapter 6.

CHAPTER 6: LOCAL CONTROLS ON JOINT ORIENTATION

6.1 Introduction

Results within Chapter 4 and 5, indicate that a regional jointing pattern may be identified within south-central Ontario and that it is controlled by the regional stress field. However, there is considerable variability at individual sites within the study area which can not be ascribed to the regional stress field. Local controls may cause either increased scatter within joint orientation measurements at individual sites or if the local control is of great enough strength, it may override the regional controls so that these sites may show an anomalous trend when compared to surrounding sites. Within the study area, three factors were found to be the dominant local controls, lithology of the material exposed, the direction of Late Wisconsinan ice flow movement over the site, and the orientation of the face on which joints were measured. The importance of each local control on joint orientation within glacial sediments and bedrock may be different due to differences associated with lithified and unlithified materials.

6.2 Bedrock

6.2.1 Lithology

Nickelson and Hough (1967) identified a correlation between bedrock lithology and joint orientation in the sedimentary rocks of the Appalachian Plateau of

Pennsylvania. They determined that this correlation was the result of the different strengths of the materials, and the differences in times of lithification. South-central Ontario, with its large variation in bedrock lithology over a relatively small area, seems a likely area to examine the influence of lithology on joint orientation. Williams *et al.* (1985) analyzed the jointing pattern within the Palaeozoic rocks of the Niagara Peninsula (the Clinton and Cataract Groups, and the Queenston, Lockport, Guelph, Bertie, Oriskany and Onondaga Formations) and found that there was no correlation between joint orientation and lithology. However, data collected within this study suggest that bedrock lithology does control to some extent the pattern of jointing within south-central Ontario. This control is best illustrated by contrasting the joint orientation trends measured within the Georgian Bay, Amabel and Queenston Formations (Fig. 4-1).

The influence bedrock lithology has over joint orientation trends in south-central Ontario may be apparent in several ways. All sites where joints were measured in the Georgian Bay Formation (Sites 20, 31, 32, 40) contain a strong east-northeast/west-southwest to northeast/southwest oriented joint set, although at Site 31, the east-northeast/west-southwest joint set is ancillary to a northwest/southeast trend (Fig. 4-1). The strong east-northeast/west-southwest trend was demonstrated equally well by both the limestone and shale interbeds of the Georgian Bay Formation. This trend is slightly different from the regional jointing pattern of northwest/southeast, northeast/southwest and north/south trending regional joints, but is unique when

compared to surrounding sites in both its consistency of orientation (L ranges from 26.32 to 56.90) and the strength of the trends (Raleigh number ranges from 0.998 to 1.000).

There also appears to be a correlation between bedrock lithology and the consistency of joint orientation within the Queenston and Amabel Formations. The rose diagrams for the Queenston Formation (Sites 12, 14, 18, 22, 24, 29) and Amabel Formation (Sites 28, 30, 35) in Figure 4-1, show much greater directional variability in joint orientation than the other rock formations analyzed in the study area. The very friable, thinly bedded Queenston Formation (Chapters 2 and 3) has low internal strength and may therefore be affected by minor local stresses which may not affect bedrock with greater internal strength (for example limestone, sandstone or dolomite). The consistency measurements and Raleigh numbers for the sites where the Queenston Formation was exposed are overall lower than those determined for other formations (L ranges from 10.64 to 45.24, Raleigh number ranges from 0.184 to 1.000).

At Sites 28, 30 and 35 where the massive dolomite of the Amabel Formation is exposed, there is also a large amount of directional variability in joint orientation (consistency values of 19.30, 33.82 and 19.57 and Raleigh numbers of 0.921, 1.000 and 0.939 respectively). At these sites, directional variability may be related to the reef knobs present within the Amabel Formation (Section 2.2.2). The reef knobs probably cause randomly oriented internal weaknesses which are reflected in joint orientations trends at these sites.

