THE KARST GEOMORPHOLOGY OF MANITOULIN ISLAND

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OF

MANITOULIN ISLAND

By

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ABSTRACT

Manitoulin Island is formed of glacially-abraded dolomite and limestone bedrock widely exposed across the island. The dominant karst landform is dolomite pavement, its form strongly controlled by lithology and classified according to appearance and karren characteristics. Pavement was found to be most extensive and well developed on the Amabel Formation, which also featured a pitted littoral zone along the southern Lake Huron shore. The Fossil Hill Formation featured good pavement only on a limited number of sites. Other carbonates had only very shallow, limited pavement due to presence of clay or silica rich insolubles, thin beds and frequent shale interbeds. Clint and grike karren forms were the most common on Manitoulin Island pavements. Grikes on these pavements were found to be on average 13 cm wide, 83 cm deep and 367 cm in length, with much variation across pavement types. Grike orientations were dominated by a 90^0 regional set, with sets at 60^0, 120^0, 30^0 and 150^0 of secondary importance

Investigation of the island's hydrogeology revealed that the main karst aquifer is divided in half by the Cabot Head Shale aquiclude. The northern aquifer is formed of less soluble carbonates and is dominated by fluvial surface drainage. The southern aquifer has developed in highly soluble dolomites and is dominated by holokarstic drainage, mainly diffuse, and several internally draining lakes. A lack of fluvial karst except some immature systems is attributed to few streams crossing the border between the two extremes of drainage type. There is little macro-karst except Mindemoya Cave, indicating there are limiting factors to karst development on Manitoulin including age since deglaciation, rock solubility and physiography.

Tree density on alvars, a sparse parkland type vegetation, was examined on the pavements. Density was directly related to pavement type as a function of amount of debris in grikes which allows trees to take root. The impacts of deforestation likely enhanced erosion, resulting in the development of this type of vegetation.

The relationship between hardness and specific conductivity for Manitoulin Island surface and subsurface waters was established in this study. The waters were found to have high hardness, similar to values on the Bruce Peninsula.

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CHAPTER I - INTRODUCTION

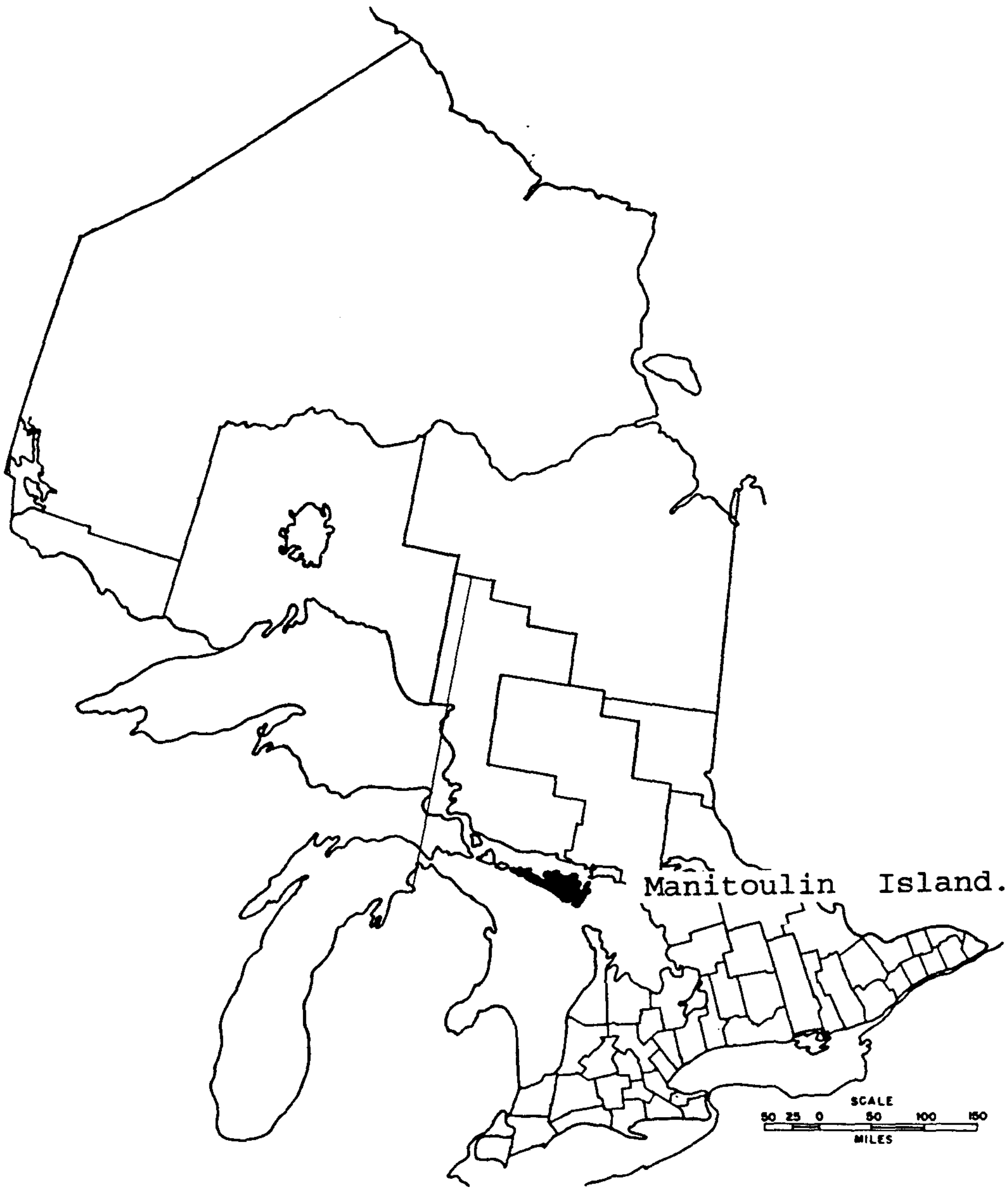
1.1 - Purpose

This research represents the first attempt to survey, classify and explain the karst features, with a principal focus on surface karst, on Manitoulin Island (located in Figure 1.1). It examines various aspects of the karst on the island but the emphasis is on dolomite pavement and the small-scale forms which are found on it. Other topics considered in less detail include hydrogeology and hydrology, vegetation density on pavements, and water chemistry.

Various authors have noted the prevalence of flat dolomite and limestone pavements on the island (Liberty, 1969, Morton, 1977, Pearen, 1992 and others) but no attempts have been made to study these pavements and other karst forms in detail. Manitoulin Island was chosen as a study site because along with the Bruce Peninsula (studied by Cowell, 1976), it represents the most extensive occurrence of glacio-karstic features in southern Ontario. Because so much of the carbonate bedrock is exposed to the surface, it was believed that a great variety of karst forms would exist on the island.
Although it was expected that Manitoulin's geomorphology would be similar to that on the Bruce Peninsula, it merited independent study due to significant differences in geology,

Figure 1.1

Location of study site in Ontario (Hoffman and Wicklund, 1959).



glacial history, climate and land-use. With studies on the Door Peninsula in Wisconsin (Rosen et al., 1987) and many such studies in the British Isles, this research will form part of a database on glaciokarst landscapes across the world. It may aid in understanding of the morphology and the genesis of such landforms.

The most widely found and significant karst landform on Manitoulin Island is dolomite pavement. Pavement is defined as "a roughly horizontal exposure of limestone [or dolomite] bedrock the surface of which is approximately parallel to its bedding and is divided into a geometrical pattern of blocks by the intersections of widened fissures" (Williams 1966, in Paterson and Chambers 1982). Karren are the small-scale dissolution forms which develop on these pavements. The dominant forms are grikes (solutionally enlarged fissures following joint sets) and clints (isolated blocks created by intersection of joints). A variety of lesser karren forms develop on the clints. Pavements best develop on thick to massively bedded strata. Since eventually erosion degrades the pavement into rubble, they have greatest potential to develop where some stripping agent restores the surface. Many pavements are glacio-karstic in origin (Sweeting, 1973). On Manitoulin Island, during the Wisconsin period glaciation stripped away pre-existing soil or cover along with the top few bedrock beds. Therefore, the maximum age for karstification is set when Manitoulin emerged from Lake

Algonquin, between 11,000 to 9,000 B.P.. (later than for the Bruce Peninsula, set by Cowell (1976) at 11,000 - 13,000 B.P.). Following this glacial stripping action, the carbonate bedrock was exposed to intense solutional attack from precipitation and biological activity. Pavement can develop both under thin, preferably acidic, soils as well as on bare rock. Varying surface conditions result in development of different types of karren.

Most pavement research in the world has been on limestones, such as on the Carboniferous limestones in Britain (eg. County Clare, Eire). The only detailed studies of dolomite karren are of the Bruce Peninsula by Cowell (1976), the Door Peninsula (Rosen et al,, 1990) and some high latitude pavements in the Northwest Territories (Lundberg and Ford, 1994). However, since the solution processes acting on dolomites are the same as for limestones, the morphology is likely similar on both types of bedrock. The main difference would be the rate of solution, resulting in slower solution processes and more subdued forms on dolomites (White, 1988). Karren on dolomites preferentially develop in joints, bedding planes and other small lithologic features. Therefore, the most common type of karren is rock-controlled while other types are fewer in number. Since dolomites are less soluble than limestones, already present openings such as fractures may be preferentially enlarged, while forms resulting from surface flow take longer to develop (Ford and Williams, 1989).

Previous karst research in Ontario is reviewed by Cowell (1976). Important works include Pluhar and Ford (1970) on small scale karren forms and Ford and Quinlan (1973) on general karst classifications and occurrence of larger-scale forms. Most research focused on the Niagara Escarpment, since most of southern Ontario carbonates are impure with many shale interbeds, and are mantled by thick glacial sediment which greatly inhibits karst development. Although most of the Ontario carbonates are dolomites (which are less soluble than limestones), the Manitoulin Island and the Bruce Peninsula findings demonstrate that there is still potential for karst development given the right circumstances.

1.2 - Karstic Solution Processes

There are several important controls on the dissolution of carbonate rocks, both lithological and environmental. Differential erosion is common in the evolution of karst landforms because the erodability of a given rock varies under given erosion regimes (Trudgill, 1985). The main lithological controls are rock purity, grain size, texture, porosity, permeability, mechanical strength and mineral solubility. These are summarized in Table 1.1.. The two most common types of carbonate rocks are limestone ($CaCO_3$: mainly calcite, minor aragonite) and dolomite ($CaMg(CO_3)_2$), formed by replacing earlier calcium with magnesium.

Interacting with these lithological controls, the main environmental control on the solution process in most meteoric

Table 1.1
LITHOLOGIC CONTROLS ON KARSTIC SOLUTION PROCESSES

1) Mineral Solubility

- is congruent in karst, where all components of a rock disintegrate together into different molecules and components and then diffuse into solution.
- solubility of calcite and dolomite in pure, de-ionized waters with H^+ addition from water dissociation is very low (14 mg/l for calcite)
- at pH 7 calcite solubility is 100 mg/l and dolomite solubility is 90 mg/l at pCO_2 of 10^{-3} bar
- increases with increased pCO_2; is 500 mg/l for calcite and 480 mg/l for dolomite at pCO_2 of 10^{-2} bar

2) Rock purity

- best karstification if rock greater than 70 % pure $CaCO_3$
- solubility decreases as percent dolomite and insolubles (clay, silica) increase (little karst if 20 - 30 % impurities)

3) Grain size and texture

- as grain size decreases, exposed surface area for solution increases
- solubility decreases if all uniform, fine grains closely packed together (porcellaneous texture)
- solubility increases as heterogeneity increases roughness
- heterogeneity affects karren form and distribution

4) Porosity and Permeability

- primary bulk rock porosity influences permeability of erosive agents
- more important is secondary porosity : fissures and conduits, including penetrable bedding planes, and joints, which control access of erosive agents to bedrock, guide solution conduits, align major features
- best karst found if widely spaced joints and in medium to massively bedded bedrock (without clastic interbeds) since thin beds disperse solutional attack

5) Mechanical Strength

- determines if large scale features such as caves can develop
- most carbonate rocks are quite strong due to inter-particle bonding
- thin beds and high fissuring decreases strength

(Adapted from Ford and Williams, 1989)

waters is CO_2 availability. The general equations of carbonate dissolution illustrate these processes (Ford and Williams, 1989). CO_2 dissolution, hydration and dissociation produces carbonic acid to provide H^+ (although in some cases H_2S is important):

$$CO_2 \text{ (gas)} \rightarrow CO_2 \text{ (aq)} \tag{1}$$

$$CO_2 \text{ (aq)} + H_2O \rightarrow H_2CO_3 \tag{2}$$

$$H_2CO_3 \rightarrow H_+ + HCO_3^- \text{ (rapid dissociation)} \tag{3}$$

In karst groundwaters, the pH lies usually between 6.5 - 8.9, therefore HCO_3^- is the predominant species. Thus in general carbonate dissociation proceeds as :

$$CaCO_3 + CO_2 + H_2O \rightleftharpoons Ca^{2+} + 2\ HCO_3^- \tag{4}$$

$$CaMg(CO_3)_2 + 2\ CO_2 + 2\ H_2O \rightleftharpoons Ca^{2+} + Mg^{2+} + 4\ HCO_3^- \tag{5}$$

Depending on the acidity of the water, the reaction proceeds as Ca ions are balanced in relation to bicarbonate ions, while the acidity creates excess H^+ for hydrolysis of Ca^{2+}, therefore this enhances carbonate dissolution:

$$CaCO_3 + H^+ \rightleftharpoons Ca^{2+} + 2\ HCO_3^- \tag{6}$$

Organic acids and dissolution of CO_2 in water, creating H^+, are the main sources of acidity in the natural waters (Trudgill, 1985). In general, the solution of calcite depends on the equilibria of these ion species and is determined by their dissociation. These equilibria also depend on the contact and exchange between the gas (CO_2) and liquid (water) during calcite dissolution. In the open amount of HCO_3^- is limited by H^+ ion supply present. In a closed system, the gas and liquid phase are in contact as calcite dissolution proceeds, thus there is a constant supply of H_2CO_3 and CO_2 replenishment. In a closed system, no solid calcite is available when pure water reaches equilibria with CO_2, thus the reaction proceeds when there is no gas phase (Atkinson, 1977).

Temperature and pressure changes can affect these reactions. At pCO_2 = 0.03% calcite solubility increases from 55 mg/l at 25^0 C to 75 mg/l at 0^0 C. On introduction of CO_2 bubbles to groundwater under pressure, CO_2 solution concentration can increase at a rate of 6 mg/l per 100 m depth of water (at 25^0 C) to 400 m depth (Ford and Williams 1989).

Water flow rates dictate the supply of reactants to the mineral surface and the removal of weathering products, as well as determine the solid-solvent contact time (Trudgill, 1985). Flow rate is optimum when contact time is long enough to allow dissolution to proceed to a greater extent but flow should be rapid enough to remove the weathering products. Factors such as slope angle, texture of surface sediments and vegetation can slow flow therefore enhance dissolution. Also, in porous media such as soils, flow is slower, allowing for enhanced dissolution if soils are not thick enough to deplete water of its solution capability. Through soils, organic matter may enhance Ca^{2+} leaching while litter also increases water acidity. The role of soils and vegetation on carbonate dissolution will be examined in greater detail in Chapter Six.

1.3 - Methodology

The field work for this research was performed in three time periods. In early May, 1993, on a reconnaissance trip the extent of karst occurrence on Manitoulin Island was determined and some potential sites for detailed study were identified. The study area was narrowed to exclude the Wikwemikong Peninsula. The Peninsula was excluded due to problems of access; much of it is very isolated with few roads, and there are problems involved with obtaining permission to do field work in an Indian Reserve. A few water samples and observations are the only data presented for this portion of the island. In June and July 1993, the majority of the research was performed: classifying pavement areas, characterizing drainage areas, sampling alvar sites and collecting water samples for data Set 1. At this time, Set 1 samples were analyzed for calcium and magnesium hardness along with measurement of conductivity. In early May, 1994, the final field data were collected: on additional pavement and alvar sites and water samples for Set 2 were measured for conductivity and temperature only.

The study of the karst features on Manitoulin Island were undertaken at two scales of generality:

1) The full extent of karst on the island was examined by reconnaissance. The study emphasized comparison of karst features on the two major scarps of the island: the scarp formed by the Manitoulin and Kagawong formations along the

north coast and the Niagara Escarpment capped by the Mindemoya, Amabel and Fossil Hill formations in the central region of the island. It was found in the reconnaissance that karst landforms were limited to the above formations only, plus some small karst springs on the Lindsay.

2) Detailed North-South transects were taken across the scarps (on different geologic structures) for selected areas with well developed dolomite pavement. These cover the east-west extent of Manitoulin, from Little Current to Meldrum Bay.

The following characteristics were used to describe and classify distribution and morphology of the karst pavement:

<u>A) Micro - karst</u>

Dolomite pavement may be characterized according to jointing which is the most important guide of linear dissolution, and by its lesser karren features. Since the main forms are clints and grikes which are found on nearly all sites, primarily they were used to classify pavements. Transects were taken at a number of sites, which were of variable length according to the size and extent of pavement at each site, between 10 to 25 m. At each transect the following were measured :

1. joint orientation, by compass (referenced to magnetic north in the text).

2. joint width at top of the grike . Often this was variable but it was attempted to measure the average.

3. joint depth at point of width measurement. This was often

difficult because many joints were filled with debris, soil and decaying vegetation. It was attempted to measure maximum depth.

4. joint length. This was extremely variable and often reflected the confluence of several joints, or was interrupted by vegetation growth.

5. additional descriptive characteristics of clint and grike formations were noted such as roughness, amount of debris, etc.

6. The occurrence of other types of karren were noted, where they were found (on slopes or flat plains), extent of their coverage (complete to little coverage on pavement), also details of their form (scale, whether sharp or smooth).

In the field it was also noted whether the pavement occurred on flat plains, scarps or whalebacks to further distinguish them. The areal extent of pavement was noted in the field (a rough estimate), as well as calculated from 1:20,000 scale air photos.

B) Hydraulic Gradient

At each site mean elevation a.s.l. was noted in order that the hydraulic gradient could be calculated. This was using the local elevation difference (between the scarp top and above the blocker beds of the Cabot Head Shales).

C) Glacial features

Their occurrence was noted. These included whalebacks and drumlins, striae and the Lake Nipissing shoreline, and their relation to the karst features was noted.

D) Lithology

Samples of the major formations exhibiting karst features were collected at several sites across the island. They were analyzed for the amount of insoluble residue, etc. Thickness of bedding in the field was noted since it influences karst potential.

E) Coastal Pitting

This research surveyed littoral zone pitting at the Lake Nipissing shoreline. It was found only on the Amabel Formation. Although it was common along much of the southern shore, at the three best sites counts of pits per 1m^2 of grid were taken to determine pit density, and pit width and depth were measured. The three sites were found on : whalebacks (South Baymouth), tilted blocks (Providence Bay) and flat to stepped plains (Meldrum Bay). Pits were also recorded far inland (Misery Bay), approximately 1 km from the present lake level.

This research is also the first attempt to use a Geographic Information (GIS) for analysis in a regional karst study. GIS was deemed to be a useful tool for such a study since karst development is influenced by a number of factors which act in combination and can be represented in map form, and thus input into a GIS. The GIS analysis yielded interesting results about Manitoulin Island karst and may give direction to future use in regional karst studies.

Prior to presenting the findings of this study, a review of the physiography, Palaeozoic and Quaternary geology is presented as a background to understanding the main influences on the karstification of Manitoulin Island. Then the major focus of this research, dolomite pavement, is presented in Chapter 3. Findings on the hydrology and hydrogeology are reviewed in Chapter 4. The water chemistry analysis is presented in Chapter 5. Chapter 6 summarizes the research on alvar vegetation on the island, while Chapter 7 reviews GIS methods and analysis, although results are used to support findings in the field throughout the paper.

CHAPTER II - BACKGROUND OF MANITOULIN ISLAND

2.1 - General Physiography and Climate

Geologically, Manitoulin Island is part of the Niagara cuesta and is aligned with the Bruce Peninsula, Cockburn, Drummond and St. Joseph's Islands and the Door Peninsula of Wisconsin. In size it is 110 kilometres (76 miles) long and ranges from five to 50 kilometres (three to 30 miles) wide. The general physiography follows the strike of carbonate bedrock scarplands that dip very gently southwards (overall dip of the bedrock is less than 5 degrees). The bedrock was scoured by Quaternary glaciation and is widely exposed at the surface, since most sediments were removed by post-glacial wave action (Ontario Geological Survey, 1984).

The most striking feature of Manitoulin is its double escarpment, a continuation of southern Ontario's Niagara Escarpment. One is situated on the north shore and forms steep cliffs above the North Channel (approximately 150 metres above lake level), while the second inland scarp forms bluffs around a series of large inland lakes (typically 245 - 275 metres a.s.l.). These scarps have been shaped by glaciation. Ice from the north and northeast breached the east-west trending cuestas, dividing them into narrow promontories (almost mesas or buttes in some cases), separated by deep re-entrants that became a series of bays and lakes. The highest point on the island is over 335 metres a.s.l.(at the Cup and Saucer), with the level of Lake Huron located at 176.8 metres (580 ft) a.s.l. Locally, relief is affected by the presence of biohermal units of the carbonate bedrock which often forms small scarps, along with ice-formed features such as whalebacks and rock drumlins.

There are 108 inland lakes on Manitoulin Island, covering one-third of the surface area. The largest are lakes Manitou, Mindemoya and Kagawong (covering 200 square kilometres). These lakes, along with Lake Wolsey and Bayfield Sound, are oriented in the direction of ice-scour. The scarp promontories which contain these lakes control their direction of outflow drainage as well. Lakes Manitou and Mindemoya drain to the south through scarp breaches but Lake Kagawong's drainage is blocked by the scarp and overspills to the north.

There are few larger rivers, the major ones draining the larger lakes such as Blue Jay Creek, Mindemoya and Manitou Rivers in the south and toward the north those at Kagawong and Sheguindah. Most creeks that cross the northern scarp form waterfalls there. Although there are lakes and surface rivers, there is a pronounced lack of surface drainage in many areas, especially to the south and west. This is due to karstic drainage which has developed on the exposed dolomite plains. In these areas there are a number of smaller lakes which drain internally. The dominant geomorphic landform on Manitoulin Island is karst pavement. Groundwater drainage has outlets in the form of numerous springs, many emerging at or near lake level around the entire island. Marshes are present in several areas, usually flat regions with impermeable bedrock or soils. Overall, the geomorphology of the island is complex, a result of influences of geology (Palaeozoic and Quaternary) and karstic processes.

The climate of the island features cold snowy, winters with mean temperatures of - 11^0 C (17^0 F) and warm summers with mean temperatures of 18^0 C (62^0 F). The extremes range from - 41^0 C (- 41^0 F) to 38^0 C (100^0 F). There are on average 125 to 129 frost-free days, with the average season extending from May 26 to the end of September although frost is possible in any month. Spring is late, the growing season lasting between 178 to 186 days, from April 24 to October 21. Precipitation patterns are characterized by a winter maximum and a summer minimum, resulting in quite a high frequency of summer droughts. The average annual precipitation is 789 mm (31.57 inches), with the amount snowfall on average 250 mm (10 inches) water equivalent (Hoffman et al., 1959).

2.2 - Palaeozoic Geology

2.2.1 - Introduction

The Palaeozoic geology is one of the strongest controls of karst development on Manitoulin Island. The bedrock is almost entirely composed of carbonate sedimentary rocks (limestones and dolomites), and shales, with varying carbonate content, from the mid Ordovician and mid Silurian periods. These uncomformably overlie Precambrian Shield granites and quartzites. The sedimentary rocks were deposited on the northeast fringes of the Michigan basin 500 million years ago when it was covered by subtropical seas. Manitoulin Island was at this time 10^0 to 20^0 south of the paleoequator with the Precambrian continental landmass to the north (Figure 2.1). The strata overall strike east - west and dip southwest into the Michigan basin at 7m/km (35 ft/mile) . They can be correlated with strata in northern and central Ontario, Michigan and Wisconsin and New York State.

The Niagara Escarpment is the most prominent feature on the island, to the north capped by the Silurian Manitoulin and Kagawong Formations (Figure 2.2), while the cuesta to the south is capped by Amabel, Fossil Hill and Mindemoya Formations (Figure 2.3). The stratigraphy of the island is complicated by numerous revisions concerning nomenclature in the past 50 years. This review will follow that of Liberty and Bolton (1969) which was used in the GIS analysis as the source for the geology maps. Revisions from Liberty (1968) and Sandford (1978) are used to simplify this classification for the purposes of this thesis. In later discussion, the term "formation" will be used for individual units, although they may be submembers of a group. Figure 2.4 shows the geology of the whole island, while Figure 2.5 gives the vertical

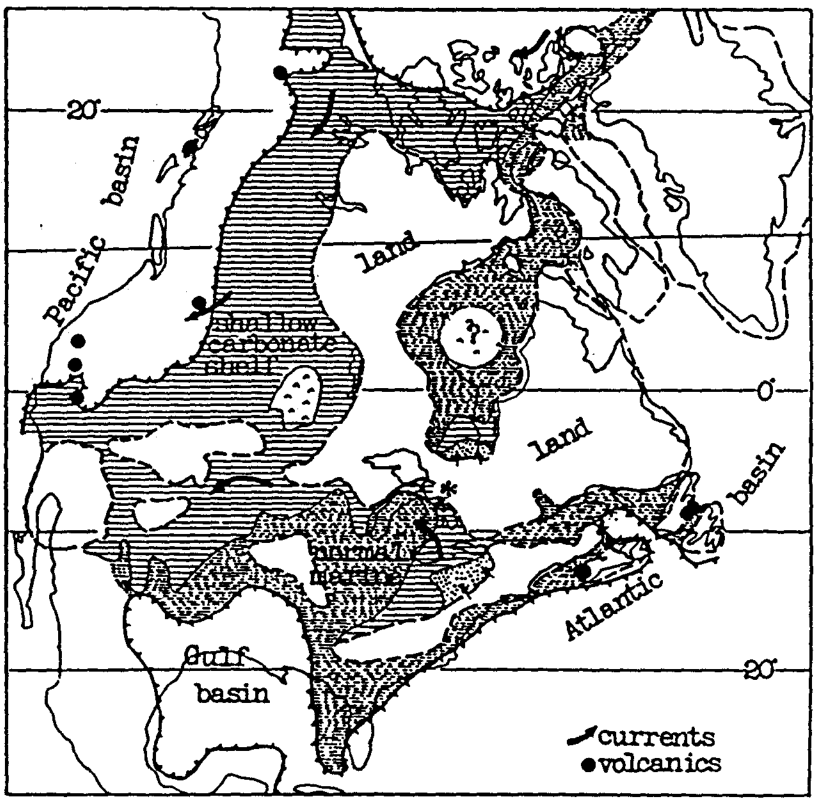


Figure 2.1

Paleogeography of North America in the late Ordovician, showing approximate position of landmass (Manitoulin Island at *).
Copper, 1978).

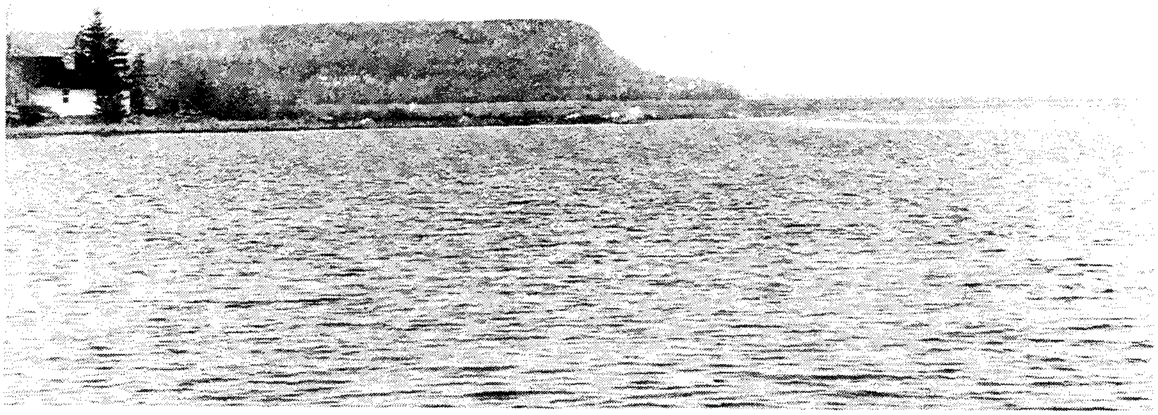


Figure 2.2 View of northern scarp on the North Channel, west of Lake Wolsey.