The lithologic control on joint orientation in bedrock may also be demonstrated in vertical sections where more than one type of bedrock is exposed. This control is illustrated by Site 7, where joints were analyzed within the Reynales, Thorold and Irondequoit members of the Clinton Group and the Gasport member of the Lockport Formation (Fig. 3-11). Although the joint orientations measured at the site are fairly consistent overall, the amount of directional variability within each bed varies considerably. The Reynales sandstone shows a very strong preferred north/south joint orientation trend with an overall Raleigh number of 1.000 and consistency level (L) of 66.06. This contrasts sharply with the variation shown by the Thorold sandstone at the same site. On one face the Thorold sandstone had a Raleigh number of only 0.217, complemented by consistency level (L) of only 7.92. These statistical values, along with the rose diagrams in Figure 3-11, suggest that bedrock lithology may exert a control over the joint orientation characteristics within different lithological beds at individual sites, and that certain formations show more directional variability than other rock formations as a result of differences in the strength and fracturing characteristics of the materials.

6.2.2 Face Orientation

An attempt was made to measure joint orientation in bedrock on several faces at each site, so that joints at a low angle to the section face would not be undersampled. However, this was not possible at Sites 19, 29 and 31 due to the limited extent of river exposures and quarry accessibility. At these sites, there are differences

in the strength of the joint orientation trends when compared to surrounding sites. The dominant joint sets measured at these sites are ancillary joint sets at the surrounding sites and suggests that at Sites 19, 29 and 31 the face orientation has prejudiced the overall joint orientation trends obtained.

At Site 19, the strongest joint set measured is a north/south trend although ancillary northwest/southeast and east-northeast/west-southwest trends are also present (Fig. 3-7). This contrasts with the joint orientation trends at surrounding sites where northwest/southeast and east/west joint sets dominate (Fig. 4-1). The northwest/southeast joint set at Site 19 is parallel to the face orientation (140°) and is likely undersampled.

Similarly, at Site 29, a north-northeast/south-southwest oriented joint set is dominant, although a strong northwest/southeast joint set is also present (Fig. 3-17); at nearby sites (Sites 18, 22, 24), the northwest/southeast trend forms the dominant joint set (Table 2). The section face at Site 29 is oriented at 130°, approximately parallel to the northwest/southeast joint set which dominates Sites 18, 22 and 24, and again may have been undersampled.

The joint orientation measurements obtained at Site 31 may also have been influenced by face orientation. The dominant joint set at Site 31 (northwest/southeast) is only the secondary joint set at surrounding sites (32 and 40), while the secondary

joint set at Site 31 (east-northeast/west-southwest), is the dominant joint set at Sites 32 and 40. The face at Site 31 is oriented 75°, similar to the undersampled joint set. It appears therefore that joint orientation may be influenced by the orientation of the face on which joints were measured.

6.2.3 Direction of Ice Movement

Broster *et al.* (1979) demonstrated that the orientation of at least one joint set, measured in bedrock which had been overridden by a glacial ice at Cranbrook, British Columbia, is oriented perpendicular to the direction of ice flow. Although the direction of ice flow movement does not appear to control the regional jointing pattern in south-central Ontario (Section 5.2), it may control the jointing characteristics in bedrock at individual sites.

The control ice flow direction has over joint orientation may be examined in detail at individual sites within the study area where jointed glacial sediments overlie grooved and striated bedrock pavements. Since Wisconsinan glacial sediments overlie the striated bedrock, it is assumed the striations are of Wisconsinan age. At two sites within the study area (Sites 6 and 5/17), striations were measured on the upper bedding plane of exposed bedrock. At Site 6, the striations are oriented at 49° (northeast/southwest) indicating that the glaciers likely flowed to the southwest over the site. If glacial ice movement has influenced joint orientation, a strong north-west/southeast oriented joint set should be identified within the bedrock. However, as

Figures 3-10, 4-1 and Table 2 show, only a minor northwest/southeast trend is present within the bedrock at this site, and a north/south trend dominates. This suggests that the direction of ice flow may have a minor control over the joint orientation at Site 6.