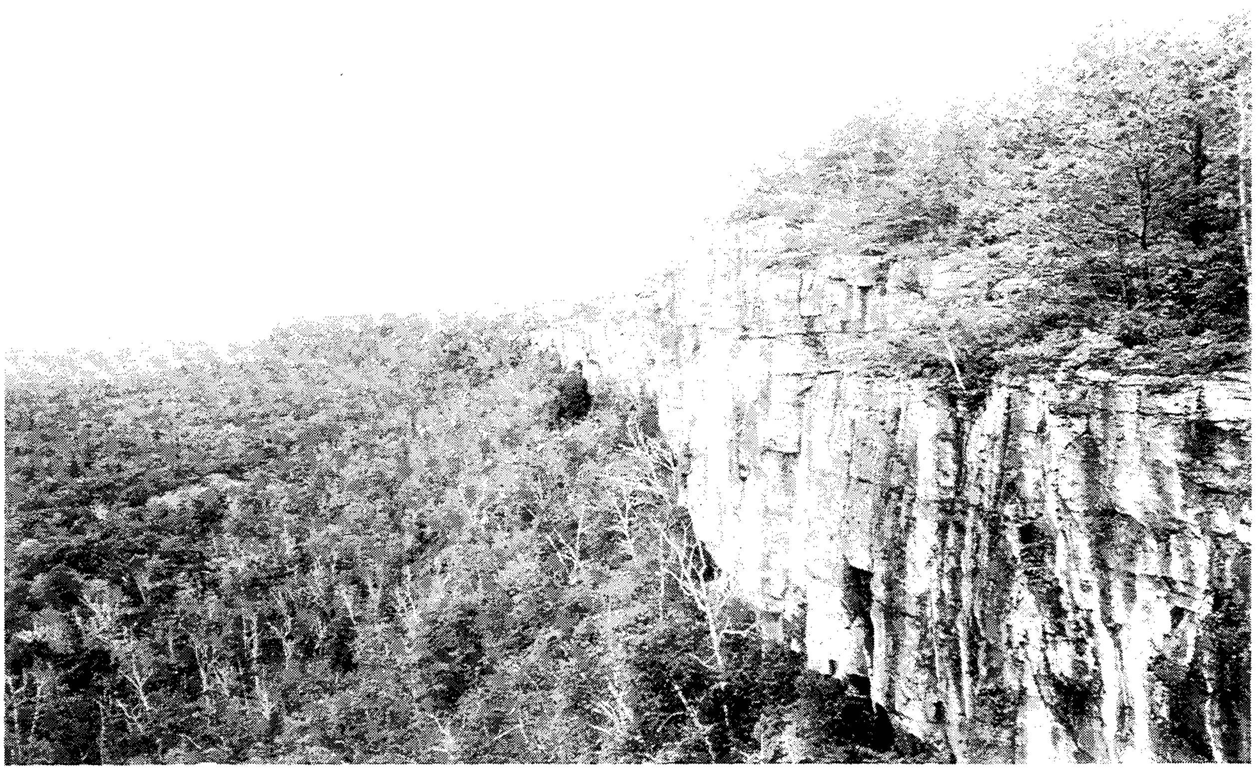


Figure 2.3 The Niagara Escarpment at the "Cup and Saucer", the highest point on Manitoulin Island.

Figure 2.5

Vertical stratigraphy on Manitoulin Island (adapted from Liberty (1968) and Sandford (1978)).

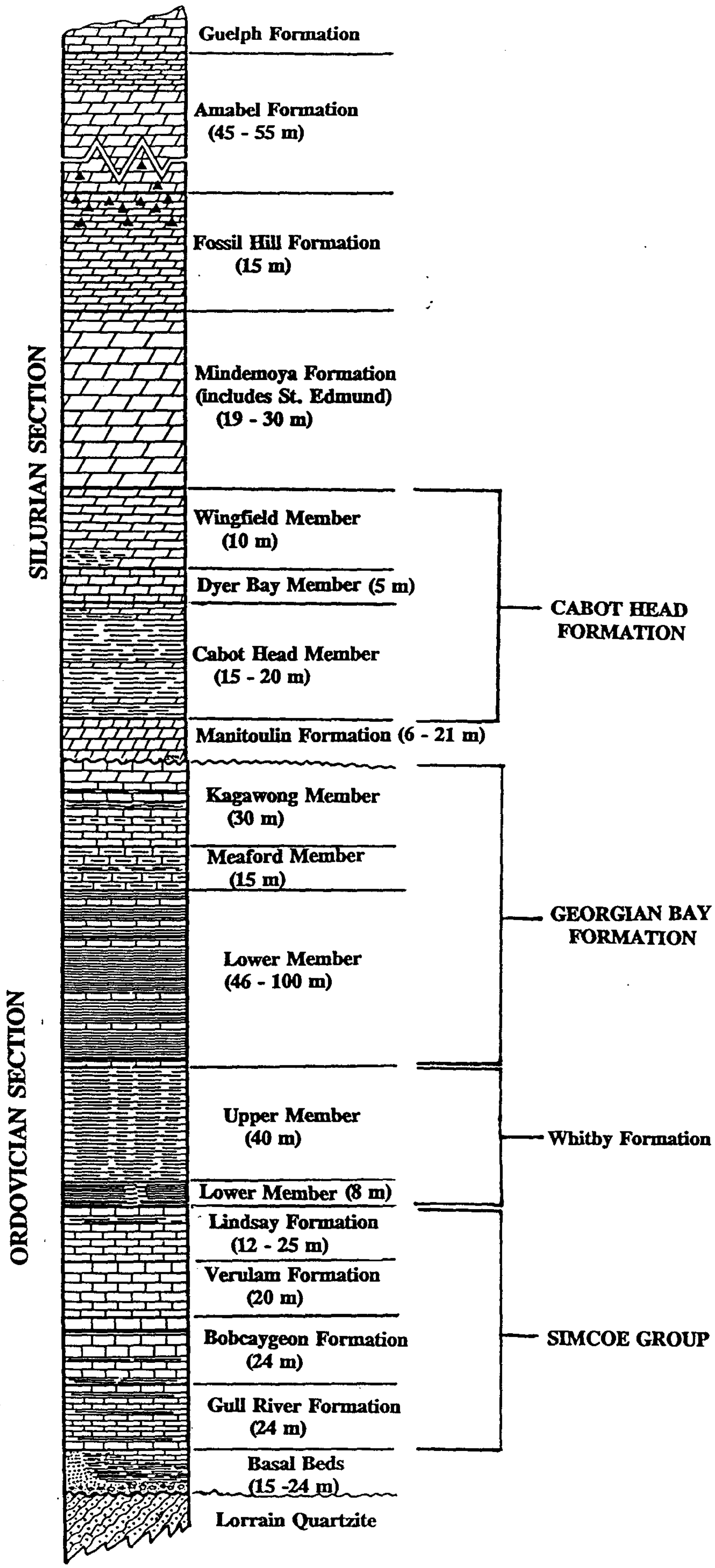


Figure 2.4a : The Geology of Manitoulin Island

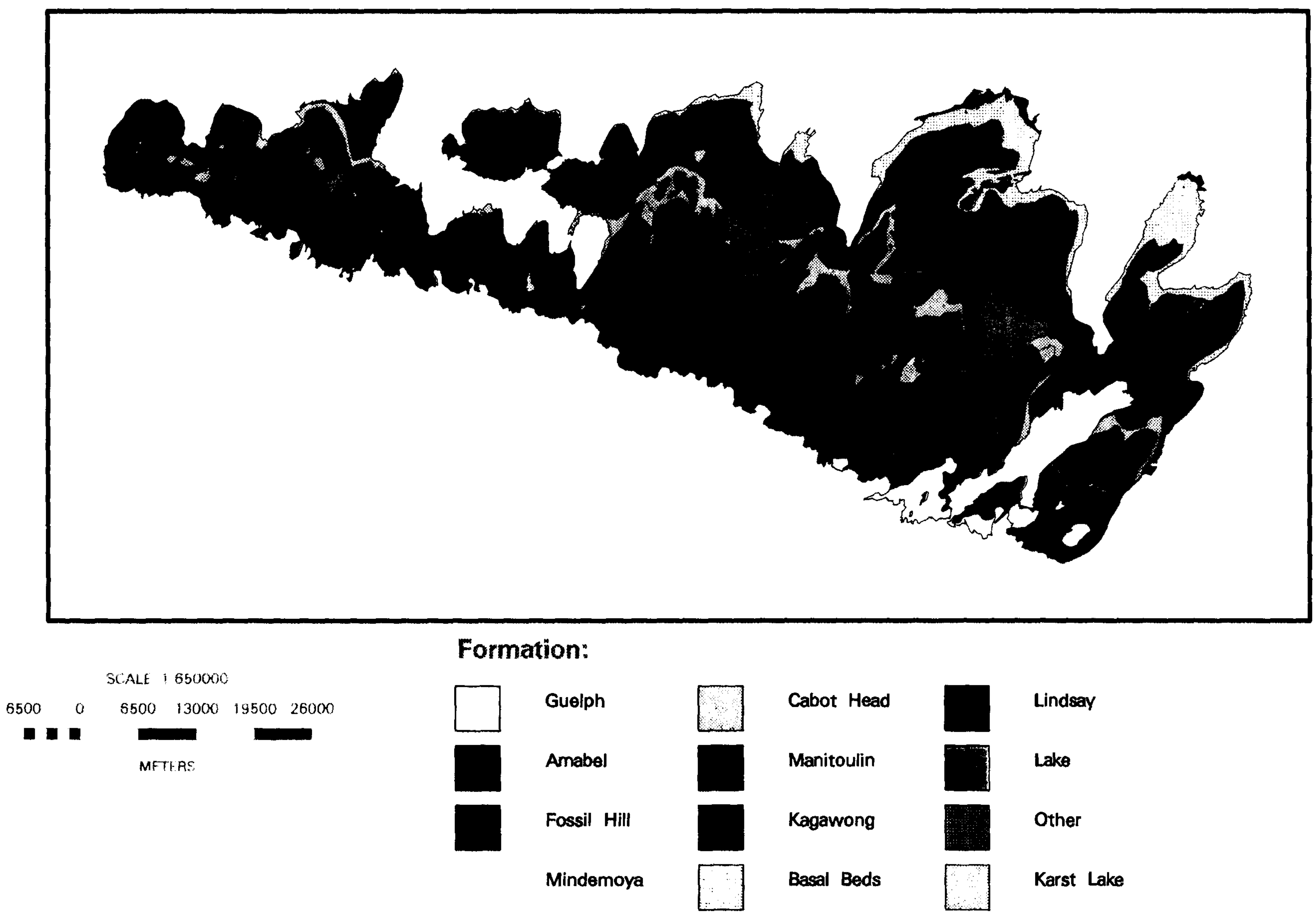


Figure 2.4: The Geology of Manitoulin Island

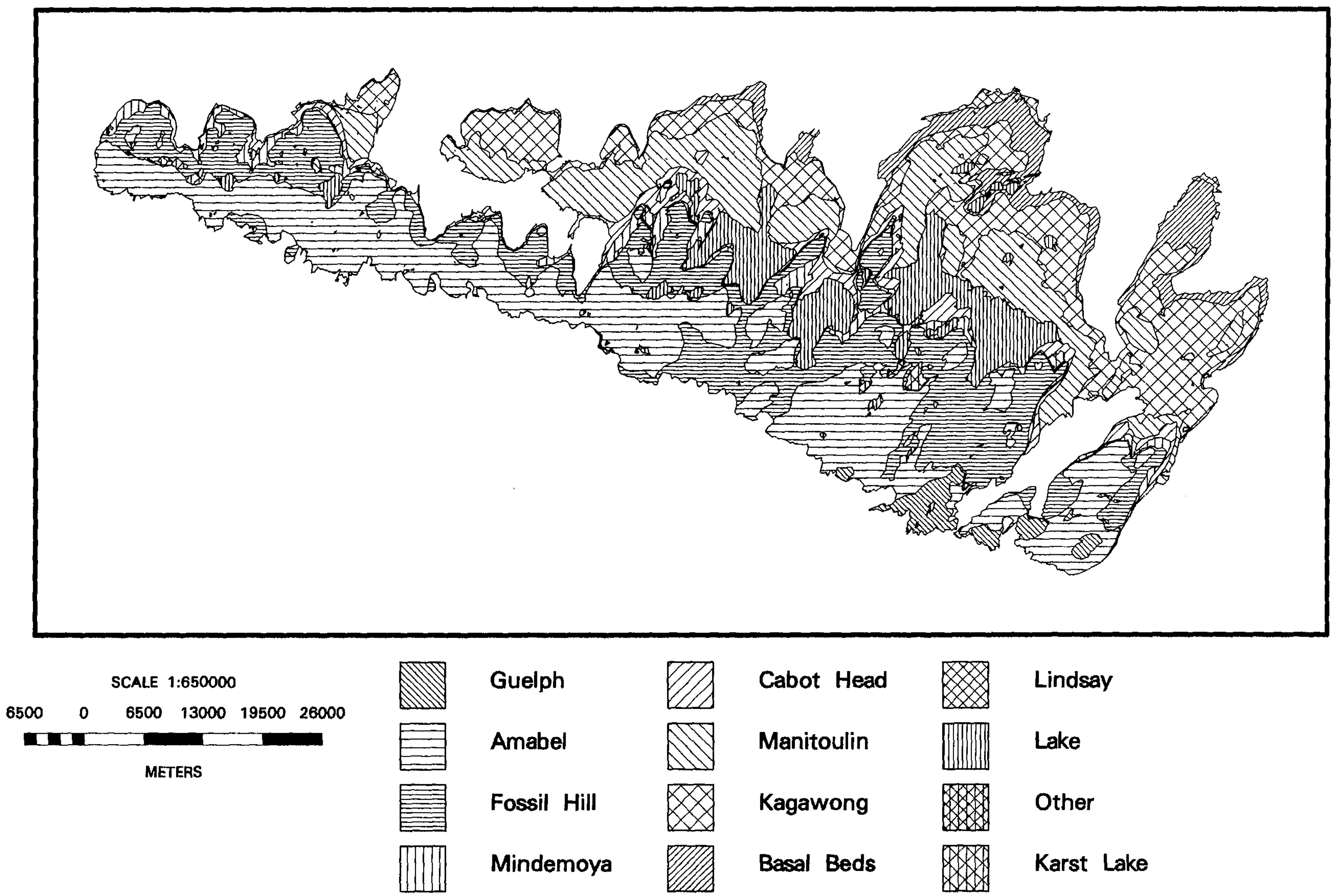
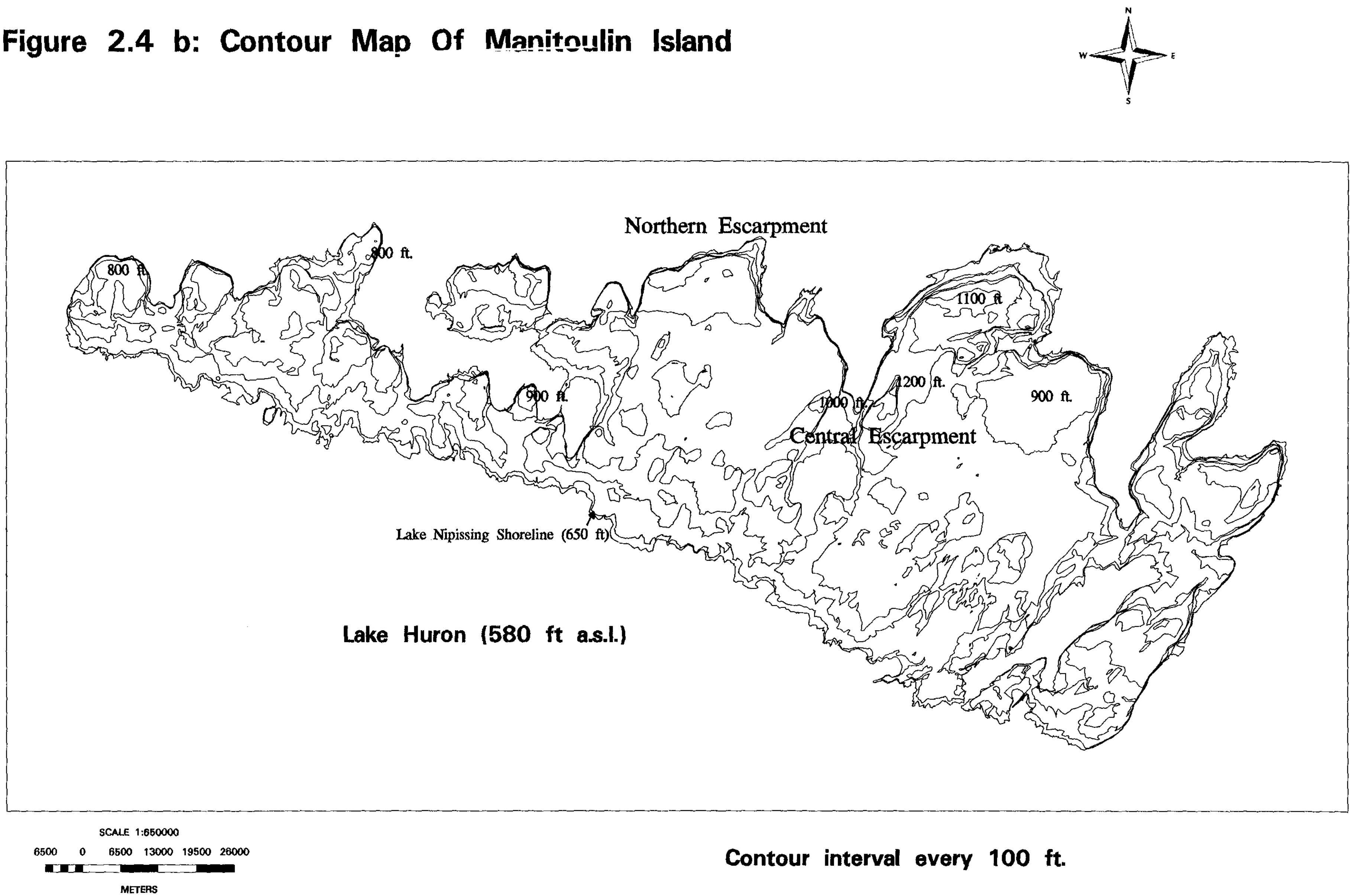


Figure 2.4 b: Contour Map Of Manitoulin Island



Contour interval every 100 ft.

stratigraphy.

2.2.2 -Stratigraphy

ORDOVICIAN STRATA

Basal beds -

These are red and green mottled shales and sandstones which outcrop only north of Manitoulin Island, with a maximum thickness of 15.2 - 24.4 metres (50 - 80 ft). They are situated on top of an unconformity above the Lorrain Quartzite.

Simcoe Group -

This includes the Gull River (Swift Current), Bobcaygeon (Cloche Island), Verulam and Lindsay submembers and is maximum 117.4 metres (385 ft) thick. Only the Lindsay submember outcrops on Manitoulin Island, in the Little Current area. These units are carbonate, being mostly grey, lithographic and sub-lithographic, very finely crystalline limestone. At some locations the units are brown, finely crystalline and dolomitized. The Verulam is composed of alternating limestone and thin shale partings. These first three members are mapped as the Verulam in the GIS work. The Lindsay formation (Cobourg Beds) is 12 to 25.6 metres (40 - 85 ft) thick and composed of grey, finely crystalline, argillaceous limestone and grey sublithographic limestone with minor, finely crystalline dolomite. In some areas there are shaley interbeds. Dolomites in the Sheguindah area host some oil. In the Michigan Basin, these are associated with dolomitization following fracturing (known as tectonic dolomitization).

Whitby Formation (Collingwood Beds)-

This formation consists of dark grey fissile shales above the Simcoe Group and below the Georgian Bay Formation, approximately 39.6 metres (130 ft) in thickness. The members are petroliferous and may be the source beds for oil reservoirs in underlying formations. The lower member is 7.6 m (25 ft) thick, while Sandford (1978) includes the Sheguindah beds as the upper member. This member is up to 39.6 m (130 ft) of grey fissile shales, and is grouped as part of the Georgian Bay Formation by Liberty (1968).

Georgian Bay Formation-

This includes the Ordovician strata below the Manitoulin Formation. Its upper member is the equivalent of the Queenston facies in Southern Ontario. The lower submember (Wekwemikongsing Beds) consists of a 45.7 to 100.6 metre (150 to 330 ft) thick sequence of shale (blue, grey clay shale, 0.9 - 3.7 metres (3 - 12 ft) thick) alternating with hardband alterations (dominantly limestone with some dolomite, three to nine centimetres (0.1 - 0.3) ft thick, varying finely crystalline to finely cacarenitic in texture). In GIS this submember is mapped with the Whitby as shaley, non-karstic bedrock. The upper-lower submember is the Meaford Formation, 15.3 metres (50 ft) of grey-brown, finely crystalline, argillaceous limestone with thin shale beds of six to nine centimetres (0.2 - 0.3 ft). The Upper-upper submember is the

Kagawong Formation (Figure 2.6). This formation is 30.5 metres (100 ft) thick and is composed of fossiliferous, brown, mottled, finely and very finely crystalline limestone and grey sublithographic limestone, with the dolomite form present on the Wikwemikong Reserve and biostromes found in Mudge Bay and Maple Point.

SILURIAN STRATA

Manitoulin Formation -

This formation is composed of weathered grey, brown and bluish grey finely to medio - crystalline dolomite, with some dolomitic limestone present as well. There are both bedded and non-bedded deposits. The non-bedded are biohermal or patch reefs, and are of algal origin with silicified fossils including *Palaeophyllum* species. These occur in several locations, reaching a maximum of 21.3 metres (70 ft) thickness, with both vertical and horizontal bedding (Figure 2.7). The bedded deposits are maximum 6.1 metres (20 ft) thick ("normal" Manitoulin) and formerly were the reef platform with only a few fossils. The Manitoulin and the underlying Kagawong formations are separated by an unconformity although sedimentation is believed to have been continuous at this time (Liberty, 1968).

The best example of a Manitoulin bioherm is at a roadcut on Highway 6 four kilometres south of Manitowaning which was studied extensively by Grawbarger (1978). This crescentic shaped bioherm is approximately 3.8 km (2.38 miles) long, 200

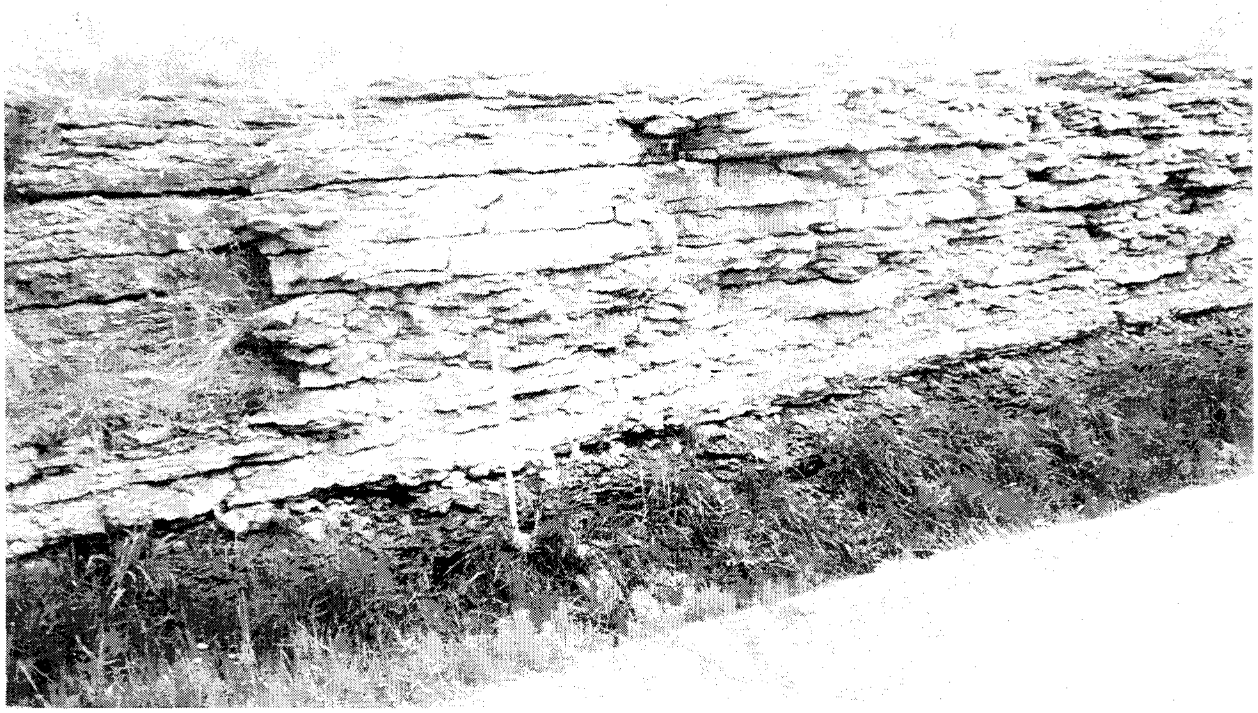


Figure 2.6 Kagawong Formation outcrop at roadcut south of Sheguindah, showing thin bedding with frequent shale interbeds.

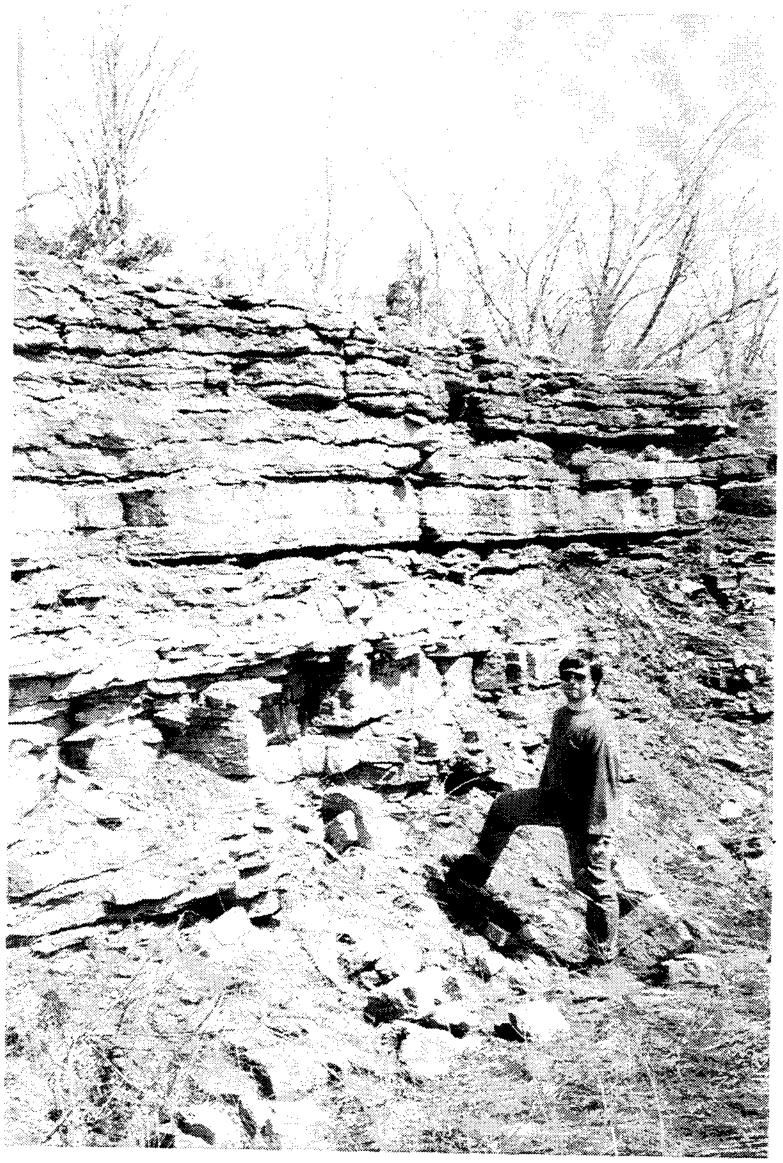


Figure 2.7 Outcrop of normal bedded Manitoulin Formation at Maple Point.

- 300 m (656 - 984 ft) wide, 5 m (16.4 ft) thick and passes into the stratified Manitoulin sediments below (Figure 2.8). Flanking beds of fore and back reef sediments dip away 5 to 10 towards the south and north for 3 - 4.5 metres (9.8 - 14.8 ft). There are a number of sharp unconformities within the bioherm which suggest the carbonates were dissolved in past cycles of emergence, aeration and karstification of the bioherm which would have been an intertidal terrace. From the unconformities four phases have been recognized which represent minor episodes of marine regression where the reef progressed from a quiet water environment to shallower, higher energy environment above the wave base. This is also suggested by a decrease in faunal abundance in the oldest portions of the bioherm.

Cabot Head Formation -

Liberty divided this formation between the Manitoulin and Fossil Hill into 4 sub-members : the Cabot Head shales and the Dyer Bay, Wingfield, St. Edmund members (all crystalline dolomites with shales). These units are overall 33.5 metres (110 ft thick) and were mapped as one in the GIS work to represent shaley, non - karstic bedrock.

The Cabot Head lower submember is restricted on Manitoulin Island, outcropping infrequently. It is at maximum 19.8 metres (65 ft) thick and consists of soft red and green clay shale with thin sublithographic dolomite beds and gypsum. This represents an intertidal environment or shallow marine

Figure 2.8 Manitoulin bioherm, exposed at a roadcut on Highway 6 south of Manitowaning.

environment with both shoreward and intertidal facies (Grawbarger, 1978).

The Dyer Bay Member consists of 4.6 metres (15 ft) of thin bedded blue-grey, brown-grey, mottled, finely crystalline dolomite and digitate dolomite. Chert nodules and silicified fossil are common.

The Wingfield Member is 9.8 metres (32 ft) of ribbon dolomite, thin beds (six centimetres or 0.2 ft) of green-grey, grey very finely crystalline to sublithographic dolomite with thin interbedded seams of green shale

The St. Edmund Member is made up of 2.4 metres (8 ft) of massive, mottled brown, greyish-brown medio - lithographic crystalline dolomite overlain by 1.2 metres (4 ft) of soft grey shale (the latter not present on Manitoulin). The Mindemoya and St. Edmund were classified by Sandford (1978) as the St. Edmund for the unit below the Fossil Hill.

Mindemoya Formation -

This formation, widespread on Manitoulin, is distinguishable into two members, in total varying from 18.3 to 30.5 metres (60 - 100 ft) in thickness from the east to the west end of the island. The lower member is a thinly bedded, thinly laminated, tan-grey lithographic and sublithographic porcellaneous dolomite. The upper member consists of thin and thick massive beds of grey-brown sublithographic, finely crystalline dolomite with 0.6 to 0.9 metre (2 -3 ft) thick biostromes of brown, finely crystalline dolomite. The lower contact between the Mindemoya and St. Edmund and the upper contact with the Fossil Hill is distinct.

Fossil Hill Formation-

This formation is made up of thin and thick irregular bedded dark grey weathered fine to medium crystalline dolomite, both biohermal and non-biohermal (Figure 2.9). The lowest 6.1 metres (20 ft) is very fossiliferous and massive, non-bedded but with horizontal jointing. Above this lies the biohermal section, 9.2 to 35 metres (30 - 115 ft) thick with bioherms, flank strata, interbiohermal facies (thin beds , very fossiliferous and cherty). Some beds, especially in the west are very cherty, with tabulate corals and brachiopods (pentamerids) frequently found. These were silicified through reorganization of biochemically deposited silica which was precipitated in a fine state, then re-precipitated after resolution (chert and fossil silification in diagenesis following dolomitization).

Amabel Formation -

The Amabel is a reefal complex and can be divided into four lithic units which are not related to Bolton's on the Bruce Peninsula. This formation outcrops over most of southern and western Manitoulin as well as outcropping on top of scarps in the centre of the island (Figure 2.10). The Amabel in thickness ranges from 45.7 to 54.9 metres (150 to 180 ft) where there are bioherms to 15.2 metres (50 ft) in flank areas. The lower unit, A, comprises transitional strata from

Figure 2.9 Fossil Hill Formation at typesite north of South Baymouth. Shows very thin bedding and fossil rich beds.

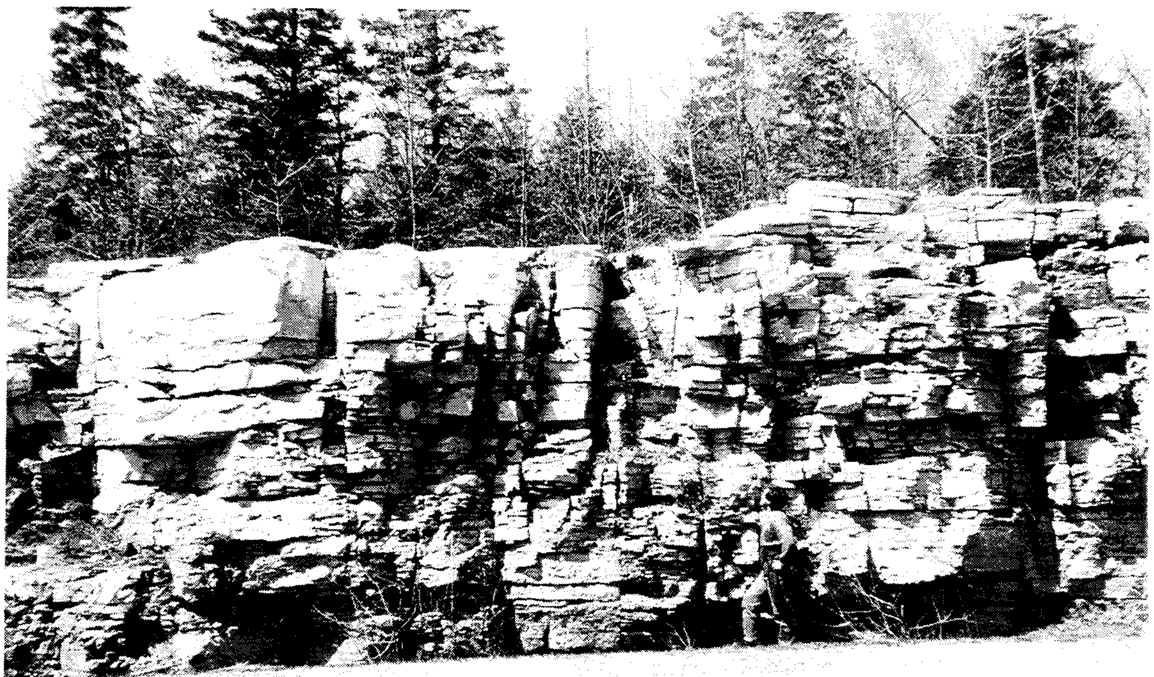


Figure 2.10 Amabel Formation outcrop north of South Baymouth. Shows very massive bedding and deep grikes.

the Fossil Hill (few centimetres to few metres thick) and is composed of grey - white, evenly textured finely crystalline dolomite. Unit B consists of 9.2 to 27.4 metres (30 to 90 ft) of biohermal and biostromal deposits with occasional Fossil Hill interbeds. This outcrops south of Lake Mindemoya and in "The Slash" area. This grey-white, bluish mottled (streaky), fine to very fine crystalline dolomite is equivalent to the Wiarton and Colpoy Bay units on the Bruce Peninsula. They are massively bedded with horizontal jointing, but with few vugs or porous zones and in the past were known as the Eramosa Formation. Unit C consists of knoll - interknoll facies of smaller bioherms, of grey-green, sublithographic finely crystalline dolomite, 12.2 metres (40 ft) thick, visible in the Providence Bay to South Bay area. Unit D is rarely seen due to the present erosional surface. It is the reefal equivalent of the Eramosa on the Bruce Peninsula and is greater than 12.2 metres (40 ft thick). It consists of flanking bedded deposits six to 15 centimetres (0.2 to 0.5 ft) thick.

Sandford (1978) divided the Amabel into pre- Eramosa (light grey, medio - crystalline to fine dolomite), Eramosa (light tan, finely to fine - medio crystalline dolomite) and post - Eramosa (light grey, fine -medium crystalline and vuggy dolomite).

Guelph Formation -

On Manitoulin Island this formation is only visible near

South Baymouth and on the southern Wikwemikong Reserve. The strata are bedded on Manitoulin, not reefal as on the Bruce Peninsula. They are fine, evenly textured, finely crystalline dolomite with beds three to 24 centimetres (0.1 to 0.8 ft) thick, which weathers brown and scraggy. Sandford disputes the presence of the Guelph on Manitoulin, classifying it as part of the upper Amabel.

2.2.3 - Sedimentary Environments

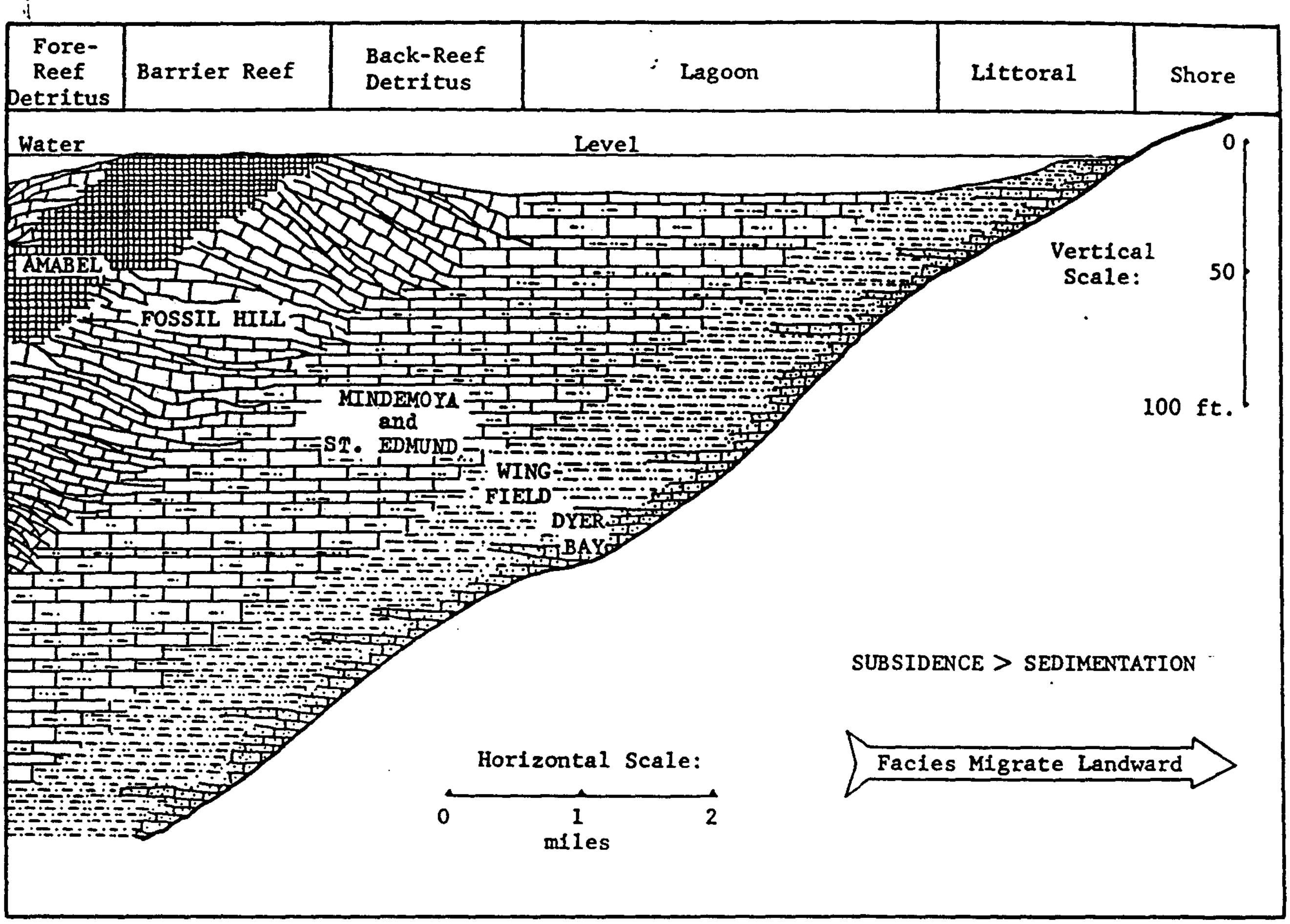
The Silurian period only lasted 30 million years, much shorter than the 70 million year duration of the Ordovician, but the Silurian sediments are very important in the Michigan Basin. It is assumed that the Niagaran phase of the Silurian represents a single sedimentary series which displays several facies superimposed on top of one another as marine transgression occurred over this time period. The units above the Cabot Head shales are interpreted as part of one large transgressing littoral-lagoonal-reefal association where the rate of subsidence was greater than the rate of sedimentation, with each formation representing a particular sedimentary or faunal province (Sheldon, 1968). The mid-Silurian sediments on Manitoulin are located on the edge of the intercratonic Michigan Basin, and are part of an off-shore reefal complex (Figure 2.11), as follows:

1. littoral zone - characterized by active sedimentation and moderate to gentle surf.

2. lagoon - with a quiet bottom involving carbonate and

Figure 2.11

The hypothesized sedimentary environment of Niagaran carbonates on Manitoulin Island (Sheldon 1968). Proposed genesis from a transgressing barrier - reef - lagoon - littoral association.



argillaceous mud accumulation.

3. back - reef detrital zone - with high energy sedimentation, coarse detritus and sand deposition.

4. reef-core - featuring carbonate secreting algae partly exposed at low tide.

5. fore-reefal detrital zone - which is similar to the third lithotope with some patch reefs.

The Dyer Bay Formation was part of the littoral zone, while the Wingfield was part of a clastic lagoonal environment when there was a seaward progression from beach sediments to lagoonal muds. The St. Edmund and Mindemoya represent carbonate lagoon facies with dominant lithotopes of carbonate mud (representing more shoreward parts in the lower member) and calcareous sand lithotopes reflecting a situation closer to the reefal platform in the upper Mindemoya. This represents a progression from a littoral sedimentary environment (Dyer Bay) to a quiet bottom (Wingfield) to a near-reef lagoon (Mindemoya). Manitoulin Island may lie at the extreme east end of a marginal complex, observed from tracing sediments into Michigan and Wisconsin, thickening to the west and thinning out to the south on the Bruce Peninsula. However the Niagara Escarpment in the Bruce Peninsula may transect a more developed marginal complex. The areal extent of this marginal complex is in question, since it is not known what sediments lie under the Great Lakes.

The reefal phase of this marginal complex is represented by the Fossil Hill and Amabel formations. The Fossil Hill represents back-reef detritus as well as fore-reef detrital beds while the Amabel represents the reef-core carbonates, massive in southern Manitoulin. The Amabel is among the purest of Niagaran rocks, consisting of algal-stromatoporoidal accumulations. There are some knolls and intermound facies in the South Bay area. These facies are not continuous since the organic reefs have been dissolved by deeper water passes between the lagoon and ocean. These are the major river passes on southern Manitoulin and are filled with cherty material.

Overall, an equatorial climate with prevailing shallow conditions is suggested for the mid-Ordovician to late-Silurian times. This is from the presence of dominantly carbonate sediments with red beds (representing rich calcareous algal flora) as well as corals , sponges and biohermal and biostromal deposits. The growth and proliferation of these benthic communities was interrupted on occasion as indicated by some deeper water phases (Collingwood and Sheguindah beds) and periods with rapid influxes of mud in shallower water (Shadow Lake and Cabot Head shales) (Copper, 1978).

2.3 - Quaternary Geology

2.3.1 - Quaternary Deposits

The Quaternary deposits on Manitoulin Island are of glacial origin from the Wisconsin period. The last major glacier advanced towards the southwest from eastern

Manitoulin, as interpreted from bedrock striae and flutings as well as from drumlin orientations. However at the Sheguindah quartzite there was local westward ice flow and on the north shore there were two coalescing ice lobes, one flowing south from northern Ontario, the other flowing southwest from Quebec (Lewis, 1970). Only a small portion of Manitoulin Island is now covered with glacial sediments, because the dolomite and limestone bedrock uplands were washed free by the action of the post-glacial lakes (especially Lake Algonquin). Some of this sediment was deposited in the lowland depressions and valleys.

The bedrock outcrops on rock drumlins, whalebacks and roche moutonees, show evidence of glacial erosion with gouges and flutes running 20^0 - 40^0 west of south (200^0 - 220^0 azimuth) (Figure 2.12). Striae are well preserved where they were covered by soil, most pointing 40^0 west of south (220^0 azimuth, similar to the Bruce Peninsula), on western Manitoulin pointing 15^0 - 20^0 west of south and pointing 60^0 east of south on Barrie Island (120^0), indicating an earlier set of striae (Ontario Geologic Survey, 1984).

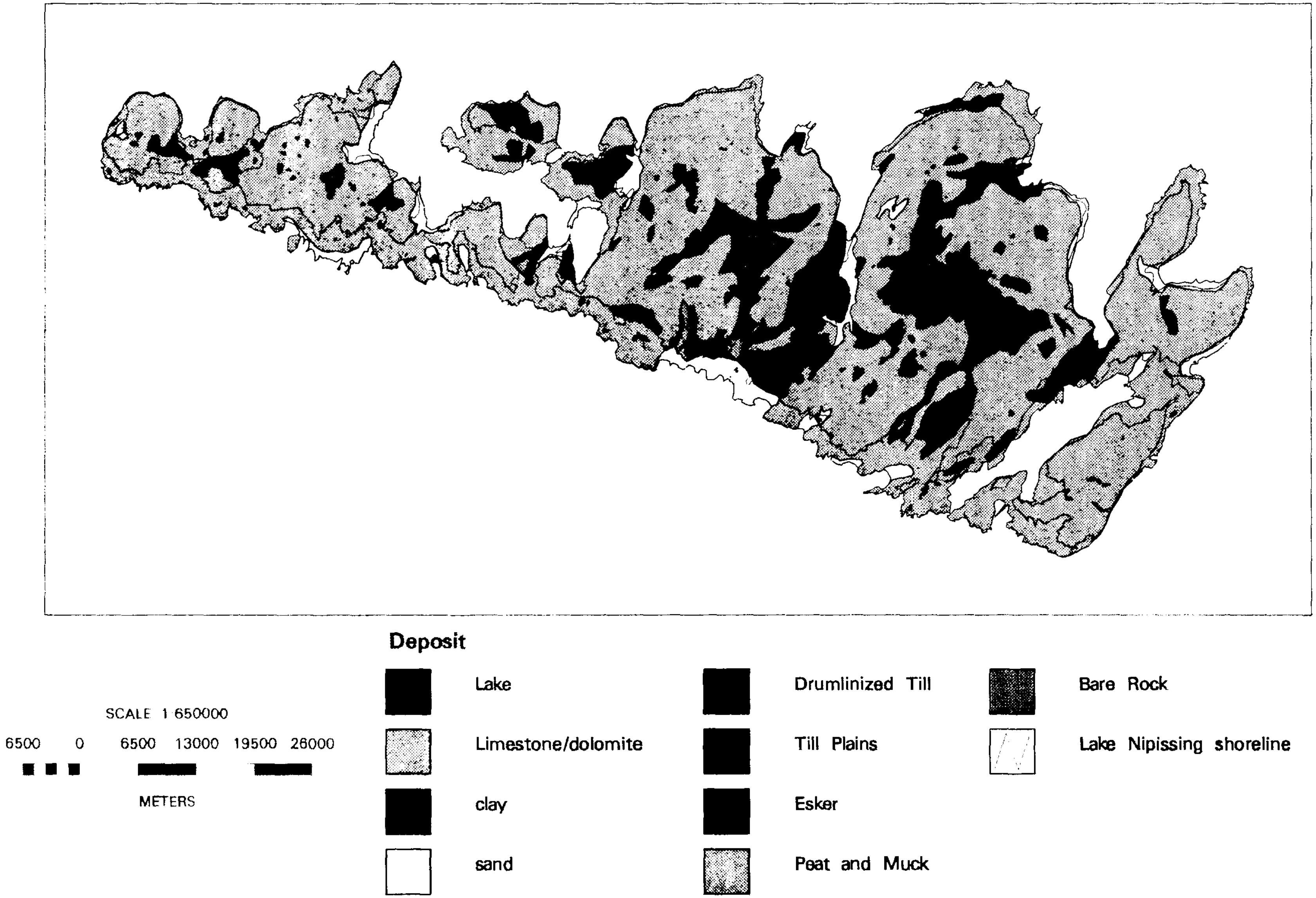
Figure 2.13 illustrates the Quaternary geology of Manitoulin Island. Surface deposits are divided into four main classes (Hoffman, 1968) and (Hoffman and Wicklund, 1959):

<u>1. Glacial tills -</u>

These are found north, south and east of Lake Manitou and Manitowaning Bay, in patches on the west end near Silver Lake,

Figure 2.12 Polished Amabel outcrop, recently exposed due to quarrying near Nameless Lake. Bedrock shows striae which have not been erased by solution.

Figure 2.13 : Quaternary Deposits on Manitoulin Island



and in the Little Current area. The tills are coarse in texture, made up of boulders, cobbles and gravel as well as sand, silt and clay. They form loam or clay - loam soils, which are usually stony, and exhibit topography varying from regular to moderately sloping to hilly and irregular. Usually this till is found in the form of ground moraine, with knolls and sloughs (also known as "swell and swale"). However south of the Little Current area there are rough hills representing terminal moraine.

There are also in total 175 drumlins on Manitoulin. They are formed of unsorted, medium textured till with stones and boulders and they develop loam and clay-loam soils. These are long, thin cigar shaped features, many with their crests indented by Lake Algonquin wave action. In the South Bay area they are formed from acid Precambrian material while in the west they mostly consist of dolomite and limestone material. These are found south and southwest of Lake Manitou in the Long Lake and Sandfield area, around Ice Lake and south of Gore Bay, on Barrie Island and to Silver Waters in the west.

2. Glacio-fluvial deposits -

These may be divided into two types:

(i) outwash deposits of coarsely sorted glacial till. Outwash plains were formed where running water in front of melting glaciers deposited coarser materials (sands and gravels) and washed away finer silts and clays. These are found around Sandfield, north of South Bay, south of Lake Mindemoya, Gore

Bay, Wolsey Lake and on Barrie Island. The topography is gently sloping with some gravel bars.

(ii) There are also some kames, low hills of re-sorted till and boulders, mostly sand and gravel, on the outwash plains.

3. Lacustrine deposits -

These sediments were deposited by Glacial Lake Algonquin and are bedded deposits of clays, silts and sand. There are extensive patches of clay plains south of lakes Manitou, Mindemoya, Wolsey and Kagawong. Varved clay deposits are found in the Blue Jay Creek area. The topography is gently sloping with few stones, yielding a soil of silt-clay-loam in texture, with ice-rafted deposits found in some areas. There are also several stages of Lake Algonquin represented by gravel bars on Manitoulin Island.

Additionally, Lake Nipissing shoreline deposits in the form of gravel bars are found nine to 15.2 metres (30 - 50 ft) above the present water level. On the south shore there are low bluffs and sand dunes which mark the old shoreline (from aeolian sand deposits from Lake Nipissing).

4. Recent alluvial sediments -

These include deposits of post-glacial sands, silts and clays along larger rivers south of Lake Kagawong, Manitou and Mindemoya. There are also marsh-muck deposits from the organic decay of vegetation in poorly drained lowlands. The topography is immature and depressional.

2.3.2 - Quaternary Lake Level Changes

The main events following the last glaciation are characterized by a succession of late glacial and post-glacial lakes as well as deformation of the crust (glacial rebound) due to differential uplift rates. Regional glaciation was from a north to northeast direction. The major Wisconsin re-entrants interrupted the two main cuestas on Manitoulin in the northern coastline creating isolated uplands and large ice scoured basins today occupied by lakes including lakes Manitou, Mindemoya and Kagawong. These events have affected shoreline features on Manitoulin Island.

Initial deglaciation began at approximately 13,000 B.P. with the retreat of Port Huron stade ice from its maximum extent at the south shores of Lake Huron. The ice withdrew from the island in one recession, as inferred from the occurrence of only one major recessional moraine ridge on the northern island. As the ice receded, Lake Algonquin waters took its place, fully submerging Manitoulin until the main Algonquin phase (a stable period after 11,000 B.P.), when lake level was at 184.5 metres (605 ft) (Eschman and Karrow, 1985). At this time three points on Manitoulin emerged above lake level, which were the highest points near Little Current, Sheguindah and High Hill, which are marked by erosional strandlines. Between 10,970 and 9,275 B.P. post-Algonquin lake levels were lowered as ice continued to retreat and new outlets were opened. Shoreline warping since 9,000 B.P. ranges from a maximum at the northern limit of deformation (hinge line) to southern Lake Huron, with younger shorelines less warped than older ones (showing an exponential decrease).

The Lake Nipissing shoreline is the best developed and most continuous one surviving on Manitoulin Island. It is a result of rising water levels that reached a stable position at approximately 5,500 B.P. This was likely due to differential uplift of the North Bay outlet to the same elevation as stable southern outlets at Chicago and Port Huron. The lake level was at 184.5 metres (605 ft) between 8,000 - 6,000 B.P. The Nipissing phase lasted to about 4,000 B.P. when the Port Huron outlet was downcut while continued upwarping occurred on Manitoulin. There are some beaches below the Lake Nipissing strandline marking this phase, which lasted until the Algoma phase when the lake was at 190.5 to 180.5 metres (625 to 592 ft). The Port Huron outlet stabilized to the present shoreline elevation of 176.8 metres (580 ft) at 2,500 B.P.. Both erosional and constructional beach forms can be traced around the whole island at elevations of 195.1 m (640 ft) on the south shore to 199.6 m (655 ft) on the north shore near Killarney. Total Nipissing emergence was between 18 to 23 metres (60 - 75 ft) with 6.7 metres (22 ft) due to lowering of lake level by outlet erosion and the rest due to isostatic uplift of the crust (Lewis, 1970).

Post-emergence uplift is the difference between the present beach elevation and the former beach elevation, which represents former lake level. The uplift in the Lake Huron basin ranges from 0 m at the southern end (Georgian Bay) to 280 m (918.4 ft) at North Bay over a time period of 11,500 years for glacial Lake Algonquin. For Lake Nipissing, the upwarp of the shoreline ranges from 0 to 28 m over a time frame of 5,500 years (Lewis, 1970). The time-uplift curves show uplift was greatest immediately following deglaciation, then declined rapidly to present (believed to continue today in the northern basin).

2.4 - Soils

2.4.1 - Introduction

The Quaternary glacial deposits, plus the bedrock to a much lesser extent, form the parent material for the soils. Limestones and dolomites usually contribute little to soil formation because they have few insoluble residues. In addition, since the solution process is slow, only a very thin layer of soil could develop through post-glacial weathering of the carbonate bedrock (Carroll, 1986). Thus on Manitoulin Island the availability, thickness and location of the Quaternary deposits determines the different textures, relief and drainage of the soil types, in addition to influences from climate and vegetation (Hoffman and Wicklund, 1959). Almost two-thirds of the island is covered by Brown Forest soils less than 12 inches thick, that rest directly upon bedrock. Deeper soils are located in areas of deeper drift such as Barrie Island, and south of Lakes Kagawong, Mindemoya and Manitou.