Striations were also measured on the bedrock surface at Site 5/17. The striations at this site are oriented at 40° (northeast/southwest) which suggests that ice movement was to the southwest, and that a northwest/southeast joint set should dominate the orientation measurements. Within the bedrock at Site 5/17, there are two equally strong joint orientations, a northwest/southeast joint set and a west/east oriented joint set, although there is considerable variability in joint orientation at this site (Fig. 3-3). The joint orientation at Site 5/17, appears to be in part controlled by the direction of ice flow.

6.2.4 Unexplained Anomalies

There are two noticeable anomalies which may be identified within the pattern of jointing in bedrock within the study area. The great amount of directional variability within glacial sites precludes the identification of glacial sites which show an anomalous joint orientation trend. Joint orientation trends at bedrock sites near the Niagara River (Sites 10, 11 and 19) and near Hamilton (Sites 4, 7 and 33) show strong north/south oriented joint sets which are not present elsewhere in the study area. Lolcama and Flint (1985) found that the dominant joint sets near Niagara Falls are parallel to the orientation of the Erigan, Crystal Beach and St. Davids pre-glacial

channels which are also oriented north/south. This similarity suggests that the joint systems may have controlled the orientation of the valleys and that the jointing pattern within this area is pre-glacial in origin.

Perhaps the most striking anomaly in joint orientation patterns within the study area is found at Site 7. Here, there is a very strong north/south preferred joint orientation as well as an ancillary west/east trend (Fig. 3-11). Only measurements taken within the Thorold member show a strong northwest/southeast oriented joint set, which is the dominant joint orientation within the entire study area, although a minor northwest/southeast joint set is present within the Gasport member. There is no apparent explanation for the strong north/south, west/east joints orientations since measurements were taken from several differently oriented faces as well as several different formations (Reynales, Irondequoit, Thorold and Gasport members of the Clinton and Cataract Groups). Perhaps the north/south oriented joint set is a remnant feature resulting from local disturbances.

6.3 Glacial Sediments

6.3.1 Lithology

The type of glacial sediment present did appear to exert a minor control over joint orientations at several sites within the study area, although the control is much less important than lithology on bedrock. At Sites 3, 36 and 37 where the Sunnybrook diamict was exposed, the joint orientation trends are strikingly similar

(Figs. 3-19, 3-22, 4-2). The affect similarity in material has over joint orientation may also be demonstrated at Sites 10 and 11. At these sites where glaciolacustrine clay was exposed, a very strong north/south trend was measured which is not seen at the surrounding sites (Fig. 4-2). The only common factor amongst Sites 3, 36 and 37, and Sites 10 and 11 is the type of sediment present.

6.3.2 Face Orientation

Unfortunately, at many sites where glacial sediments were exposed, joints could be measured on only one face (Sites 10, 24, 25, 26, 39, 41). As a result, the reliability of the joint orientation trends measured at these sites may be suspect due to an undersampling of the joint set oriented parallel or sub-parallel to the section face. The effect of face orientation has on joint orientation trends is clearly demonstrated at Sites 25 and 26. At both of these sites, joint measurements were taken from only one face (oriented at 72° and 51° respectively). The sites demonstrate north/south, northwest/southeast and west/east, and west-northwest/east-southeast and northeast/southwest oriented joint sets respectively (Figs. 3-21, 4-2). At Sites 25 and 26, it is likely that the west/east and northeast/southwest joint sets are respectively undersampled since these joint sets are approximately parallel to the section face.

6.3.3 Direction of Ice Flow

The local control ice flow direction has over joint orientation in glacial sediments may be examined at Site 5/17 where Late Wisconsinan glacial sediments

overlie the striated bedrock. Striations measured on the bedrock surface at this site are oriented at 40° which suggests that the Late Wisconsinan ice movement was to the southwest, and that a northwest/southeast joint set should dominate the orientation measurements glacial sediments. The glacial sediments at Site 5/17 contain strong north-northwest/south-southeast and east-northeast/west-southwest oriented joint sets although there is considerable variability in joint orientation at this site (Fig. 3-3, 4-2). Therefore, glacial ice movement does appear to control in part the joint orientation trend at this site although the dominant joint orientation trend has a slightly more northern/southern trend than would be anticipated.