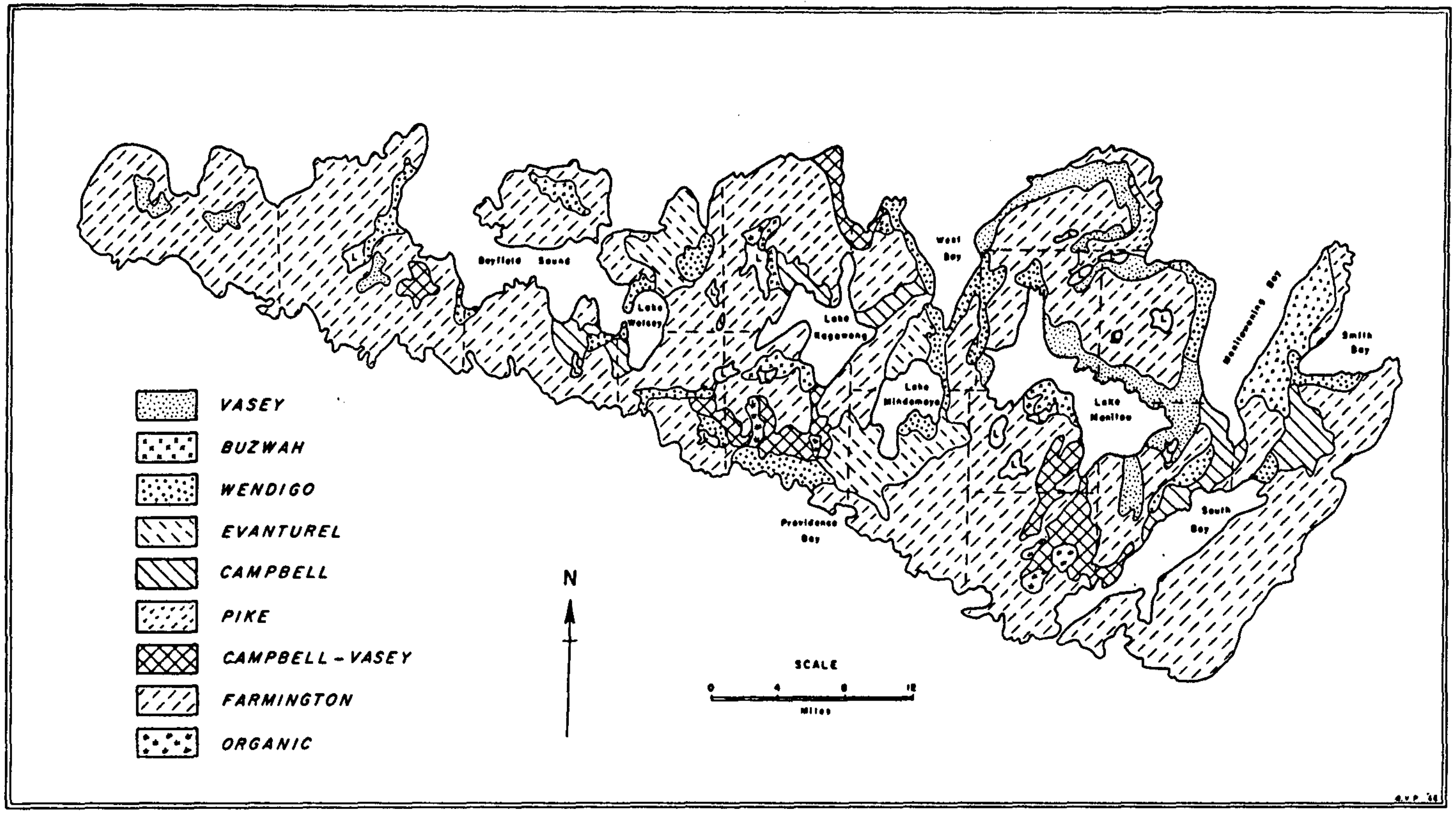
In the cool humid climate found on Manitoulin Island, forest is dominant under natural conditions. The acids released from this vegetation leach material from upper layers of the soil into lower layers, forming horizons of different thicknesses, colours, textures and structures. Removal of bases from surface layers, especially calcium, occurs as waters percolate through these soils. In the A horizon where maximum weathering occurs, upper parts (A_1) have the largest amount of organic matter, while A_2 displays the greatest leaching or eluviation. B horizons accumulate leached material from A, and are finer textured and more compact due to accumulation of clay and fines carried down from A. C horizons are basically unaltered or slightly altered from the bedrock or glacial deposits. Sometimes there is a distinct G, or gley horizon that is found in poorly drained soils where a layer of intermittent water logging causes partial oxidation and reduction of iron. This creates a bluish-brownish grey and mottled horizon with iron concretions (Hoffman and Wicklund, 1959).

2.4.2 - Soil Series

On Manitoulin Island 81 series of soils have been mapped. They are grouped according to parent material, and drainage (Hoffman and Wicklund, 1959). Figure 2.14 provides a general map of the main soil groups. The main soil series are:

1. Shallow soils - These are the most important soils in the context of this thesis, since they offer the greatest potential

Figure 2.14 Soil Associations of Manitoulin Island



Soils developed on:

Vasey - Stoney till (ground moraine)
Buzwah - till (calcareous clay loam)
Wendigo - outwash sands & gravels
Evanturel - lacustrine silt loams
Campbell - lacustrine silty clays
Pike - clay lacustrine deposits
Farmington - shallow soils on limestone/dolomite

(Hoffman, 1969)

for karst. They developed from calcareous loam and silt loam parent material underlain by limestone and are the dominant soil type on Manitoulin Island, accounting for 71.1% of total soils by area. They are known as the Farmington Series and are less than 30 cm (12 in) deep. In some places soil merely infills grikes. These are brown forest soils. Shallow soils also include those forming from calcareous clay underlain by shaley parent material.

2. Soils developed on glacial till - These develop from stoney calcareous, sandy loam parent material (0.2%), calcareous loam (3.9%) or calcareous clay-loam parent material (7.3%). They form Grey-Brown Podzolic, Brown Podzolic or Grey wooded soils if well drained, and Dark-grey gleyzolic if poorly drained. They are deeper soils, from 52 to 78 cm (20 to 30 in) in depth.

3. Soils developed on outwash (sandy-loam) parent material - These include soils from stone and gravel parent material (0.5%), medium to fine sand parent material (5.5%) and loam to sandy-loam parent material (2.3%). All except the medium-fine sand are calcareous, and depths range from 46.8 cm (18 in) to greater than 90 cm (3 ft). The sandy soils are common on the southern island. Grey-brown podzolic, Regosols and Podzols are formed from well drained soils, while Dark Grey Gleyzolic and shallow soils are found on poorly drained sites.

4. Soils developed on sands underlain by silty-clay parent materials - These are loam to sandy loams, are calcareous and

form podzols on well drained sites and Dark Grey Gleyzolic soils on poorly drained sites. They are up to 90 cm (3 ft) deep and account for 1.2 % of the island's soils.

5. Soils developed on lacustrine deposits (silty clay loam) - These soils develop from non-calcareous silt loams underlain by silty-clay (0.6%), on calcareous silt loams (3.2%) chiefly limestone in origin, on calcareous silt clay parent material (6.3%) and on calcareous parent material (0.8%). Non-calcareous parent material forms podzols, while on well drained sites calcareous material forms grey wooded soils and dark grey gleyzolic on poorly drained sites. The soils range in depth from 30 to 90 cm (1 to 3 ft).

6. Organic soils - These are very poorly drained soils formed from organic material (decomposition of grasses and wooded debris) and are known as mucks, accounting for 3% of the islands soils.

7. Miscellaneous soils - This group includes marshes, the Wendigo rock complex (limestone bedrock pocketed with sand) and rock outcrops of quartzite near Sheguindah making up 1.5% of the island's soils.

2.5 - Settlement and Landuse

2.5.1 - History

The first settlement on Manitoulin Island dates to 7180 +-250 B.P., from a settlement on the uplifted Lake Algonquin shoreline at Sheguindah (Mason, 1981). Ottawa Indians occupied the island at the time the first white explorers arrived

(Samuel de Champlain in 1615 followed by missionaries). The original Native population was estimated to be 20,000 in 1600, but was reduced to one half by disease by 1640 (Pearen, 1992). In the mid seventeenth century the Iroquois invaded the island and drove away the Ottawas. According to oral tradition, in the 1650's the Natives purposely set fire to the island to get rid of the evil (sickness and trouble) brought to Manitoulin by the whites. For 100 years the island was not permanently occupied. At the time white settlement was initiated in 1862, Odawa and Ojibwe Indians resettled in Wikwemikong forming a population of 350. An Indian treaty opened up west and central parts of Manitoulin for colonization (Liberty, 1968). The island's population grew to 11,000 by 1900 including 2000 Natives. Despite fluctuations, it has remained steady to the present; in 1982 the total population was 10,555, or four persons per km^2, with 4140 Natives (Pearen, 1992).

The early years of settlement featured exploitation forestry as the main industry. This has become less important because of diminishing forest resources. Although most of the original forest was cut, Manitoulin remains forested today but it is secondary growth of lesser quality. The island is predominantly rural with approximately 40 % of the land occupied by farms, the annual cropped areas forming approximately 36,000 acres. The most important crops include pasture (for cattle and sheep), oats, mixed grain and corn. Farming areas are concentrated in the lowlands where soils are thicker around Lakes Manitou and Mindemoya, on Barrie Island and in Gordon Township. The largest town on the island is Little Current (population approximately 3,500), with other important settlements including Gore Bay, Mindemoya, Manitowaning and in the west Meldrum Bay. The east side of the island is occupied by the Wikwemikong Unceded Indian Reserve and there are six smaller reserves scattered to the west. Besides farming and local business, tourism is an important industry with a large number of summer cottages scattered over the island; hunting, fishing and recreation are the main attractions (Ontario Geologic Survey, 1984).

2.5.2. - Natural Vegetation

Manitoulin Island lies in the Great Lakes - St. Lawrence Forest vegetation zone (Morton, 1977). Original surveyors described Manitoulin's natural vegetation in great detail, which provide the main source for vegetation present during most of the time period for karst development (Wightman, 1982). The original vegetation on most of the island was forest, containing species of the Carolinian forest, although more northern species dominated. The vegetation was very mixed and locally complex, with hardwoods on both well-drained fertile land and the thin soils, common on uplands. The forests were composed of sugar and hard maple, red, white and black oak, yellow birch, pine, hemlock, white spruce, and beech on the uplands. There was also a softwood complex including evergreens (mostly white cedar with spruce, balsam and on drier regions jack pine) along with poplar and birch which grew in profusion. On wetter sites were cedar, tamarack and black ash. These softwoods occupied a greater portion of farmable land. Conifers were mostly found in small stands or individual clusters with moderate tree sizes. Due to burning, timber harvesting and exploitation of land for agriculture and pasture, much of the forest today is poorer, secondary growth, as noted.

CHAPTER III: KARST PAVEMENT ON MANITOULIN ISLAND

3.1 - Classification of Dolomite Karst Forms

Ford and Quinlan (1973) provide a classification scheme first separating karst forms into surface and subsurface forms (caves and their phenomena). These are then classified by the scale of their greatest dimension: microforms (less than 10 metres: such as karren), mesoforms (10 to 100 metres: sinkholes), and macroforms (1000 metres, large caves). The focus of this chapter is on microforms, which are the overwhelming dominant karst forms on Manitoulin Island. A classification scheme for karren is provided in Table 3.1. Only those features which are found on Manitoulin Island are described and summarized. Complete descriptions of all types of karren on dolomite are available in Pluhar and Ford (1970) and Cowell (1976). These classifications are mainly morphologic, with some inference on genesis which is not completely understood.

In general, hydrodynamically controlled karren result where surface flow is possible, whether in the form of sheetflow (producing rillenkarren) or channel flow (resulting in rinnenkarren on bare surfaces or rundkarren under soils). Structurally controlled karren are elongated along lines of

Table 3.1
KARREN CLASSIFICATION SCHEME

1) Hydrodynamically controlled forms

A) Sheetflow
- rillenkarren - sharp crested, parallel troughs on the top of steep bare slopes originating with the incipient stages of sheetflow
- are evenly spaced (few cm apart), length increasing with slope
- only develop near top of slope on exposed surface
- only found on fine-grained carbonates

B) Channelflow
- rinnenkarren - semi-circular channels with sharp lips and round bottoms, ranging from a few cm to fractions of a metre wide
- develop on limestone surfaces of all slopes (often on drumlins and whalebacks), bare and covered, if their is runoff long enough for channel flow
- on steep slopes they tend to be linear and oriented along the slope while on shallow slopes they may meander.
- are sharper on bare bedrock, while under soil solution is concentrated at the runnel bottom
- hohlkarren - termed by Bogli where excess widening on bottom creates overhanging walls
- rundkarren - rounded forms
- occur under deeper soils which inhibit flow
- water reaching the bedrock in the form of percolation, thus channel geometry is lost and usually vague

2) Structurally controlled forms

A) cleftkarren or kluftkarren (grikes) -are the master karren features and principal drains on pavement
- many intersect at 60°, 90°, and 120°, a result of shear and tension systems
- range from few cm to m in width, m in depth, several m in length
- length is inversely proportional to joint density
- may have parallel or tapering walls with other karren forms (eg groovekarren) commonly occurring on the walls
- beneath soil tops of grikes may be much wider (cutters).

- cleftkarren develop on bare rock exposures, and have sharp edges and vertical walls (more curved if soil filled, open joints extend down to terminate in a narrow crack
- kluftkarren or trench karen are similar but terminate upon reaching resistant beds therefore have flat bottoms.

B) groovekarren - develop in the horizontal and are grooves dissolved along bedding planes, often within the sides of grikes
- may completely isolate blocks (clints)

3) Mixed forms

A) pit and tunnel karren - develop along a joint as it is not widened uniformly from surface to depth
- flow is diverted into small vertical solution openings and then horizontally enlarged
- may later develop into trench karren
- terminate downward at the first readily penetrable bedding plane

4) Circular forms

A) solution pans (kamenitzas) - form from stagnant water ponds with algae, moss and plant debris which greatly enhance the corrosiveness of rainwater
- have flat, horizontal bottoms and can be several m deep
- are found on bare or lightly vegetated surfaces
- usually deepen greater at the bottom which tends to be wider than the top

B) solution pits - circular, oval, irregular plan forms, with round bottoms and diameters of 1.0 cm to 1.0 m
- commonly develop in heterogenous rock eg. reefal rocks
- may be aligned along small joints, striae etc.
deeper pits are colonized by mosses, algae etc. which enhances dissolution

C) solution wells (shafts) - vertical solution along several joints intersects creating a localized centre for groundwater input
- range from metres in diameter and depth
-walls may be smooth from solution etching or grooved

(from Ford and Williams, 1989 and Pluhar and Ford, 1970) structural weakness (joints, bedding planes etc.) are termed "splitkarren" (Pluhar and Ford, 1970). These openings are sharply tapered and where found in greater densities inhibit development of sheet or channel flow. The most common karren forms are grikes (cleftkarren or kluftkarren forms). Groovekarren exploit horizontal weakness lines along bedding planes and commonly develop inside grikes. A mixed form found on Manitoulin Island is pit and tunnel karren, a result of downward shaft solution along a fracture. Circular forms (pits and pans), are very common in the littoral zone, both in freshwater and saltwater environments, where they are found in greatest densities. They also exist on inland pavements, often colonized by mosses. Biological activity may be very important in their development although initiation agents for pitting are not known for certain.

The pavement of Manitoulin Island may be divided first according to lithology, secondly by other factors such as dip, jointing direction, appearance and karren development. The two formations with the best pavement are the Amabel and Fossil Hill. There is also good pavement on the Manitoulin bioherm and minor, very shallow pavement on the bedded Manitoulin Formation. The Mindemoya Formation, limited in where it outcrops, also has some small patches of pavement. A third type identified by Cowell (1976) on the Bruce Peninsula, is the intensely pitted littoral zone, a result of environmental factors and is found in greatest profusion on the Amabel in the modern littoral zone of Lake Huron, and sparsely on the Amabel and Fossil Hill pavements inland.

Variation of pavement type within a formation will be analyzed according to grike width, depth, length, and jointing trends. Additionally, the spatial distribution of different types of pavement and regional jointing trends across Manitoulin will be examined. These data will be compared to studies of jointing over the entire Michigan basin (Holst, 1982). Additionally a comparison with pavement types on the Bruce and Door Peninsulas will be provided.

Site-by-site data on Manitoulin Island pavement are presented in Appendix 1 in the form of rosette diagrams for joint set orientation (180^0 measurements) and frequency histograms for grike width, depth and length in Appendix 2. Summary diagrams and histograms for each formation to show major trends were also created. The total site data set includes additional sites where only few measurements were possible thus no individual diagrams were created. Figure 3.1 maps the location of the study sites (eleven Amabel, five Fossil Hill and four Manitoulin Formation pavement sites) across the island. Table 3.2 gives estimated areal extent and elevation of the sites.

The statistics used in this research are important to characterizing pavement morphology and to understanding its development. Immediately following glaciation, joints likely were slightly opened (1 - 10mm) but not solutionally enlarged

Figure 3.1: Location of Pavement Sites on Manitoulin Island

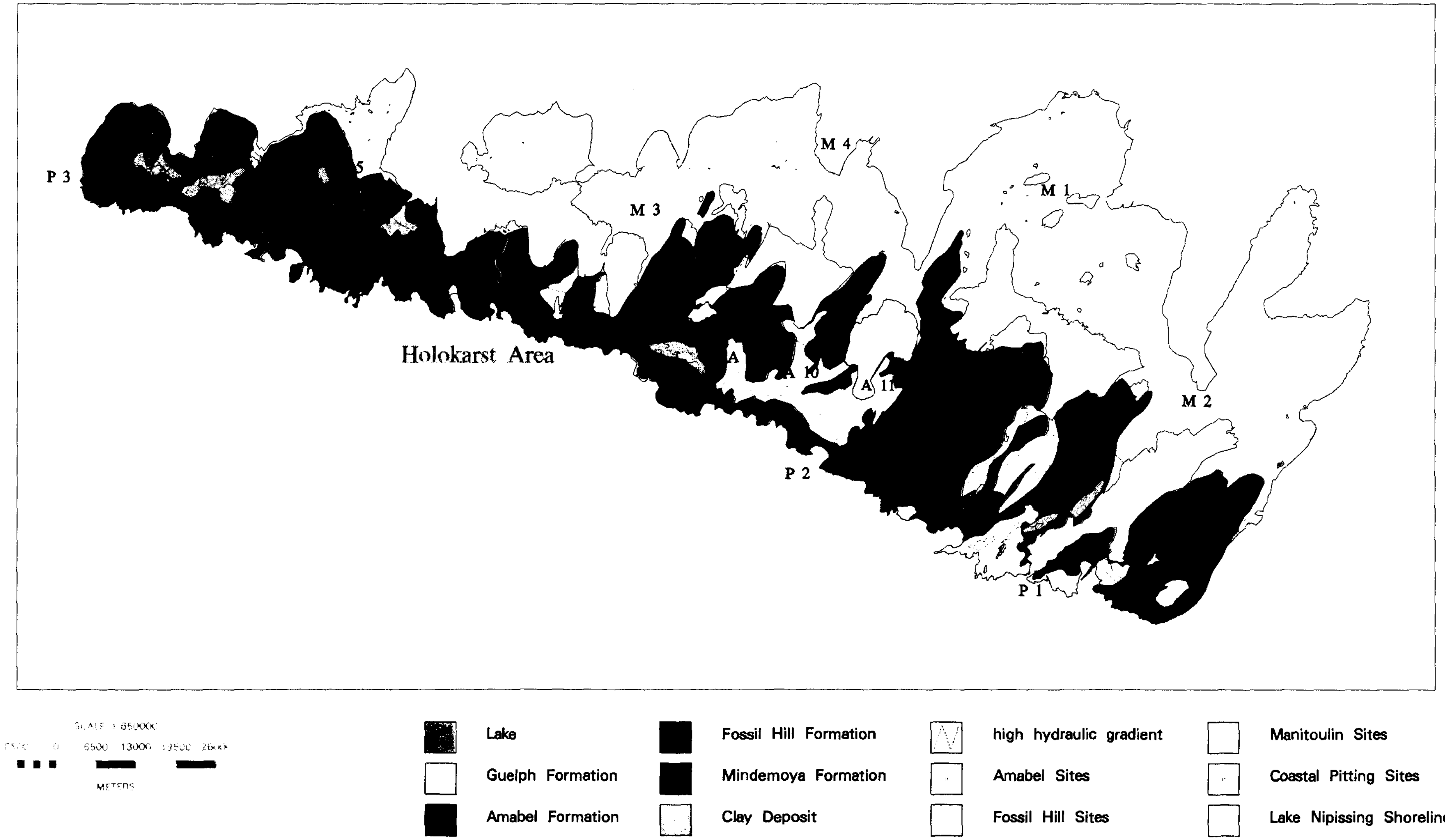


Table 3.2

Manitoulin Island Pavements:
Elevation and Area

Site Number	Elevation (m)	Approximate Area of Scarp (km^2)
Amabel - A1	221	14
A2	221	9
A3	244	15
A4	213	13
A5	213	12
A6	198	10
A7	213	30
A8	206	25
A9	213	12
A10	221	25
A11	206	22
Fossil Hill F1	236	17
F2	236	0.1
F3	244	<0.01
F4	206	<0.01
F5	206	<0.01
Manitoulin M1	244	<0.01
M2	221	0.1
M3	183	0.3
M4	267	<0.01

(Calculated from air photos and/or with GIS analysis)

(D. Ford, personal communication). This sets the time frame for development of grikes as well as other features such as karren. Initial post-glacial width is assumed to be zero: joints are very tight fractures. Thus the average widths show the amount of solutional enlargement possible in the last 9,000 to 11,000 years. A bimodal pattern of joint widths at a given site may indicate surviving pre-Wisconsin grike bases, or normal post - glacial grikes in intervening beds (Paterson and Chambers, 1982). Width is a fairly accurate characteristic since it is measured at the top, although some grikes appear to taper slightly. Some very large widths appeared to be from disintegration of narrow clints between the grikes. On the Manitoulin Formation width was difficult to measure accurately since the joints were soil and vegetation filled to the surface.

Depth reflects the number of beds that a given joint penetrates. Joints conduct water flow from the surface until an impenetrable bed is reached. However, horizontal solution along bedding planes creates paths for groundwater, linking to perhaps other sets of vertical pathways at greater depths. Measurement of depth was highly affected by the amount of debris filling in grikes, including soil, forest litter, and growing vegetation. Thus, two sets of depths may indicate filled and unfilled grikes, the latter being a more accurate measure of true depth.

Length was a highly variable measurement, since it was also affected by infilling, vegetation growth and rock debris if the pavement was very fragmented. Some grikes were up to 50 metres long, and as indicated by air photos, lineaments 100's of metres in length could indicate series of joints linked together.

3.2 - MANITOULIN ISLAND PAVEMENT

3.2.1 - AMABEL PAVEMENT

In general, the Amabel displays the widest occurrence and variety of dolomite pavement on Manitoulin Island. It was found on nearly all the Amabel sites inspected, from scarp uplands to lowland plains where there is an absence of glacial deposits. The pavement is much more exposed than on the other formations, obscured only by heavy forest on highest scarps such as the "Cup and Saucer", which was possibly never deforested. It also displays the widest range of karren types and varying surface characteristics resulting from glacial modification.

Trends from joint orientation, width, depth, length, in addition to overall appearance and karren occurrence were studied to determine whether the Amabel pavement may be divided into distinct sub-types. The following division was established:

TYPE 1)

These are pavements with very flat, smooth surfaces, found on gently sloping scarp lands where the bedding is nearly horizontal (Figure 3.2). Presence of joints dominate

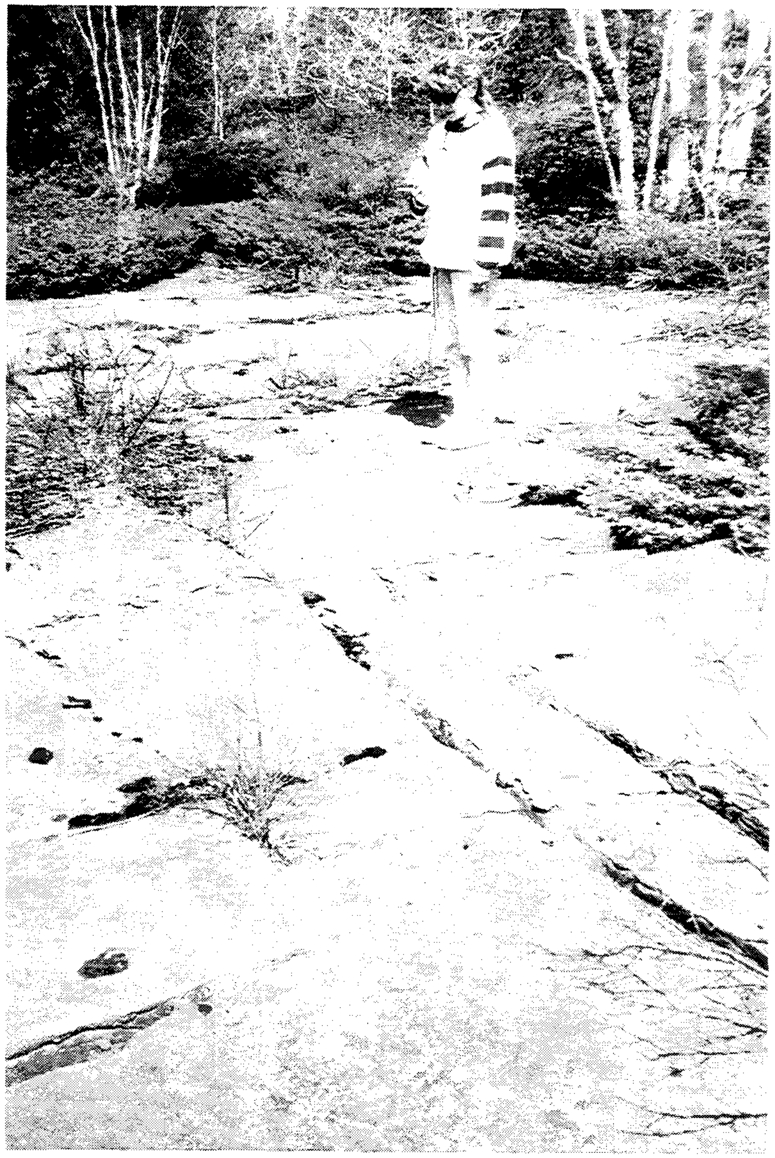


Figure 3.2 Type 1 Amabel pavement, near Lorne Lake (Site A6). The pavement has a very smooth surface with regularly intersecting grikes.

the karren forms. The main forms are clint and grike. In addition, pit and tunnel karren develop along a joint, where vertical solutional openings are enlarged non-uniformly. They are much smaller scale than grikes (less than 50 cm long) but many pits may develop along a given fissure (Figure 3.3). Other types of karren are few in number, principally limited to shallow pitting and a few pans. Since the surface is very flat, there is little surface or channel flow to permit formation of rillenkarren and rinnenkarren.

Grikes are often comparatively narrow on these pavements, and have distinct sharp edges. They form very regular networks. These pavements do not fragment easily, thus there is little rubble on the surface and measured depths may be greater than on the other sites. The three sites at which this type is found are Site 4 (north of Britainville), Site 6 (east of Lorne Lake) and Site 11 (north of Monument Corner).

TYPE 2)

These pavements are found on fairly flat terrains on scarp tops. Their surfaces are very pitted and irregular (Figure 3.4). The dominant karren type next to grikes is pitting, which is very common. Pits are not as deep or well developed as in the littoral zone, but may cover a large percentage of the surface. They are usually filled with mosses. Pans are common, and occasionally appear to exploit structural openings (pit and tunnel karren). There are few forms resulting from surface or channel flow, since the

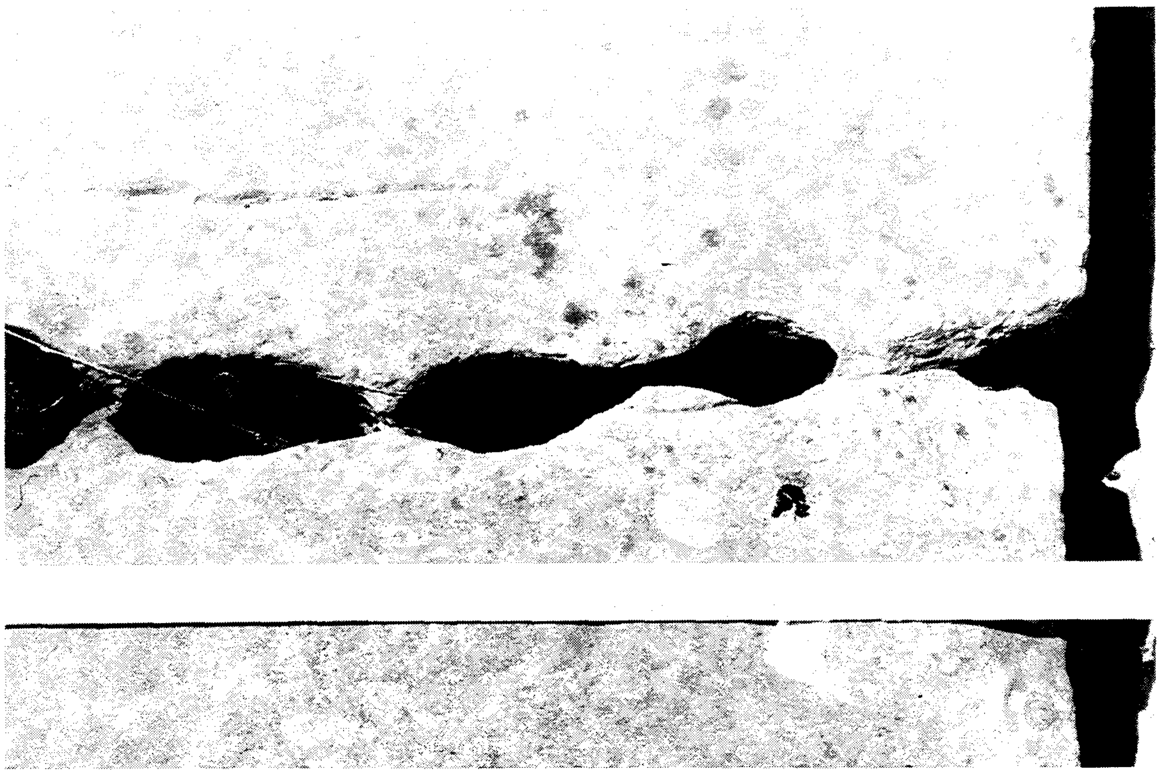


Figure 3.3 Pit and Tunnel Karst on Site A6. Circular solution occurs along a fissure. Overall length is approximately 75 cm with the pits about 15 cm in length and 7 cm in width.

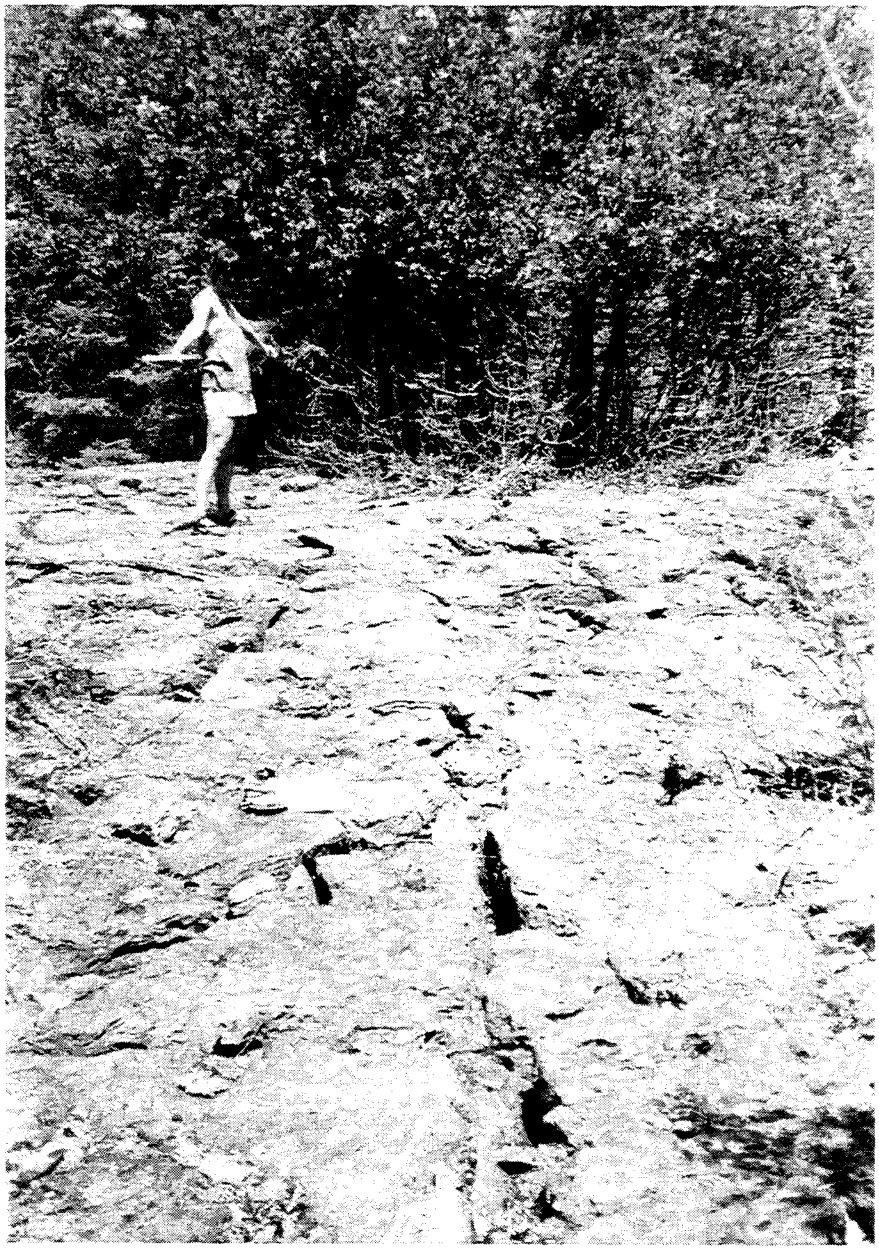


Figure 3.4 Type 2 Amabel pavement, near Nameless Lake (Site A1). Pavement has a very fragmented "clitter" surface, with many grikes filled with debris.

gradient is relatively low, and the rough surface pitting may hide any evidence of such features. This pavement may be divided into two sub-types:

A) Pavement with a very flaky, broken surface, or "clitter: (scattering of local rock fragments). It is found on sites 1 and 9 (Nameless Lake area), 5 (west of Evansville) and 10 (north of Spring Bay).

B) Pavement similar to 2B without the flaky surface. This is found on sites 7 and 8 in the west end of the island.

TYPE 3)

These pavements have irregular, often "clitter" surfaces and are formed on undulating terrain, on scarptops, commonly on the whalebacks and possibly biohermal deposits (Figures 3.5 and 3.6). They display the widest variety of karren, including all forms found on types 1 and 2 plus surface and channel flow forms especially rinnenkarren (Figures 3.7 and 3.8). Smaller Rillenkarren are not common (Figure 3.9), but there are some at the micro-scale. This type of pavement is found on sites 2 and 3 south of Lake Kagawong. Along the southern shore around Providence Bay, whalebacks on the Amabel Formation are very common. However, in many cases only the whaleback top is visible outcropping above a covered surface (usually shallow soils). These areas were too small to be used for site studies but were noted (eg. Figure 3.10).

Figure 3.5 Type 3 Amabel pavement, commonly found on whalebacks. Site A2 west of Mindemoya Lake.

<u>Figure 3.6</u> Rough fragmented surface appearance of Type 3 pavements, Site A2.

Figure 3.7 Rinnenkarren on Type 3 pavement at site A2. These karren forms are only found on surfaces with slopes greater than 45 degrees.

Figure 3.8 More meandering, channel-like rinnenkarren on shore of Silver Lake.

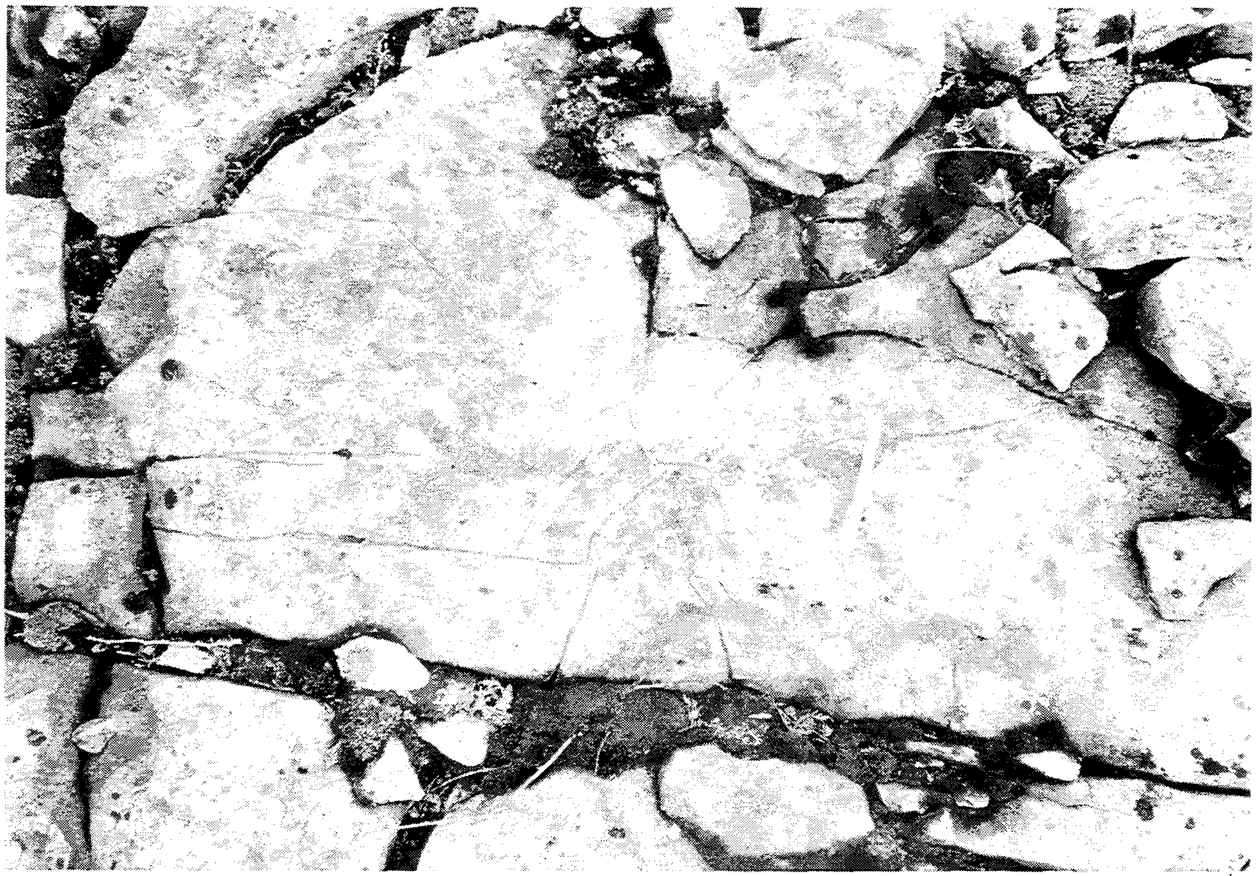


Figure 3.9 Micro-rills, possibly exploiting fractures, on Site A2. These forms are only few millimetres wide and deep, and generally following direction of jointing .

Figure 3.10 Exposed Amabel whaleback east of Providence Bay. In this area, Type 3 pavement is limited to such outcrops.

TYPE 4

This pavement is found in the littoral zone. It is common along the full extent of the Lake Huron shore wherever the Amabel formation is exposed. This zone also extends for several kilometres inland although its features exist in greatest profusion on the coast. It corresponds to the area inundated by Lake Nipissing, approximately 5500 B.P.. Pits often aligned with striae or small fractures. Data were collected for three sites for pit density, size, and shape. This type of pavement will be discussed following other inland pavement types.

QUANTITATIVE ANALYSIS

Table 3.3 provides the means for width, depth and length. Frequency histograms with data from all sites are given in Figure 3.11. This table also provides the most common jointing directions for each Amabel pavement site. Table 3.4 summarizes width, depth and length according to pavement type and geographic location.

Width

The average width for all sites was 12.3 cm. The minimum was at site 11 (9.9 cm) and the maximum was at site 8 (15.1 cm). Most joints were between 6 to 15 cm wide (79.86 %). Examining spatial trends, in general grikes at central sites were less wide than those on southern sites (Sites 2 and 8 had the greatest widths). Grikes at western sites overall were close to average but had greater intersite ranges. For

Table 3.3

Amabel Pavement Sites
Summary of Joint Characteristics

* = dominant direction

SITE NO.	MEAN DEPTH (cm)	MEAN WIDTH (cm)	MEAN LENGTH (cm)	DIRECTION (degrees)
1	59.17	12.12	341.88	90* 120,30
2	59.96	15.00	242.50	90* 75,120,15
3	121.54	11.89	434.29	30 - 120* 90, 75
4	74.70	13.57	226.88	90* - 180 150
5	72.19	10.72	169.23	90* 45, 30
6	86.09	10.28	534.50	60* - 120* 45
7	25.40	13.23	253.04	30* 105, 120
8	119.84	15.13	320.95	120* 75, 150
9	53.85	11.31	350.00	45* 90, 30
10	91.83	12.49	259.66	90* 150
11	78.93	9.92	350.00	90* 120, 150
OVERALL MEAN	76.68	12.33	316.63	90*, 120 30, 150

Figure 3.11

Amabel Formation Pavements: Summary of joint characteristics histograms.

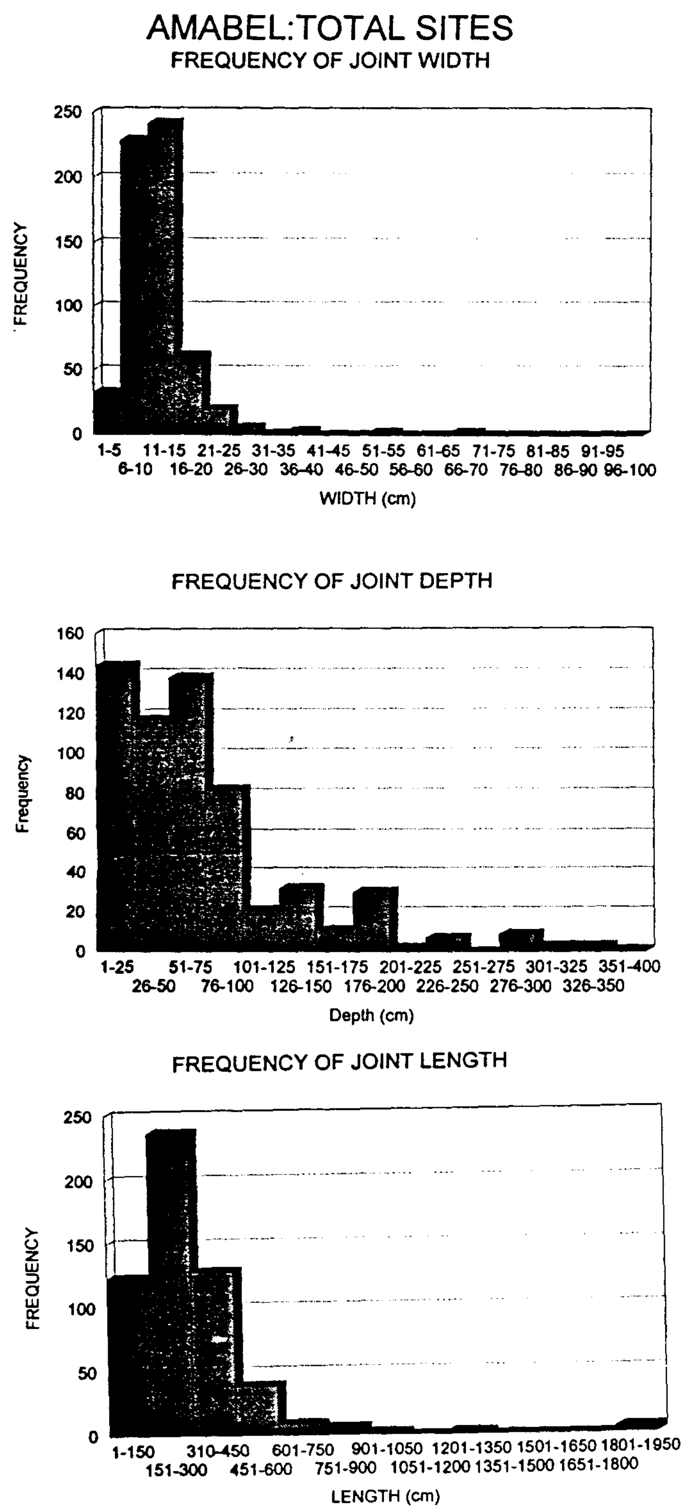


Table 3.4

Amabel Pavement:
Joint Charactersitics According to Type and Location

SITE NO.	MEAN DEPTH (cm)	MEAN WIDTH (cm)	MEAN LENGTH (cm)
Type 1	79.91	11.26	370.46
Type 2A	69.26	11.66	280.19
Type 2B	72.62	14.18	287.00
Type 3	90.75	13.45	338.40
Central	78.19	11.77	375.39
South	76.36	12.75	269.76
West	75.88	12.34	319.48
OVERALL MEAN	76.68	12.33	316.63

pavement type, widths were less than average for Type 1 pavements while Type 2A, Type 2B and Type 3 sites had mean widths greater than average. There was greater intersite ranges for Types 1 and 3 and less for Types 2A and 2B. In general, the smoother, flatter the pavement, the narrower the grike width, with width increasing as roughness and degree of pitting increases, on flat compared to undulating pavement.

There is little suggestion of a bimodal width distribution as in some areas of England (Paterson and Chambers, 1982). Thus all grikes are taken to belong to one age group, the post - glacial or Holocene. Mean widening rates can be calculated: over 11,000 years joints on average widened 12.3 cm, yielding a rate of 1.1 mm per 100 years.

Depth

The average depth measured on Amabel pavements was 76.7 cm, and the range was from 25.8 cm at Site 7 to 121.5 cm at Site 3. Examining total joint depth distribution, most joints were less than one metre deep (79.9 %). Most depths were for joints infilled with debris, while high values above 2 to 4 metres may represent possible maximum depth since they were present at many sites (8 out of 11 sites). Thus, there was more variation in grike depth distribution due to a large number of infilled joints.

For geographic distribution of depth, the mean of each area was close to the overall mean but there was much variation for sites within an area. Looking at depth trends according to pavement type, Type 1 pavements were closest to average, perhaps due to less rubble infilling the grikes. Type 2A and Type 2B had lower averages Type 3 had overall greater than average depth. These trends indicate that the more broken, fragmented pavement may have more infilling in some grikes and therefore a greater range of depth that can be measured.

Length

Mean length ranges from 169.2 cm (Site 5) to 534.5 cm (Site 6) with an overall average of 316.6 cm. Most joints were between 151 to 300 cm long (42 %), with 89.7 % less than 450 cm wide. Spatially, central sites and western sites had lengths above the average, while southern sites were below average, with some intersite variation. According to pavement type, most Type 1 sites were above average, perhaps because with less rubble they can be discerned and measured for longer distances. Both Type 2A and Type 2B had sites with mean lengths below and above average. Type 3 pavements had slightly greater than average mean lengths. This indicates that with more flaky pavement, length will be more variable since some joints will be covered with rubble and others more exposed. The longest joints will be found at optimum sites: at scarp edges on the most regularly bedded strata.

Joint Spacing

The scale of joint spacing was also examined for these pavement sites. Table 3.5 summarizes Amabel trends, for each site, while Table 3.6 gives spacing according to pavement type and location. At each site joint spacing was measured along an orientation where they appeared to be at greatest density (along 0, 90, 120 and 45), at some sites where it varied it was taken along two orientations for comparison. For sites 6 and 8, spacing was similar along both orientations while at Site 2 it varied. Figure 3.12 shows a very densely jointed Amabel pavement (compare to Figure 3.2).

The joint spacing on Amabel pavements ranged from medium (83.3 cm was the minimum) to wide (maximum 180 cm). The overall mean was 140.4 cm. Intersite variation along the same scarp (Sites 1 and 9), varied by a factor of about two. For variation according to pavement type, Type 2A had the greatest density along with 2B, while Type 1 was close to average and Type 3 above average. This suggests that very smooth, regular pavement will have close to average joint spacing. In comparison on rougher flakier pavement joints appear to be more closely spaced if this pavement is flat (Types 2A and 2B) but farther apart if it is undulating (Type 3). According to geographic variation, central sites had the closest joint spacing, followed by southern and the western sites with the most widely spaced joints. These trends perhaps reflect regional variation in jointing instead of pavement characteristics. The pavement type may result from these trends.: widely spaced joints give rise to smooth pavements

Table 3.5

Amabel Pavement Sites: Joint Spacing

For each site

Site	Orientation (degrees)	Joint spacing (cm)
1	90	150
2	0 90	128.57 180
3	110	118.75
4	0	106.25
5	90	133.33
6	45 120	166.67 168.97
7	0	83.33
8	40 120	156.25 150
9	0	86.67
10	120	118.18
11	0	106.67
OVERALL MEAN	-	140.40

Table 3.6

Amabel Pavement: Joint Spacing According to Type and Location

Joint spacing : type	**TYPE 1**	**TYPE 2A**	**TYPE 2B**	**TYPE 3**
MEAN (cm)	137.14	122.05	129.86	142.44
: location	**South**	**Central**	**West**	
MEAN (cm)	127.93	118.47	143.09	

Figure 3.12 Densely jointed Amabel pavement (Type 1).

while more closely spaced joints tend to create more debris thus result in rougher pavements.

The spacing of opened joints is usually related to bedding thickness - the thicker the bed, the more widely spaced the joint. On regular limestone pavements in Europe grike spacing is predominantly between one and three metres (Ford and Williams, 1989). The results from Manitoulin Island are in the lower end of this range, possible due to two factors. Firstly, the Niagaran dolomite bedded strata are slightly thinner with respect to jointing than many other pavements. Secondly, the reefal elements likely have irregular jointing and thus their spacing is also irregular (D. Ford, personal communication). Thus, variation in joint density across the island may be due to variation in bed thickness as well as jointing conditions (amount of stress, etc.).

Joint Orientations

The most frequent classes of joint set orientation may be used to characterize the different sites, types and locations of Amabel pavement. Each site had at least one dominant direction but usually two plus other directions which occurred quite frequently, often three to four in total. Jointing systems are observed if two or more sets intersect at regular angles. Common systems are rectangular (at 90^0) and 60^0 - 120^0 , indicating simple tension and shear systems (Ford and Williams, 1989). Joint set orientations were plotted on a 360^0 rosette for 11 Amabel sites, then summarized site by site in the joint characteristics table (provided in Table 3.3). Direction of joint sets are listed in order of dominance. Table 3.7 summarizes jointing trends according to type and Table 3.8 according to location. They show the number of sites out of the total (eleven) that a particular direction was dominant on.

The dominant joint set orientations follow a number of trends, although there is much variation around the dominant directions. It is difficult to infer regional trends for the joint sets, since most of them occur in all areas and on all pavement types. The most common for all Amabel sites, in order of dominance, were 90^0, 120^0, 30^0 and 150^0 orientations. The 90^0 orientation was the most common, and was present on all of the central, all southern but only on one-quarter of the western sites. This is the regional set, representing an east - west system. It occurred most commonly in conjunction with 120^0 (on seven sites), and 30^0 (on five sites). It was the dominant orientation on six out of eleven sites. The 120^0 orientation was common on central (2/3), west (3/4) and southern sites (1/2). The 30^0 orientation was common on all central sites and on half of the western but not present on any southern sites. The 150^0 orientation was on 3/4 of southern, but limited in the west (1/4) and not found on central sites. In general, central sites had more consistent joint set orientations of the most common 90^0, 120^0 and 30^0 sets. Southern sites had the 180^0 orientation, forming a right-angle set with 90^0. Western

Table 3.7

Amabel Pavement : Summary of Joint Set Orientation According to Type

Number of sites at which a particular direction is found (out of total of eleven sites)

Dominant Joint class	Type 1	Type 2A	Type2B	Type3
1 - 15	-	-	-	1
16 - 30	-	3	1	1
31 - 45	1	2	-	-
46 - 60	1	-	-	-
61 - 75	-	-	1	2
76 - 90	3	4	-	2
91 - 105	-	-	1	-
106 - 120	2	1	2	2
121 - 135	-	-	-	-
136 - 150	2	1	1	-
151 - 165	-	-	-	-
166 - 180	1	1	-	-

Table 3.8

Amabel Pavement : Summary of Joint Set Orientation According to Location

Number of sites at which a particular direction is found (out of total of eleven sites)

Dominant joint class	Central sites	Southern sites	Western sites	Total sites
1 - 15	-	1	-	1
16 - 30	3	-	2	5
31 - 45	1	-	2	3
46 - 60	-	-	1	1
61 - 75	1	1	1	3
76 - 90	3	4	1	8
91 - 105	-	-	1	1
106 - 120	2	2	3	7
121 - 135	-	-	-	0
136 - 150	-	3	1	4
151 - 165	-	-	-	0
166 - 180	-	1	-	1

had more peaks in orientations not found on others including 60^0 and 105^0, while the 15^0 orientation was only present on one southern site. The most commonly occurring systems was 30^0 - 120^0.

According to pavement types, the 90^0 orientation was common on all types but not found on Type 2B. The trends were very similar across types with a few exceptions, including the absence of the 30^0 set on Type 1 and the absence of the 150^0 set on Type 3. The 120^0 set was present on all types.

Examining Amabel joint set variation across Manitoulin Island, it seems latitude may be more revealing for jointing trends than location across the island (i.e. west end vs. central). Two conclusions can be drawn concerning jointing patterns on the Amabel pavement. Firstly, it is quite variable although some trends, such as 90^0 and 120^0 are the two basic joint patterns and appear on many sites. These seem to be the regional sets, with the 30^0 set comparatively suppressed. The 90^0 set lacks the 0-180^0 partner. Secondly, it is not clearly related to other characteristics of pavement, such as type and width, depth and length. There are also many local vs. overall trends, and one would need to sample many areas between these sites (presently under surface cover) to see how jointing trends change and link with other sites. It is known that for an escarpment fully covered with pavement, the type, joint width, depth, length and jointing direction are fairly consistent, although if the latitude changes greatly some joint trends may become more dominant. An example is formed by comparing Sites 1 and 9, with their very similar statistics and same pavement type. The common 90^0, 120^0 and 30^0 orientations are more dominant on Site 1 and the 45 on Site 9, with both being common sets for the area.

Some general conclusions can be drawn relating jointing direction to width, depth and length. It seems that longer joint lengths are related to the dominant set orientation. Width and depth have more variation, especially depth which is related to the amount of infilling (thus pavement type).