Therefore, the lithology of the material exposed, the direction of ice flow over the site and face orientation may act as local controls and explain in part the directional variability within the joint orientation trends at individual sites where glacial sediments and bedrock were exposed, which could not be accounted for by the regional stress field.

CHAPTER 7: CONCLUSIONS

7.1 Introduction

The aim of this thesis was to provide basic information regarding jointing within the glacial sediments and bedrock of south-central Ontario. Specifically, an attempt was made to determine the origin and pattern of vertical or near-vertical regional joints within the fine-grained surficial glacial sediments which are though to be most suitable for waste disposal sites. An understanding of the joint characteristics of these sediments is essential to the safe planning of these sites.

7.2 Summary and Conclusions

1. Within the bedrock of south-central Ontario, three regional joint sets were identified. The dominant joint orientation is northwest/southeast (sixteen of twenty-one bedrock sites) although northeast/southwest and north/south oriented joint sets are also present (at nine and ten of the sites respectively). Local variability at bedrock sites may be associated with the bedrock lithology, direction of ice flow over the site or the orientation of the face on which joints were measured.

2. A comparison of the regional joint orientation in bedrock with stress related structures (pop-ups, faults, lineaments, river valleys, earthquake epicentres and rock

squeeze) and *in situ* stress measurements suggests that the regional jointing pattern is the result of regional stress associated with intraplate neotectonism.

3. Within the surficial glacial sediments of south-central Ontario, three regional joint sets were identified. A northeast/southwest oriented joint set is displayed at fourteen of the twenty glacial sites, a northeast/southwest oriented joint set is present at twelve of these sites. A weaker, poorly defined north/south (north-northwest/south-southeast to north/south to northeast/south-southwest) trend has been classified as the third regional joint set. There is more directional variability within the joint orientation measurements at sites where glacial sediments were exposed as compared to bedrock sites. The variability at glacial sites may be explained in part by the type of sediment exposed, the direction of ice flow and the face orientation.

4. Reasonably good correlation between joint orientation trends within the bedrock and glacial sediments suggests that joints may have propagated from the bedrock into the overlying glacial sediments, and that the jointing pattern within the glacial sediments is also controlled by the regional stress field.

5. Joint orientation trends identified in this thesis may be used to predict joint characteristics and orientations within the region. This information is vital for the planning of future landfill sites. Landfill sites built in areas of high horizontal stress may be susceptible to post-construction jointing of the surrounding materials. Even

if no joints are present at the time of site development, the joints may develop at some point in the future. Lo (1978) suggests that the area of high horizontal stress within southern Ontario, may extend 30km or more inland from western Lake Ontario. As a result, much of the area currently being considered as a solution to south-central Ontario's waste disposal problem may be less suitable than currently understood.

7.3 Future Research

More information is needed on both joint orientation trends and *in situ* stress in south-central Ontario. This information is vital to the assessment of future landfill sites. This study demonstrates that many of the fine grained glacial sediments considered to be 'tight' impermeable substrate on which to site landfill facilities are often developed, are in fact extensively jointed. The jointing characteristics of substrate should therefore by carefully assessed in the examination of any potential sites.

This information could also be used to help predict the jointing characteristics and the potential for future jointing at already developed landfill sites. This jointing pattern could then be used to help predict the likely path of leachate movement. Monitoring of leachate from test wells could confirm the predicted jointing and aid in the containment procedures.

There is a critical need to develop a 'data bank' containing joint information for all of southern Ontario. Information needs to be collated from private research of

individuals and consultancy companies and public research collected by various government agencies to provide a more comprehensive data base from which the major jointing patterns could be identified. It is hoped that this thesis will stimulate such data acquisition and collation.

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