3.2.2 - FOSSIL HILL PAVEMENT

Overall, there is less karst pavement on the Fossil Hill Formation than on the Amabel. It is only extensively found at two sites. At most locations, even those with high hydraulic gradients, pavement is only exposed in patches that are close to the road where forest and soil cover have been cleared. In the lowlands there is no exposed pavement at all. The high concentrations of siliceous fossils in all Fossil Hill beds cause it to weather more irregularly than the Amabel, producing a much more rougher surfaced pavement (Figure 3.13). This also inhibits development of karren features other than grikes, pits (which seem more common than on the Amabel), pans and groovekarren down the sides of the grikes (Figures 3.14 and 3.15). These karren are more a result of attack on rock surface of varying solubility (dolomite imbedded with

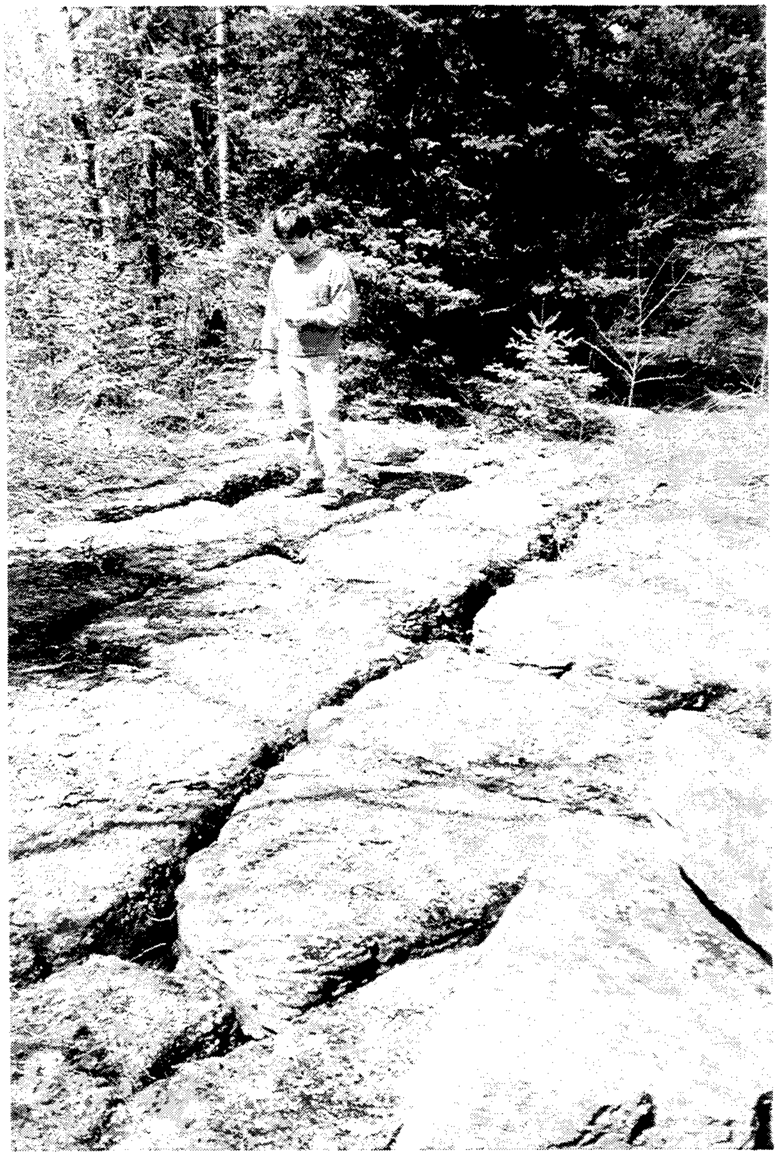


Figure 3.13 Fossil Hill pavement, near Nameless Lake (Site F1). Note very irregular, fragmented surface of pavement.

Figure 3.14 Pan on Fossil Hill pavement, Site F1. Size is 35 cm in diameter, 20 cm depth.

Figure 3.15 Groovekarren down sides of grikes and pitting at Site F1, Fossil Hill pavement. Note pits, which are colonized by mosses.

siliceous fossils), and since most sites are flat, there is little karren resulting from surface or channel flow. Groovekarren are sharper and found in greater frequency than on the Amabel pavements. Grikes are again the most common karren form. In general, mean grike depth is lower, mean width greater and length greater than at the Amabel sites. The Fossil Hill sites studied in detail include Site 1 in the central area (Nameless Lake), Sites 2 and 3 in the southeast (south of Lake Manitou), and Sites 4 and 5 in the west. Table 3.9 gives site by site data for the Fossil Hill pavements. Figure 3.16 provides the summary histograms for width, depth and length. Table 3.10 summarizes these trends according to geographical location. Due to the small number of sites that Fossil Hill pavement was found and their limited size, they were not differentiated into different types. All had the same appearance and type of karren. Site 1 was the most extensive and yielded more data than the other sites, this may skew overall summaries.

QUANTITATIVE ANALYSIS

Width

The average is width is 13.7 cm, higher than on the Amabel Formation with mean widths for most sites being between 11 and 15 cm (42.8 %). Although only a small number were greater than 21 cm (11.9 %), the proportion of comparatively wide joints was greater than for the Amabel pavements. Geographically, the central site had the greatest width,

Table 3.9

Fossil Hill Pavement Sites
Summary of Joint Characteristics

* = dominant direction

SITE NO.	MEAN DEPTH (cm)	MEAN WIDTH (cm)	MEAN LENGTH (cm)	DIRECTION (degrees)
1	24.30	17.80	633.42	75* 30, 90
2	107.67	13.58	633.33	90* - 180 30
3	45.59	15.12	275.83	90* 30, 60
4	88.13	8.75	242.18	90* - 180 30 120 ,135
5	33.24	13.17	242.18	45 - 135* 60 - 120
OVERALL MEAN	59.79	13.68	390.65	90* 30, 75 105, 135

Figure 3.16

Fossil Hill Formation Pavements: Summary of joint characteristics histograms.

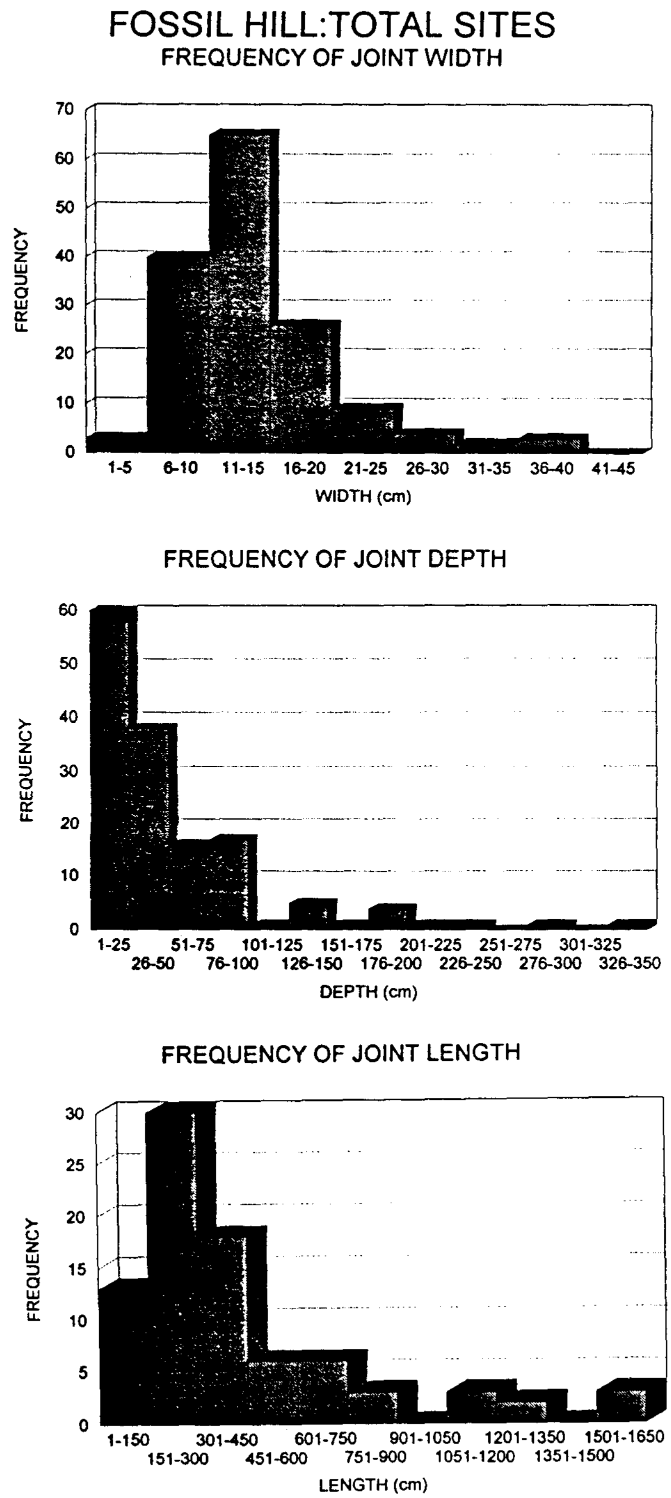


Table 3.10

Fossil Hill Pavement:
Joint Charactersitics According to Location

SITE NO.	MEAN DEPTH (cm)	MEAN WIDTH (cm)	MEAN LENGTH (cm)
Central	24.30	17.80	633.42
Southeast	76.63	14.35	454.83
West	60.69	10.96	242.18
OVERALL MEAN	59.79	13.68	390.65

followed by the southern sites (mean of 14.35 cm) and western sites had the lowest mean (10.96 cm). The widening rate since deglaciation has been calculated to be 1.3 mm per 100 years, slightly greater than for the Amabel. This is an apparent contradiction: wider joints (greater solution rates) but less extensive pavement on the Fossil Hill than the Amabel. This will be examined in the discussion.

Depth

For the five Fossil Hill sites, the mean depth is 59.8 cm, and the range is from 24.3 cm to 107.7 cm. However, the histograms show that most joints are between 1 to 25 cm deep (41.1 % with 67.1 % of grikes less than 50 cm), a much lower distribution than for the Amabel. The data are more tightly grouped than the Amabel, with few joints over 100 cm deep. This is probably because the Fossil Hill has somewhat thinner bedding and weathers more irregularly. The pavement is more likely to break up, and more grikes may become infilled, reducing measured depths. According to geographic location, depths vary across sites without much trend: each area has mean depths greater than and less than the mean. The central site has the lowest mean (24.30 cm), followed by the west (60.69 cm), and then the southeast (76.63 cm).

Length

The mean length is 390.65 cm, and most joints were between 151 and 300 cm (35.7 %) in length. A few were greater than 450 cm (27.3 %). The distribution is similar to the

Amabel. Sites 1 and 2 displayed the greatest lengths; there was greater exposed extent of pavement and thus more joints could be measured to their full opened length.

Jointing density

Joint spacing is summarized in Table 3.11 for each site and in Table 3.12 according to geographical location. The mean spacing is 251.4 cm (wide, but close to very widely spaced). Spacing ranges from a low of 115.4 cm to a maximum of 550 cm. There is a variable range at sites according to direction as shown by sites 2 and 3.

The Fossil Hill pavements have greater variation in joint spacing than the Amabel but the joints are much more widely spaced. This is another apparent contradiction since joint spacing is usually related to bed thickness (Ford and Williams, 1989). It may be that Fossil Hill pavements have greater joint spacing because of lithologic properties. Biohermal Amabel pavements may have more irregular or close spacing. Additionally, spacing is greater but depth less on Fossil Hill compared to Amabel. It could be that Fossil Hill joints extend deeper but are infilled due to the more fragmented nature of the pavement.

On both formations, all western sites display joint spacing less than 150 cm. The greatest values for Fossil Hill are at southeast sites 2 and 3, where there is no local Amabel pavement for comparison. Spacing (grike frequency) thus appears to vary with location on the island. This may be due

Table 3.11

Fossil Hill Pavement Sites: Joint Spacing

Site	Orientation (degrees)	Joint spacing (cm)
1	40	209.09
2	30 95	260 550
3	0 90	200 300
4	30	125
5	90	115.39
OVERALL MEAN	-	251.35

Table 3.12

Fossil Hill Pavement: Joint Spacing according to Location

Joint spacing	Central	Southeast	Western
MEAN (cm)	209.09	327.5	120.79

to regional trends in jointing stress or lithology.

Joint Orientation

The jointing trends when looking at site - by - site data are overall more consistent for Fossil Hill sites than for the Amabel pavement (Refer to Table 3.9). However, measurements from all Fossil Hill sites show much variation around the main trends. Although not as strong overall, on most sites are the 90^0 and 30^0 joint orientations are common. The 90^0 is the stronger direction on all sites where it is found, except on Site 5 where it and the 30^0 set are equal. The other dominant orientations are 60^0 and 120^0, also common on the Amabel, and 180^0. Other prominent directions for Fossil Hill sites include 75^0, 150^0 and 135^0, less common on the Amabel.

Table 3.13 gives jointing trends according to location. Geographically, the central site shows the two most common orientations, as well as in the southeastern sites. In the west the 15^0 set shares dominance with 90^0 and 120^0 sets. One westernmost site (5) does not have the common 90^0 orientation. These trends are similar to those found on the Amabel, although on the Fossil Hill pavements more uncommon joint orientations do occur.

3.2.3 - MANITOULIN FORMATION PAVEMENT

Karst pavement is much more limited on the Manitoulin Formation than on the Amabel and Fossil Hill. It can be divided into two types:

Table 3.13

Fossil Hill Pavement: Summary of Joint Set Orientation According to Location

Number of sites at which particular direction found (out of total of 5 sites)

Dominant Joint Class (degrees)	Central sites	Southeast sites	Western sites	Total sites
1 - 15	-	-	2	2
16 - 30	1	2	1	4
31 - 45	-	-	1	1
46 - 60	-	1	1	2
61 - 75	1	-	-	1
76 - 90	1	2	2	5
91 - 105	-	-	-	0
106 - 120	-	-	2	2
121 - 135	-	-	1	1
136 - 150	-	-	-	0
151 - 165	-	-	-	0
166 - 180	-	1	1	2

<u>Type 1</u> - This is a very shallow, flat pavement found on the regular bedded Manitoulin Formation (most sites). Joints are filled to the surface with soil and vegetation (Figure 3.17). This pavement is rarely exposed, being noted only on cleared patches on scarp tops and by roadsides, although it is likely present under thin soils and vegetation on high hydraulic gradient sites (Figure 3.18). There are no karren other than grikes at these pavements, although clint surface occasionally appears to have been etched. This pavement was studied at two sites where it occurred most extensively: Site 3 (north of Lake Wolsey) and Site 4 (Maple Point). Only some measurements of length and width were taken due to the joints being completely infilled.

<u>Type 2</u> - This a the well developed pavement found on the Manitoulin Bioherm (Site 2), which is exposed at a roadcut on Highway 6 south of Manitowaning (Figure 3.19). This pavement has a rough surface appearance and displays a variety of karren, principally rundkarren and pans (Figure 3.20), as well as some micro-rills (Figure 3.21). It is limited to the outcrop of the bioherm, along the extent of this scarp. In addition, several small patches of similar type were found on scarps on Bidwell Road, one of which had measurable features (Site 1). These exposed patches, maximum 100 m^2 in size, have a very similar appearance to the bioherm and may not represent regular bedded Manitoulin strata, although no other biohermal locations have been noted in past studies.

Figure 3.17 Very shallow pavement on well bedded Manitoulin Formation, Site M3 (north of Lake Wolsey). Grikes are filled with soil and vegetation to the surface.

Figure 3.18 Roadside pavement on Manitoulin Formation south of Little Current. This pavement is typically limited to such exposed patches in ditches and on scarp edges.

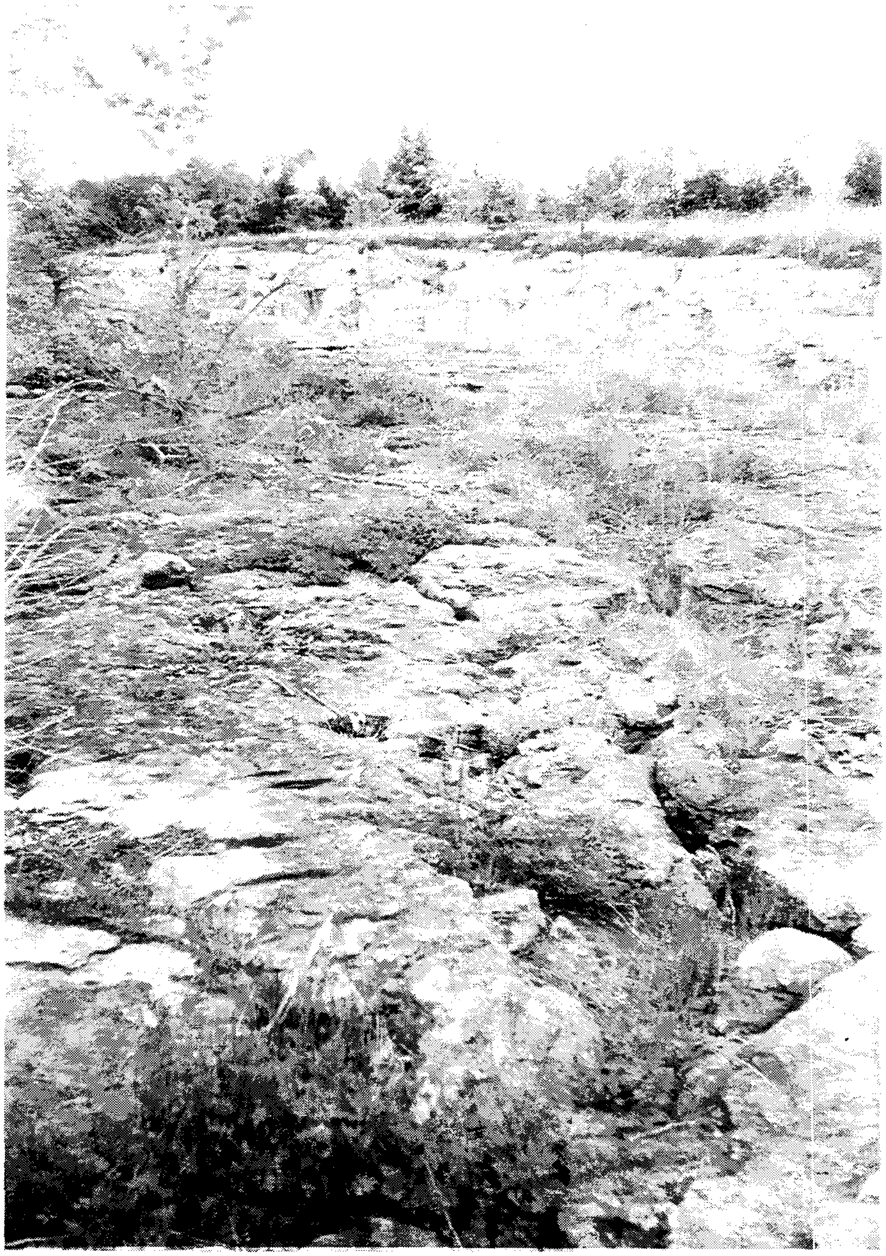


Figure 3.19 Pavement on the Manitoulin bioherm outcrop (Site M2) south of Manitowaning. Note excellent pavement form and variety of karren.

Figure 3.20 Rinnenkarren on Manitoulin bioherm, parallel to grikes. They are 1 - 2 cm deep and wide. Note groovekarren due to horizontal solution down sides of grikes.

Figure 3.21 Pan (upper right) on Manitoulin bioherm, and microrills, few mm deep and wide.

QUANTITATIVE ANALYSIS

Although there were not as many sites for the Manitoulin Pavement, some general conclusions can be made. Width, depth and length measurements were taken only at sites where they could be accurately measured (refer to Table 3.14). However at all sites joint orientation was recorded. The histograms for depth, width and length show some trends, but with a wider scatter of values and low number of observations these are not very strong conclusions (Figure 3.22).

Width

The mean width for Manitoulin pavement is 13.5 cm. The bioherm had the greatest widths, with a range from 5 to 70 cm. Most joints were between 6 - 10 cm (43.3%), and joints wider than 15 cm were on the bioherm. Type 2 pavements had a mean of 14 cm.

Depth

On Type 1 pavements joints were completely infilled. On Type 2 pavements there are two classes of joint depth: joints with very shallow depth, with skewed distribution as on the other formations, and deep grikes on the bioherm (Site 2). Most joints were less than 50 cm deep (51.3 %), but there were two other peaks: one at 176 - 200 cm and 326 - 350 cm. The latter are from the bioherm. On the bioherm (site 2) the mean depth was 182.7 cm, ranging from 35 to 350 cm. On site 1 the mean depth was 43 cm with a range of 21 to 100 cm.

Table 3.14

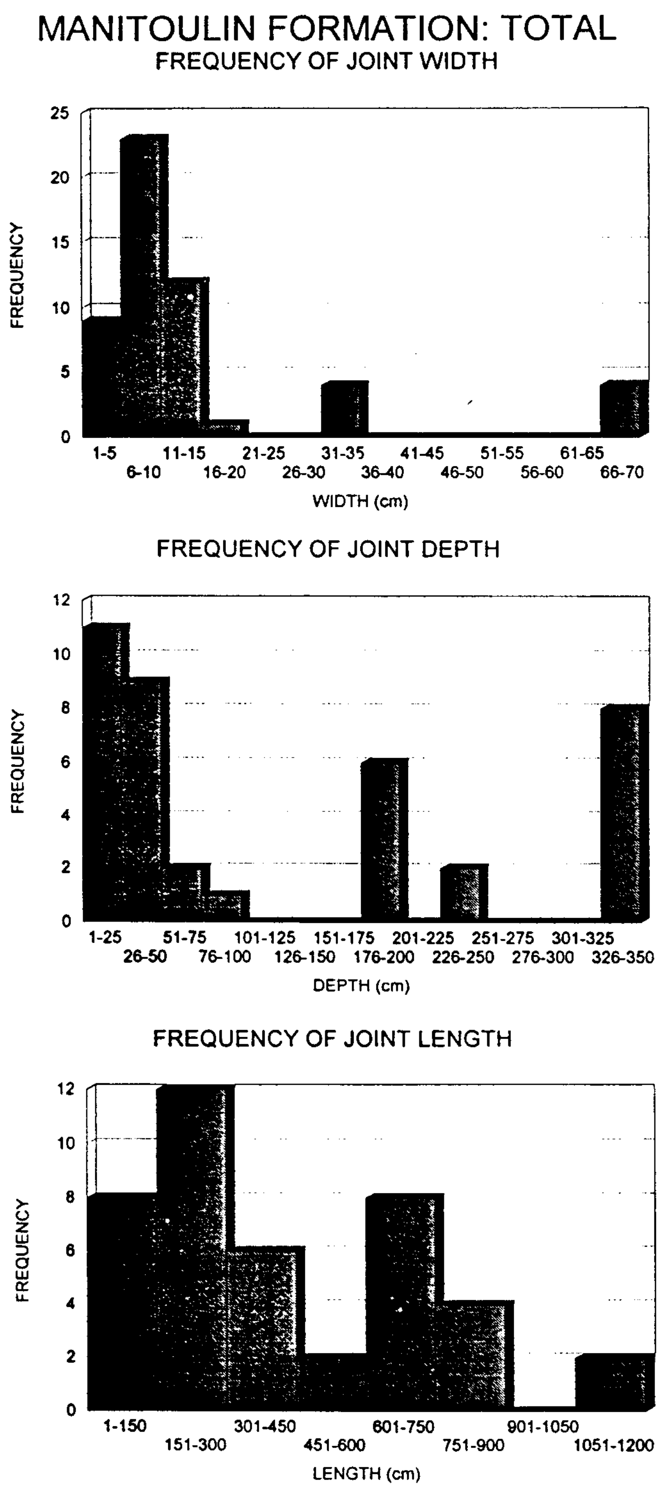
Manitoulin Formation Pavement Sites
Summary ofJoint Characteristics

* = dominant direction

Site No.	MEAN DEPTH (cm)	MEAN WIDTH (cm)	MEAN LENGTH (cm)	DIRECTION (degrees)
1	43	7.6	456.5	60 - 120* 45 - 135
2	182.67	20.47	-	90*, 150 75, 135
3	-	-	-	60 - 150* 90,45,120
4	-	12.5	330.83	90* - 180 150,15,165
OVERALL MEAN	112.69	13.52	393.67	90*, 150* 60 - 120

Figure 3.22

Manitoulin Formation Pavements: Summary of joint characteristics histograms.



Length

The mean length was 393.67 cm, and the maximum was over 10 metres in length. Most joints were between 151 to 300 cm in length, and a second peak was at 601 - 750 cm. On the bioherm length was not measured but appeared similar to Site 1. In general, because Manitoulin pavements were less fragmented than the other types, joints could be measured more accurately for their true length. This resulted in lengths greater than for the other formations.

Joint Spacing

The average for joint spacing lay between the Amabel and Fossil Hill pavements at 179.17 cm (Table 3.15). However, the bioherm (Site 2) had a value similar to the Amabel type pavements, and for one direction Site 1 also had lower spacing. Spacing appears to vary between both normal Manitoulin bedded and biohermal Manitoulin Formation pavements. All the Manitoulin Formation sites are further north and east than sites for the other pavements, this may be one influence on joint spacing along with lithology. Overall joint spacing is between the Amabel and Fossil Hill values.

Joint Orientation

For this formation the total jointing trends are influenced by variable number measurements per site, unlike on Amabel and Fossil Hill. Joint sets more commonly occur as a dominant system on the Manitoulin than on other formations (refer to Table 3.14: site data) The 60^0 - 120^0 set (shear) is

Table 3.15

Manitoulin Formation Pavement Sites: Joint Spacing

Site	Orientation (degrees)	Joint Spacing (cm)
1	60 120	250 133.33
2	90	222.22
3	70	111.11
OVERALL MEAN	-	179.17

present on half of the sites, while rectangular systems occur as 50^0 - 150^0 and 90^0 - 180^0 on half of the sites. Once again, a 90 orientation is a common trend, present on three-quarter of the Manitoulin sites. The 150^0 set is found on two-third of the sites, while 45^0, 60^0, 120^0 and 135^0 orientations are each dominant at one site. However, the 60^0 orientation is much stronger on the Manitoulin Formation pavements, present on half of sites and showing up dominant overall. The dominance of the 60^0 joint orientation could be a function of geography as much as lithology, since all the Manitoulin sites are further north and east of other pavement sites. The 30^0 trend is not dominant on the Manitoulin Formation.

3.2.4 - Other Pavements

The Amabel, Fossil Hill and Manitoulin are the formations which display pavement on Manitoulin Island, whether the extensive type with a variety of karren or limited to a few shallow joints by the roadside. The only other formation with pavement is the Mindemoya Formation, displaying some small patches east of Lake Wolsey, which were too small and fragmented to sample. Main jointing directions were at 75^0 - 165^0, the joints were less than 50 cm apart, and there where few runnels and pitting infilled with moss. Two other carbonate formations, the Kagawong and Lindsay, show no signs of pavement development other than the occasional widened joint. However, both are karstic since there is water seepage into both units (including some small sinking streams on the

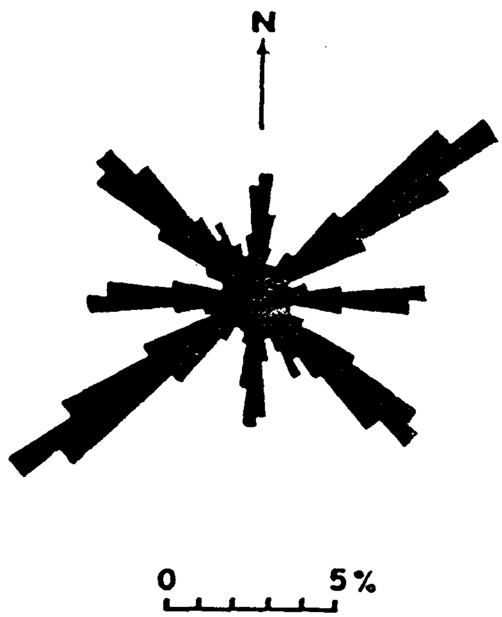
Kagawong), and springs emerge at the scarp bases of these formations. Other field observations and lab tests may lead to insight into why the above pattern is observed.

3.3 - Regional Jointing in the Michigan Basin

Various forces are responsible for joint development. They may be opened during diagenesis, later tectonism, erosional loading and unloading or caused by shear or tension forces (Ford and Williams, 1989). Holst (1982) examined joint set orientation at 142 locations across the Michigan Basin, including Manitoulin Island. He found consistent joint set orientation across different formations, ages and locations. The most frequent peaks were at 134^0 and 52^0, with secondary sets at 0^0 and 90^0 . His summary rosette diagrams are presented in Figure 3.23. Holst's main joint set directions do show up in the Manitoulin data obtained in this research, although they are not dominant. Table 3.16 summarizes jointing trends across the island. The 90^0 set is strong, as in Holst's study, but the other main joint set trends seem to be offsets of Holst's main sets. These are the 60^0 set (offset of 52^0) and the 120^0 set (offset of 134^0). These differences may be due to a number of factors. Firstly, 15 degree intervals were used to plot joint directions in this thesis, whereas Holst used 5 degree intervals. Thus in this research some measurements could be plotted in different classes than Holst's resulting in offsets from his dominant sets. Secondly, many joints are

Figure 3.23

Regional jointing in the Michigan Basin (Holst 1982).



Rose diagram of total vertical joint data from northern Michigan Basin—14,452 joints. Scale is 0% to 5% of total data within each 6° sector.

Table 3.16

All Formations : Summary of Joint Set Orientation

According to formation : Number of sites at which particular direction found (total 20 sites)

Dominant Joint Class (degrees)	Amabel sites	Fossil Hill sites	Manitoulin sites	Total sites
1 - 15	1	2	1	4
16 - 30	5	4	0	9
31 - 45	3	1	2	6
46 - 60	1	2	2	5
61 - 75	3	1	1	5
76 - 90	8	5	3	16
91 - 105	1	0	0	1
106 - 120	7	2	2	11
121 - 135	0	1	2	3
136 - 150	4	0	3	7
151 - 165	0	0	1	1
166 - 180	1	2	1	4

curved or sinuous on Manitoulin Island, and were sometimes included in the measurements, while Holst excluded these. This could also result in more variation around his dominant trends. Finally, Holst's summary rosettes include a larger number of data than this research on Manitoulin; perhaps with more measurements the results would be closer to his.

These main joint set patterns may be related to structural trends, as Holst concluded, since the regional strike is at 135^0. The 134^0 trend is aligned to a series of major folds in the Palaeozoic rock, thus could be longitudinal or bc-joints. The 90^0 regional joint set strongly dominates pavements on all formations on Manitoulin Island. This east - west set is the regional set. It may be a strike joint set since the stratal dip is to the south. However, since the 0 - 180^0 set which intersects it was found to be almost absent in this study, it is unlikely that the 90^0 set is a simple tension (contraction or unloading) set. It may represent a regional force, such as loading in the Michigan basin (D. Ford, personal communication). The 52^0 set is parallel to the maximum compressive stress present today in the mid-continent region (at 53^0). These could be extension or ac-joints, possibly caused by high horizontal stress from spreading in the North Atlantic, lithosphere-asthenosphere drag under the North America plate or "ridge-push" force (Holst, 1982).

On the Bruce Peninsula, Cowell (1976) observed most grikes following 100^0 and 155^0 orientations on the Amabel pavement, close to the 90^0 and 150^0 sets dominant on Manitoulin Island. His measurements also showed the 90^0 peak, with other peak orientations at 75^0, 160^0 and 45^0, forming two major sets 60^0 to 70^0 apart. On the Door Peninsula, Rosen and Day (1990) found the main sets to be 25^0, 70^0 and 155^0. It seems that throughout the Michigan basin, certain joint orientations are more common, but locally the dominant set varies.

3.4 - Insoluble Residue Analysis

Through the field observations, it is clear that the extent of karst pavement varies substantially between bedrock formations. There is widespread occurrence of pavement on the Amabel and Fossil Hill formations, limited pavement on the Manitoulin Formation and little pavement elsewhere. This suggests that some property of the bedrock itself may be controlling the potential and rate of karstification. It was hypothesized that variability in bulk rock solubility, as determined by percent insoluble residue, may play a major role. Thus, all formations on Manitoulin Island (excluding shales or very clay-rich formations) were sampled.

Earlier research indicates that the best karst tends to occur in rocks greater than 90 % soluble. Ford and Williams (1989) have found many young limestones and dolomites to be greater than 99 % soluble. In rocks with greater than 20 - 30 % impurities (most commonly clay and silica) good karst rarely develops. Typically, dolomites have lower mineral solubility than limestones.

Fifteen samples were taken from the five main karstic formations on Manitoulin Island and analyzed in the lab to determine the percent of insoluble residue present in the carbonates (methods reported in Appendix 3). The results are presented in Table 3.17.

The four samples from the Amabel formation have the lowest mean insoluble residue (4.9 %), with a range from 2.1 % (overall lowest) to 6.9 %. The insolubles tended to be very fine (likely clay particles), with a small amount of cherty fragments. The Fossil Hill, showing second best karstification on Manitoulin, had a mean insoluble residue of 7.3 %, ranging from 4.2 % to 12.9 %. These are higher values since all three samples had large amounts of siliceous fossil fragments in their residues, although much of the carbonate bedrock itself dissolved. The four Manitoulin Formation samples had a mean insoluble residue of 5.8 %. The bioherm sample M2 had a very low value, within the range of Amabel samples (2.6 %), while other Manitoulin samples (from normal bedded deposits) had an mean of 6.8 %. Kagawong samples had the highest percent insolubles, ranging from 8.2 % to 17.4 % (mean 12.2 %). The Lindsay sample from Little Current had 4.1 % insolubles, which is low for a formation with little karst.

A Kolomogorov - Smirnov (K-S) test was performed on the insoluble residue data for the Amabel, Fossil Hill, Manitoulin and Kagawong formations to determine whether the distribution

Table 3.17

Results of Insoluble Residue Analysis

SAMPLE	INITIAL ROCK WEIGHT (g)	RESIDUE WEIGHT (g)	PERCENT INSOLUBLES
Amabel - A1	51.0	1.1	2.1
A2	50.2	3.5	6.9
A3	49.9	1.9	3.8
A4	48.3	3.4	6.9
Fossil Hill - F1	49.9	2.4	4.8
F2	51.9	6.7	12.9
F3	52.7	2.2	4.2
Manitoulin - M1	49.2	2.6	5.2
M2	53.9	5.1	9.5
M3	49.8	2.9	5.8
MB	50.3	1.3	2.6
Kagawong - K1	49.6	4.1	8.2
K2	52.0	9.0	17.4
K3	50.7	5.5	10.9
Lindsay - L1	51.9	2.1	4.1

of percent insolubles were significantly different, i.e. not attributable to chance (Table 3.18). The tests confirms the field observations; the Kagawong Formation has significantly more insoluble material than the other three formations. Differences between the three formations exhibiting pavement are not statistically significant, as reflected by a similar range of insolubles. However, if the percent insoluble ranges for the two more karstic formations (Amabel and Fossil Hill) are compared to the two less karstic formations (Manitoulin and Kagawong), they are found to be significantly different.

The results of the insoluble residue analysis support the field observations on the amount of karstification on different formations across Manitoulin Island. As expected, the Amabel, which shows the greatest extent and variation of pavement, has lowest overall insoluble residue values. Since most of the bedrock can be dissolved, good karst is possible on many sites, and much of the soil may be lost down wider and deeper grikes, exposing bare pavement to the surface. Secondly, the Fossil Hill, although containing large amounts of siliceous fossil material, allows pavement to develop because much of the carbonate dissolves. Apparently the large siliceous fossils do not obstruct incipient karst fissures as effectively as silt and clay residues. However, their presence limits karren development and results in a very irregular, pitted appearing pavement. Less soil may be lost since pavement is less developed, and heavier forest cover may

Table 3.18

Significant Differences between Insoluble Residue Samples based on K-S two sample test

Test 1 = Amabel vs. Fossil Hill
Test 2 = Amabel + Fossil Hill vs. Manitoulin + Kagawong
Test 3 = Amabel vs. Kagawong
Test 4 = Manitoulin vs. Kagawong
Test 5 = Amabel vs. Manitoulin
Test 6 = Fossil Hill vs. Manitoulin
Test 7 = Fossil Hill vs. Kagawong

Test No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
	-	***	***	***	-	-	**

(All significance levels are given in Appendix 4)

NOTE:

*** = < 0.01 significance
** = < 0.1 significance
* = < 0.2 significance
(indicates that the samples being compared are significantly different at the above level)

regrow following clearing. The Manitoulin Formation overall has higher insolubles therefore only shallow, limited pavement develops and soil cover can be maintained. The bioherm is the exception, with few insolubles and pavement as well developed as on the Amabel. The Kagawong Formation, with greatest percent insolubles, has no real pavement although water seepage into the ground occurs. All formations show some groundwater seepage and have springs regardless of their percent insolubles. This is likely more limited and of smaller scale on the formations with higher insolubles compared to the Amabel where drainage through extensive pavement is common.

This research reinforces previous findings that for many limestones and dolomites there is significant bed - to - bed variability in solubility within a given formation. Although a much larger set of samples would be needed to clearly differentiate these variations, this preliminary work lays the ground for future research.

The contrast between well developed, widespread dolomite pavement (Amabel) and no pavement (Kagawong) is only approximately 10 % in insoluble residue, which is very low to explain the great difference in karstification. Other evidence needed to account for this variation in karst occurrence comes from field observations. The Amabel Formation is massively bedded, often occurring in the form of bioherms. This is best for karst development since it does not limit the vertical percolation of groundwater thus does not limit the solution process. The Fossil Hill is thinner bedded than the Amabel: at the Formation type section, the beds between 10 - 15 cm thick, although it is usually more massive. In addition, the high proportion of siliceous fossils evidently reduces the overall karstification potential.

For the other formations, bedding may be yet a more important limiting factor. The Manitoulin Formation beds are between 4 - 5 cm to maximum 15 cm thick, with shaley material forming the interbeds or partings. At roadcuts joints extend to a maximum depth of 2 metres (Figure 3.24 and 3.25). Siliceous vugs are common at some sites. Kagawong carbonate beds are in groups approximately 65 cm thick, with each individual bed approximately 18 cm thick. There are many interbeds of 2 to 3 cm thick, composed of a shaley, muddy material appears highly insoluble (Figure 3.26). Few shallow joints are exposed at roadcuts in the scarps. Along with the Lindsay Formation, these three tend to break up into blocky, flaky fragments. Pavement could not develop extensively because percolating water encounters many shaley interbeds, acting as blockers to flow. Water may horizontally enlarge bedding planes or seep out shortly at the scarp (shallow groundwater flow). Additionally, the rock tends to fragment easily thus any pavement would rapidly disintegrate. Overall, the more frequent the shale interbeds and the thinner the bedding, and the greater the percent insolubles, the more likely the intervening carbonates will be non-karstic. These

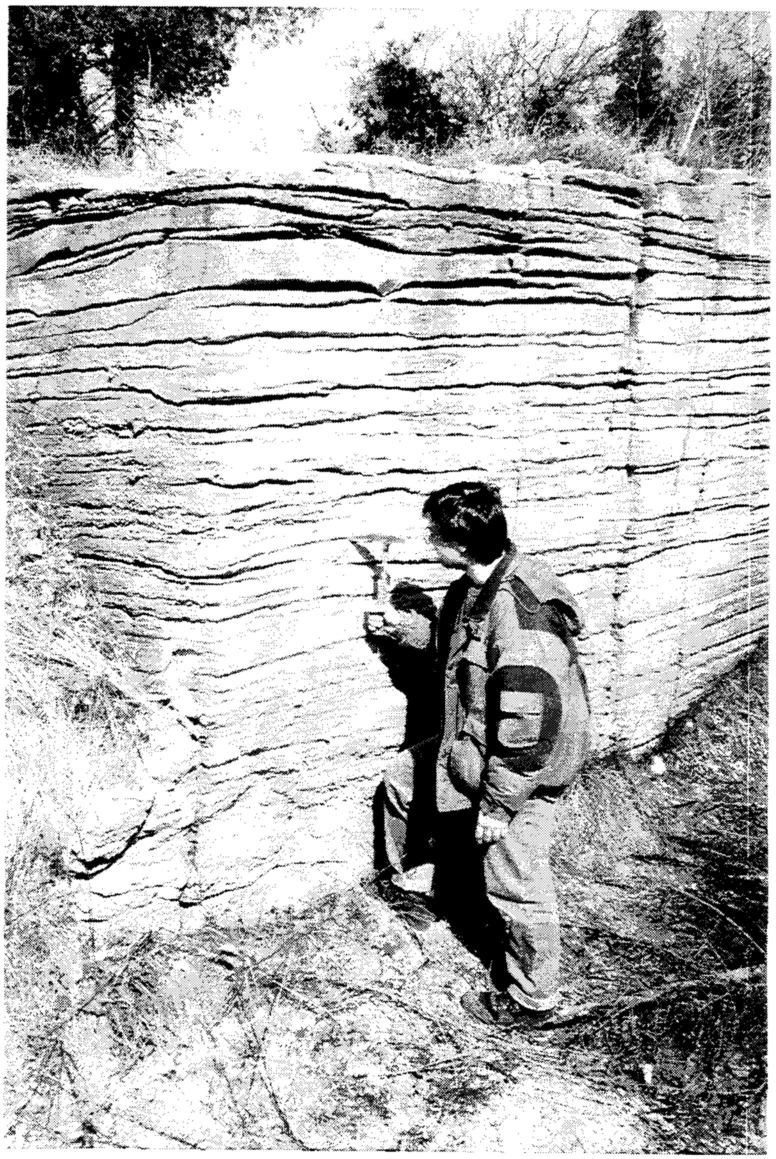


Figure 3.24 Normal bedded Manitoulin Formation at roadcut. Deep grikes are found only at the scarp edge and extend up to 2 m in depth.

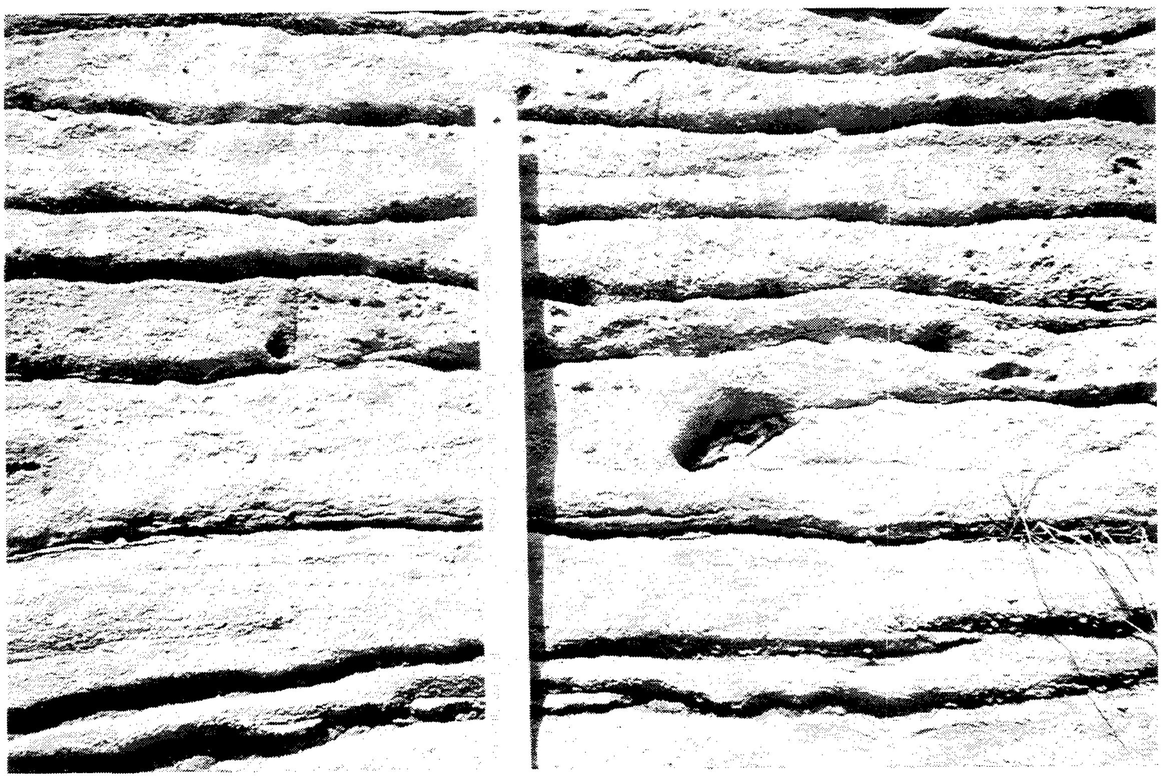


Figure 3.25 Bed thickness on normal bedded Manitoulin Formation, from 5 to 15 cm. Note large siliceous vug to right of ruler; they are quite common, up to 15 cm in diameter.

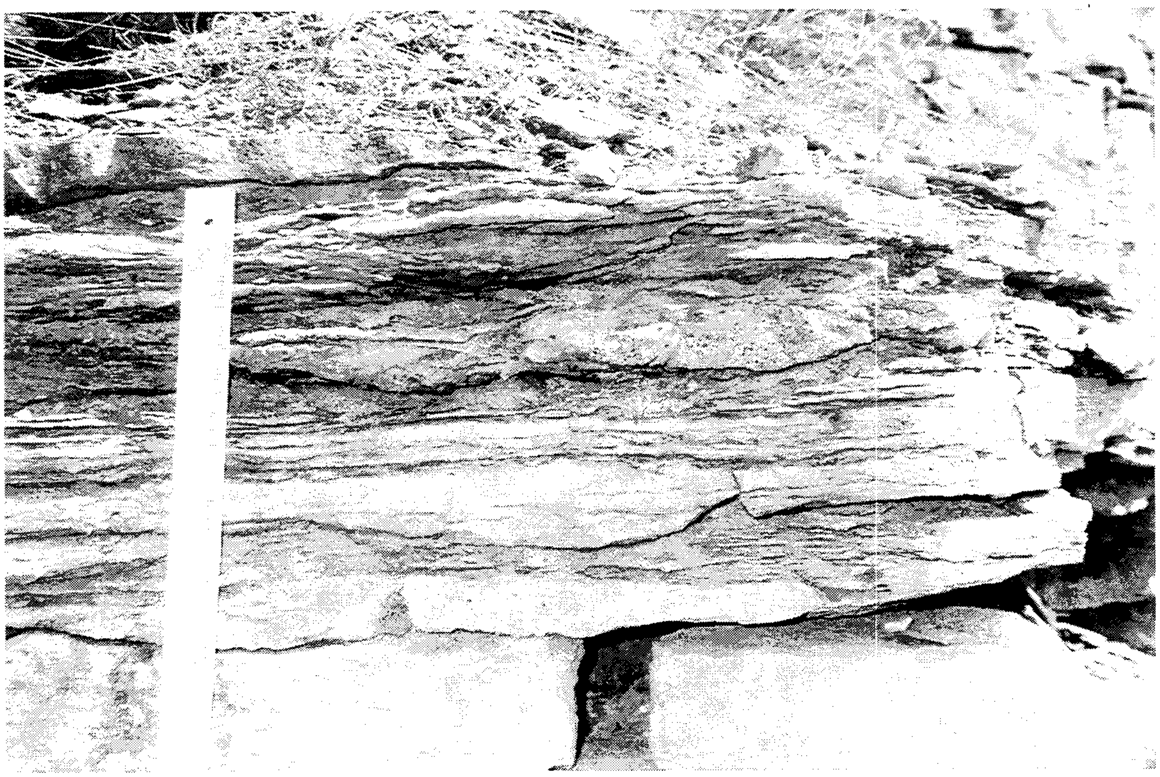


Figure 3.26 Kagawong Formation at roadcut, exhibiting very thin beds (5 - 15 cm) with frequent shale interbeds, resulting in reduction of solubility.

factors disperse solutional attack thus karst, if it develops, will be very limited. The karst that develops may be a number of small, independent or poorly connected solution conduit systems as carbonates are "sandwiched" between the shales. The greatest extent and variety of karst pavement will be on massive, highly soluble carbonates such as the Amabel with low percent of insolubles (including shale, chert and siliceous fossils) (Ford and Williams, 1989).

The insoluble residue results suggest that on dolomites greater than 90 % solubility and massive bedding is the best for karstification. If solubility is 90 to 95 %, there may be transition into limited karst if the beds are clay rich. Beyond 10 % insolubles there are few karst forms although groundwater seepage may occur. Bed thickness and frequency of shale interbeds complicates the karst potential on Manitoulin Island.

3.5 - Coastal Pitted Zone

Small scale karren features are common along the shorelines of the Bruce Peninsula and Manitoulin Island. They are present at and below the water surface, as well as extending inland to various distances. They are also found on the shores of some inland lakes, where they are much more limited in form. On Manitoulin Island features were noted around Silver Lake and Lake Manitou, but likely exist around other lakes.

Vajocki (1993) studied the morphology of subaqueous pitting on the Bruce Peninsula, and examined morphological pit variation with increasing water depth. These littoral pits are solutional in origin, with numerous processes potentially responsible for their formation, the most important being biological erosion and dissolution. Other factors may include wave, tide, spray action, salt weathering (on ocean coasts), hydrolysis, hydration, sand abrasion, mass movement and frost action. Cowell (1976) believes that rainwater initiates pits at random or in pre-existing hollows such as glacial striae, then these form preferred sites for colonization by moss, lichen and algae. The vegetation releases organic acids which enhance dissolution within the pit. The initiation of pits above lake level is supported by pitting found on Amabel and Fossil Hill pavement sites far inland on Manitoulin. However, the pits inland are smaller and found at much lower densities than on the coast. This supports the conclusion reached by Vajocki, that pits become enlarged in the littoral zone. She found that a positive linear relationship exists between increasing pit depth and increasing water depth. The zone of intense pitting is from the high storm water mark to depths of 25 m or more (maximum may be 100 m). The most common pit cross-section is parabolic. On close examination there is no evidence of biological erosion by organisms such as borers or grazers underwater. Chemical analysis revealed that the water is close to saturation with respect to limestone and dolomite in lakes, unless dissolution is possible in colder weather and during storms. All coastal pitting sites have been both completely submerged and emerged in the period since the last glaciation, approximately 10,000 years. Vajocki's model calls for pit initiation subaerially in the spray zone, with rising lake levels these zones became submerged and pits could be enlarged subaqueously.

Pitted littoral zones observed in the field research for this thesis are similar to those described on the Bruce Peninsula. For the purpose of regional comparison, pitting was examined in detail at three sites, all on the Amabel Formation.

1) South Baymouth (Site 1)

The zone of pitting at this location is on a series of whalebacks on the shoreline (Figure 3.27). The whalebacks were on average two metres in height, two to five metres across and 10 to 15 m in length. The pitting zone extending back into the forest, where pits were colonized by mosses. The pitting was greatest in density near the water mark, but was highly variable. Where measured it appeared that the average was 450 pits/m^2 on top of whalebacks; however, the maximum density appeared to be underwater where it could not be measured. In general pit width was greater than depth. Pits were on average 15 to 20 mm wide and 10 to 15 mm deep. The larger pits close to the water mark were 30 mm wide by 20 mm deep on average. Pits were circular in shape. Many pits near the water mark were amalgamated. There were also many pans on the whalebacks,

Figure 3.27 Whalebacks with dense pitting on Amabel Formation at South Baymouth (Site P1). Note increase of pitting density near water level.

on average size of 17 cm deep and 37 cm wide, although many were 10 cm wide by 5 cm deep (Figure 3.28). Many had pitting develop within the pan. Many pans had red algae in them, and the pits were covered with brown and green moss and black lichen. There were a few rinnenkarren which seemed aligned to the pits.

2) Providence Bay (Site 2)

The pits were located on flat bedding surfaces sloping gently to the water, and dissected by joints. Pit density recorded was $330/m^2$ close to the water and $69/m^2$ ten metres back from the shore. Pits were 25 mm wide and 15 mm deep on average. They were very circular and smooth, while smaller micropits (7.5 mm wide and 5.0 mm deep) were more uneven in form (Figure 3.29). Pans up to 40 - 55 cm in diameter and 6.0 cm deep were present. Pits were amalgamated, but not in as great numbers as at South Baymouth. Some pits were aligned along striae and small fractures (Figure 3.30). Zones with intense pitting or micropitting were interspersed at random with zones showing no pitting.

3) Missisagi Lighthouse (Site 3)

The pitting density here was greatest, at $665/m^2$, on flat beds sloping to the shore. The average width was 19.5 mm and depth was 14.6 mm for pits at this site. They had sharp rims and the zone of intense pitting extended back over 30 metres inland. Many were aligned to ice scour marks at 40 degrees.

At Misery Bay (Site 4), a very flat, shallow pavement (no

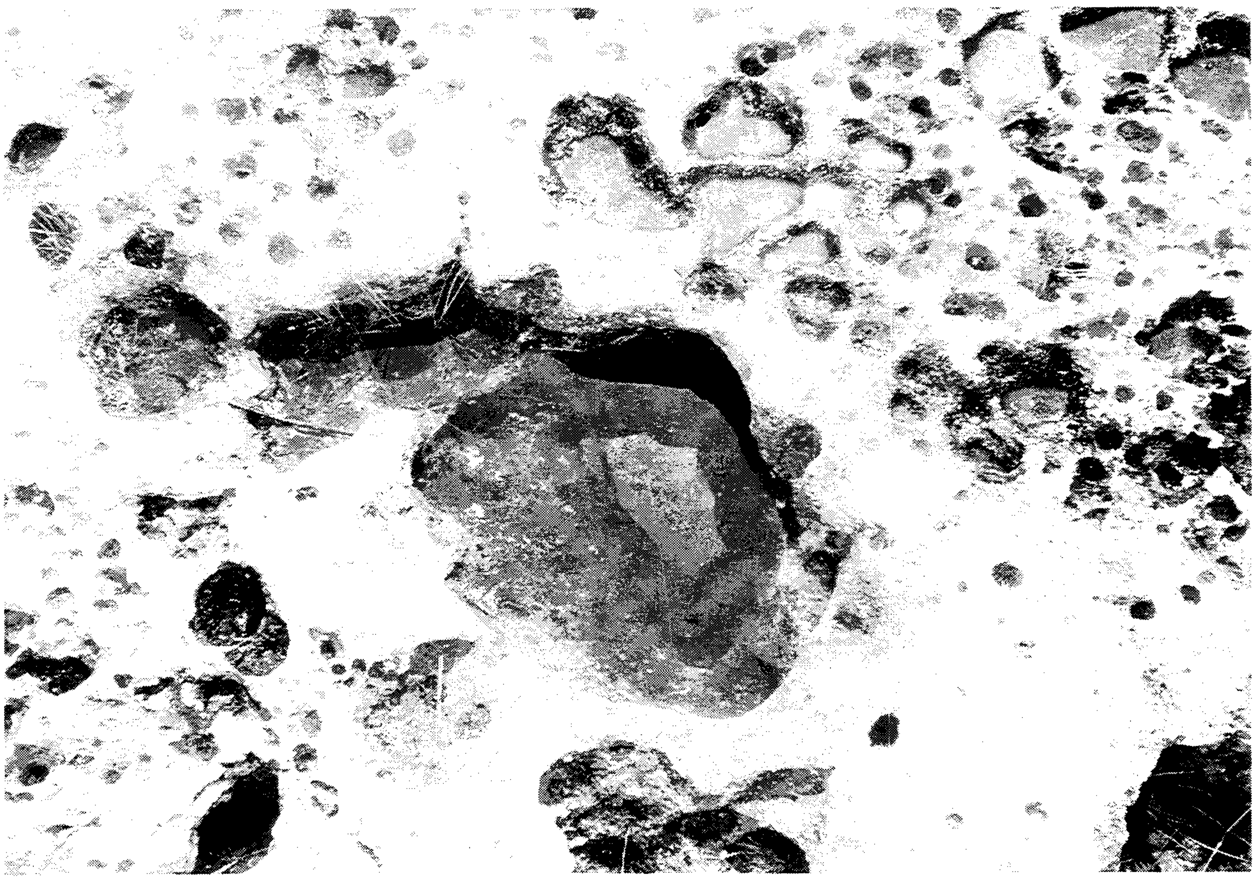


Figure 3.28 Large pan at South Baymouth, 37 cm in diameter and 17 cm in depth. Note amalgamation of pits in upper right to form larger pans.

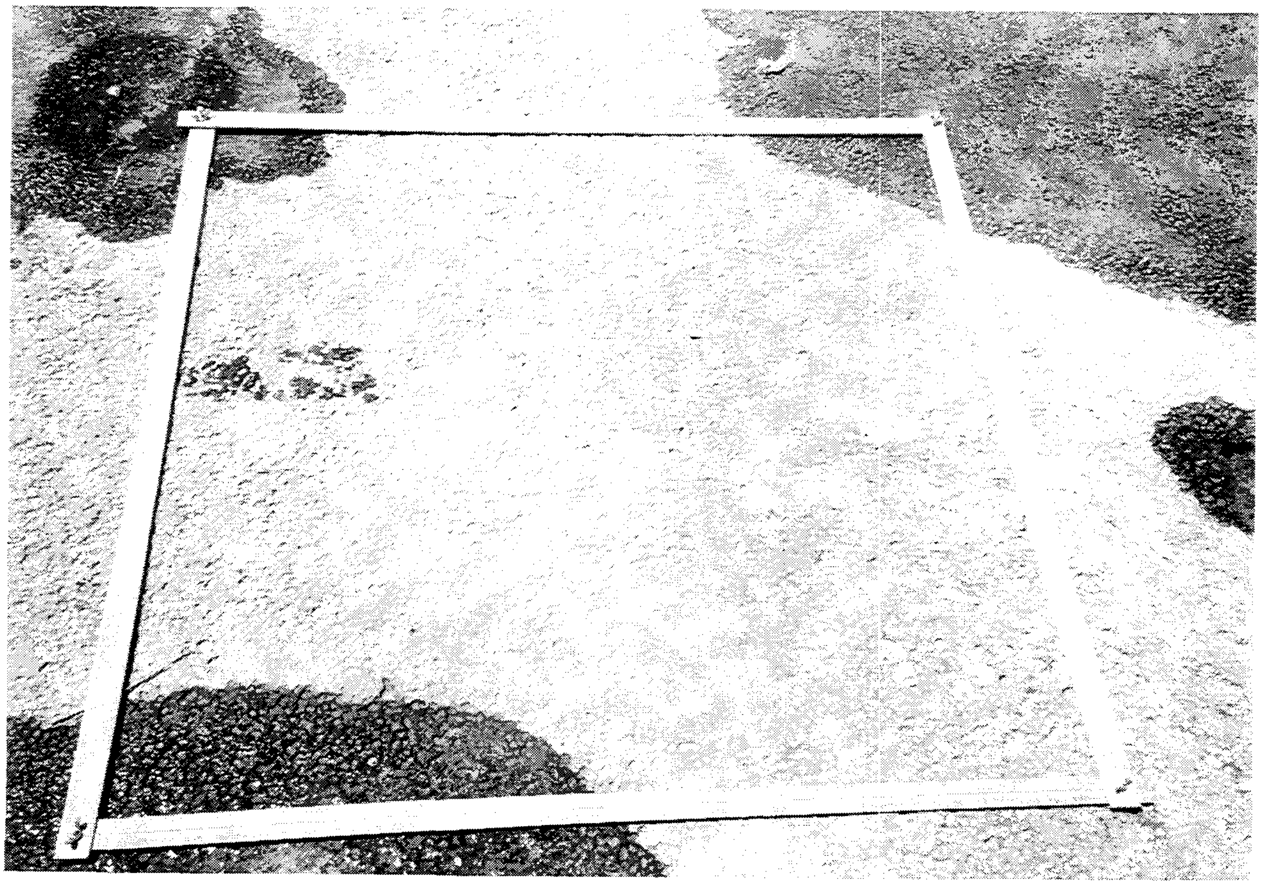


Figure 3.29 Micropitting at Providence Bay, Amabel Formation (Site P2). Pits are on average 0.5 cm in width and depth. Their occurrence varies with small patches featuring typically sized pits.

Figure 3.30 Pits aligned along fractures (striae), at Providence Bay. Many pits are infilled with moss, here 20 m back from the littoral zone.

grikes) was marked by pitting similar to that on the coast, but much less developed. This was on a site 2 km inland from the south shore (Figure 3.31).

For comparison to Vajocki's results, densities on the Bruce Peninsula pitted pavements ranged from 800 to 2200/m2 in the subaqueous zone, widths were from 9 - 19 mm and depths from 10 to 47 mm (greater range). On Manitoulin Island pitting was less dense since pits underwater were not included in this study, although widths and depths were within Vajocki's range.

3.6 - Discussion

The above classification is a simplification of the character of dolomite pavements on Manitoulin Island. These pavements display great variations according to location, lithology, stratigraphic structure and local environmental control (soil cover and vegetation history, to be discussed in Chapter 6). It is a very complex landform.

The pavement is continuous over most of southern and western Manitoulin. It is absent only in lowlands filled with thicker glacial deposits, especially clays (Chapter 7). The presence of thick glacial drift inhibits karren development, since flow is very slow or diffuse, especially if the drift is calcareous (as in Southern Ontario). Only small-scale pitting may occur. Additionally, there is greatest potential for karren development at scarp edges where there was greatest rupture by pressure from ice flow against the free face.

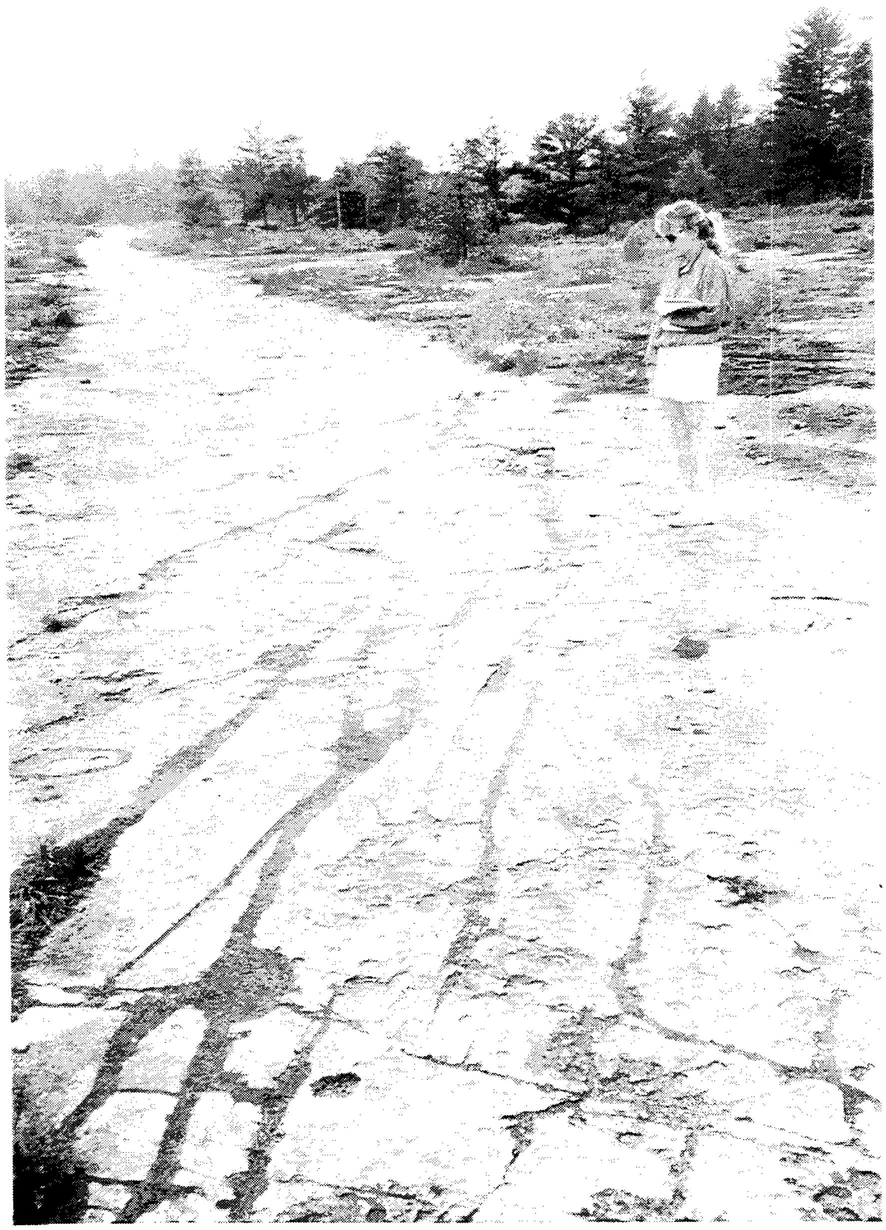


Figure 3.31 Pitted shallow Amabel pavement at Misery Bay (Site P4), 1 km inland from the Lake Huron shore. Many pits are aligned along striae.

Pavement is found over a very wide range of hydraulic gradients occurring on the Amabel including on the very low elevations near the south (Lake Huron) shore. On the Fossil Hill, it is more limited to smaller patches on scarptops, with a rougher, clittered appearance. From the exposure of pavement in roadside patches and forest clearings, it is presumed that good pavement exists under the heavier modern forest cover. Pavement development under forests would result in a rough pitted surface appearance, with subdued (not sharp) karren forms. Only where soil acids are locally concentrated are (mirco) karren very sharp. Under the forest cover, enhanced dissolution from soil CO_2 allowed for pavement development on the Fossil Hill. However, grike development may have been somewhat limited so that there would not be a great a loss of soil and vegetation as on the Amabel. Perhaps this results in greater width of grikes than on the Amabel but shallower depth. Overall, the thinner bedding on the Fossil Hill compared to the Amabel limits the depth of pavement, thus grikes can be infilled closer to the surface, retaining most of the soil and vegetation cover. In contrast, deeper grikes on the Amabel resulted in greater soil loss and did not allow full regrowth of forest on most sites once cleared.

The north - south transects reveal that there is very little pavement on the north scarp, except very close to the scarp edge. This is because pavement on the Manitoulin Formation was only well developed on the bioherm while the

Kagawong Formation exhibited no pavement. Toward the south, as the more karstic units (Amabel, Fossil Hill and Mindemoya) outcrop on the scarptops, the best pavement is found.

Compared to the Bruce Peninsula, there is not such a great variety and frequency of karren on the Amabel Formation on Manitoulin Island. The forms seem more subdued, perhaps due to a shorter time frame for pavement development on Manitoulin, due to later emergence from beneath the post-glacial lakes. An unusual feature on Manitoulin Island pavements is that rinnenkarren are rare. They are not typically found on dolomites which are coarse grained, but on Manitoulin dolomites are fine grained. Development of pavement under forest cover may be a factor here. Unlike the Bruce, there is no Guelph Formation pavement on Manitoulin, but the Fossil Hill seems to display many similarities. Solutional attack on physically heterogenous bedrock (here due to siliceous fossils) results in a very irregular and rough surface appearance, and limits development of karren except grikes and pans. Both Guelph pavement on the Bruce Peninsula and Fossil Hill pavement on Manitoulin Island are very pitted. There is also a pitted littoral zone on the Amabel on both the Bruce Peninsula and Manitoulin Island, with similar characteristics.

The dolomite pavements on the Door Peninsula in Wisconsin show a similar variety of forms, principally clint and grikes, runnels, pans, groovekarren and pitting. However, on the Door

Peninsula pavements occur in schichttreppenkarst (stepped karst) assemblages, while on the Bruce Peninsula and Manitoulin Island most do not, although there is some staircase topography on scarp crests due to variation in bedrock resistance (Johnson and Stieglitz, 1989). The stepped karst results from glacial action preferentially stripping away alternating thin and thick beds, as dictated by lithology, on the Door Peninsula. On Manitoulin Island and the Bruce Peninsula, glacial ice flow was down the stratal dip, while on the Door Peninsula it was the reverse. This may account for the lack of schichttreppenkarst on Manitoulin Island. A further contrast to the Manitoulin Island pavements is that preglacial pavement features may exist on the Door Peninsula, as inferred from a bimodal distribution in grike width (Rosen and Day, 1990). On Manitoulin Island, there is only one set of distributions for main joint characteristics and a significant pre-Wisconsin Glacial pavement inheritance is not likely.

Pavements in all three locations display similarities in their position (usually high hydraulic gradient scarp crests), jointing direction and general characteristics including karren type. They are all on Niagaran dolomites with a consistent chemical composition (Cowell, 1976). Differences are due to location within the Michigan Basin (affected by regional jointing and glacial and post-glacial history), and local factors such as lithology, presence of glacial deposits and hydraulic gradient as dictated by topography.

Chapter IV: Hydrology, Hydrogeology and Macrokarst

4.1 Introduction

The hydrogeology and hydrology of karst regions is very different from that in non-karst areas. Due to the greater solubility of carbonate bedrock, most drainage is directed underground. Much of the understanding of groundwater flow cannot be inferred through conventional techniques used to study non-karst aquifers. Linkages between input and output points in a karst system require special techniques such as dye traces, which were beyond the scope of this study. However, field reconnaissance was used to characterize drainage areas from occurrence of surface karst features. GIS analysis also proved to be a useful tool in understanding drainage patterns on Manitoulin Island.

There are two main karst aquifers on Manitoulin Island. They are divided by the main aquiclude of the Cabot Head shales, which block flow from the upper aquifer, causing groundwater flow to emerge as springs at the base of the central scarp. The upper (southern) aquifer is formed by the highly karstic units of the Amabel, Guelph, Fossil Hill and Mindemoya formations. The second, lower aquifer is formed by lithologic units lying below the Cabot Head shales which outcrop on the north side of the island (carbonates include

Manitoulin, Kagawong and Lindsay Formations). The baselevel for this aquifer is the lake level (580 ft) of the North Channel. Both are highly fractured dolomite and limestone aquifers, however, differences in lithology result in differences in aquifer characteristics including drainage type.

In karst regions hydraulic gradient determines the impetus for water to drain in a particular direction, overland or underground. Hydraulic gradient is represented by:

$$dh/dl \qquad (1)$$

and determines the quantity of water flowing through a porous medium proportional to the difference in total hydraulic head between the inflow and outflow points. Hydraulic head (h) is the sum of the elevation head and pressure head, at a given point below the water table, and is a product of depth, unit weight of water and atmospheric pressure (Ford and Williams, 1989). Figures 4.1 and 4.2 illustrate these concepts.

A hydraulic divide may be calculated along a scarp edge. This determines where there will be first order drainage down the shallow back slope either as surface or groundwater, depending on the bedrock and surface geology, or second order groundwater drainage towards the steep scarp face in karstic bedrock. Topography (local relief) controls hydraulic gradient: the highest and lowest points determine the recharge and discharge areas. The shortest distance between the two results in the steepest hydraulic gradient, therefore the most

Figure 4.1a

Hydraulic Gradient: Concepts and Calculation.
(D. Ford and D. Cowell, personal communication).

Calculation:
A right-angle triangle is formed with the scarp face as the opposite side and the distance back from scarp face as the hypotenuse. The length of the hypotenuse is calculated for where a = 1^0 (regional dip of 17m per 1000 m). This marks the early potential division between groundwater drainage downdip and groundwater drainage towards the scarp foot. 0.003 (3 m per 1000 m) is a probable final minimum for hydraulic gradients on Manitoulin Island.

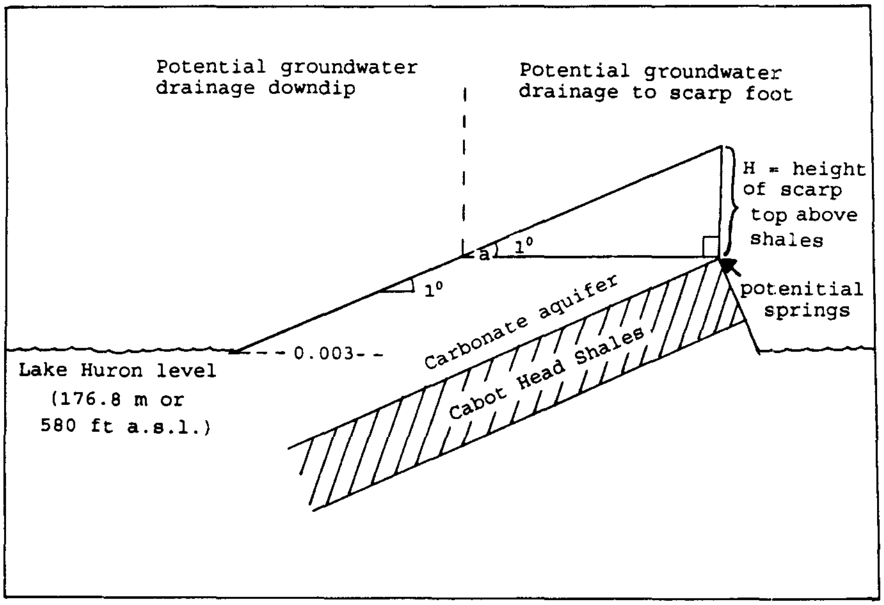


Figure 4.1b

Idealized north - south cross-section of Manitoulin Island. Illustrates location of two carbonate aquifers, shale aquiclude and general drainage features. (not to scale)

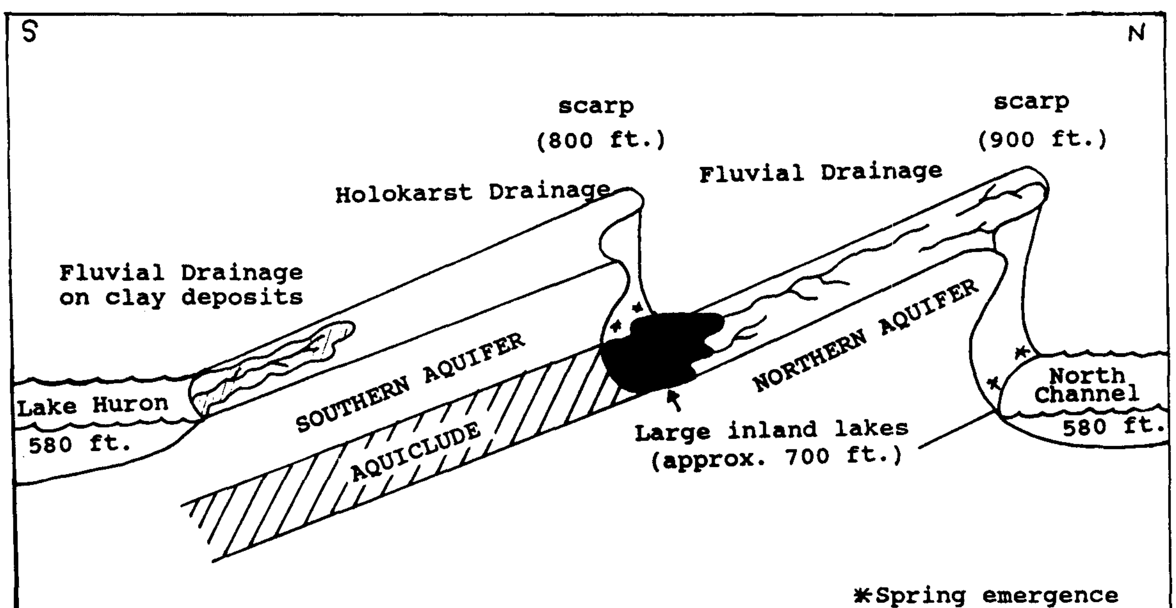
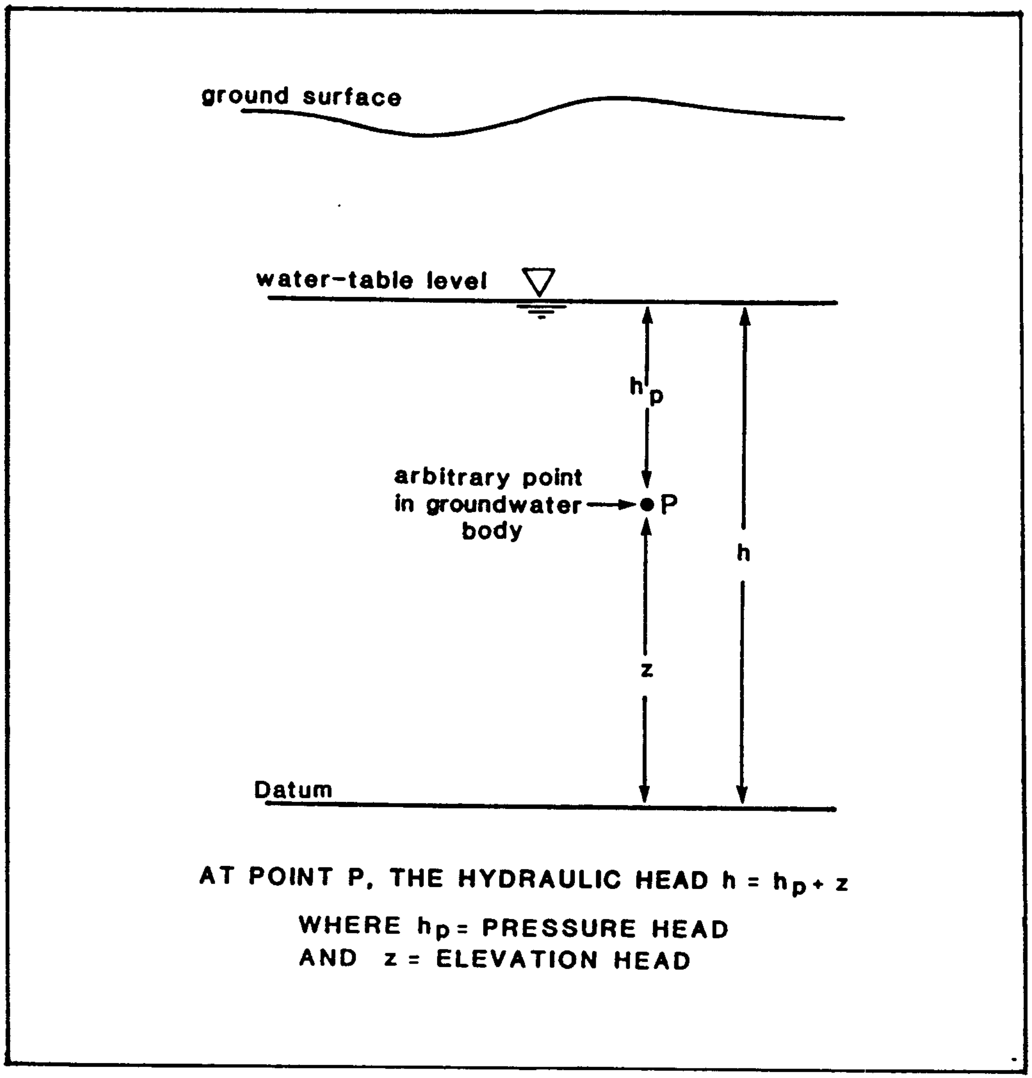


Figure 4.2

Definition of hydraulic head, pressure head and elevation head for an unconfined aquifer (Ford and Williams, 1989).



preferred route for water flow. The lowest point is either the depth of non-penetrable units (the Cabot Head Shales on Manitoulin Island), or the lake level (regional base level). For this research the zones of maximum hydraulic gradient were calculated for the southern scarp but the northern scarp was omitted because of its limited karst potential. Trigonometry was used for the calculation as explained in Appendix 5. The zone was mapped in GIS to determine the areas of the greatest karst potential.

Karst aquifers are unlike other aquifers where flow can be considered completely diffuse, such as flow through a uniformly porous material (sand). They all contain conduits to a certain degree and must be treated as if having "idealized continuum of saturated voids in a solid matrix" (Ford and Williams, 1989). "Diffuse" for karst aquifers refers to smaller size voids (less than 1 cm) distributed over a wider area while conduit refers to larger scale tubes (centimetres to metres in size). As a result of varied distribution of solution conduits, karst aquifers are both heterogenous (hydraulic conductivity *k* varies with location) and anisotropic (*k* varies with direction of measurement). Groundwater will move perpendicular to equipotential lines (lines of equal hydraulic potential) with the slope of water table (streamline , or direction of movement) in the direction of the steepest hydraulic gradient (Figure 4.3). In the vertical plane the flow net (a mesh formed by a series of

Figure 4.3

Illustration of a flow net in carbonate aquifers (diffuse type flow) (Ford and Williams, 1989).

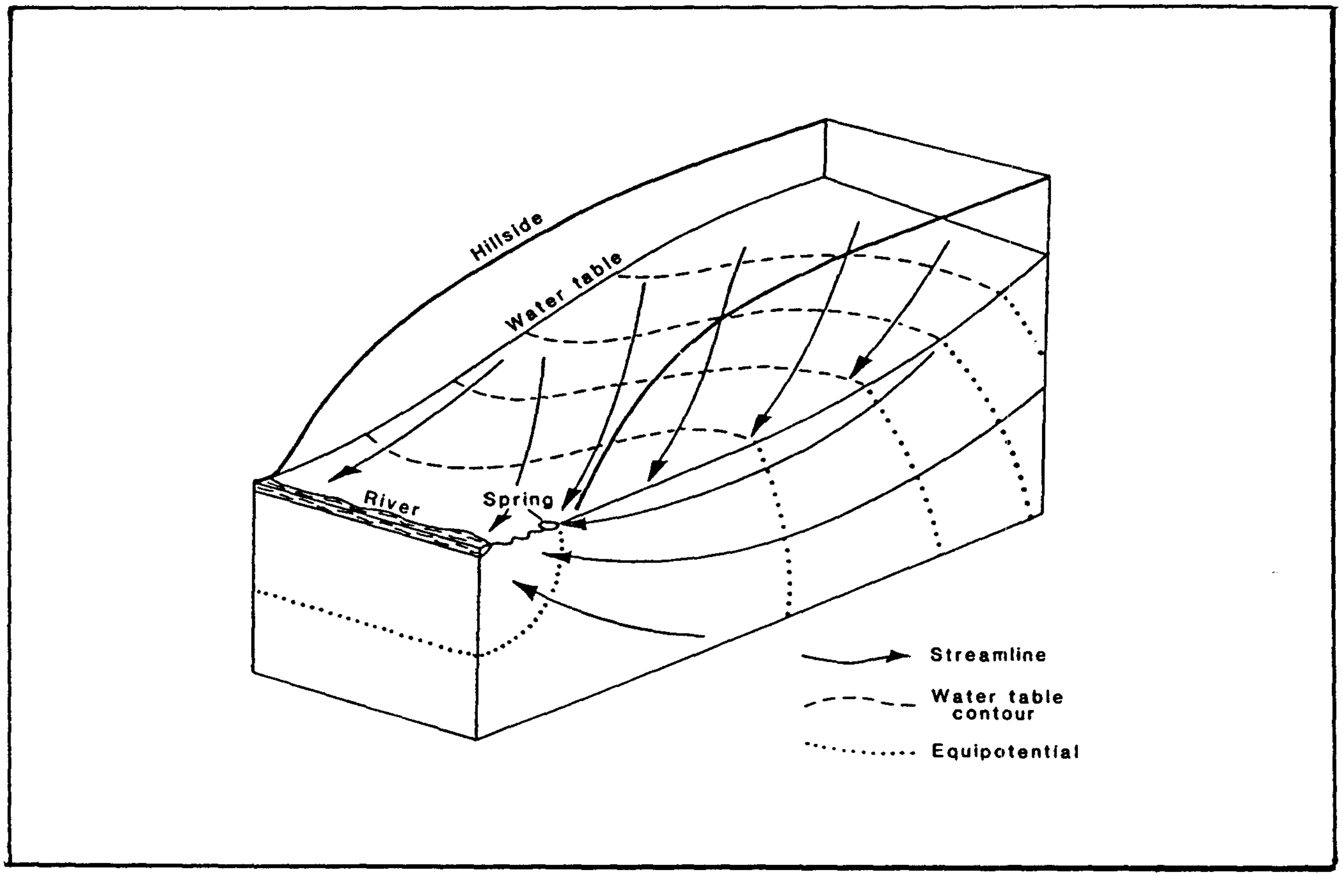
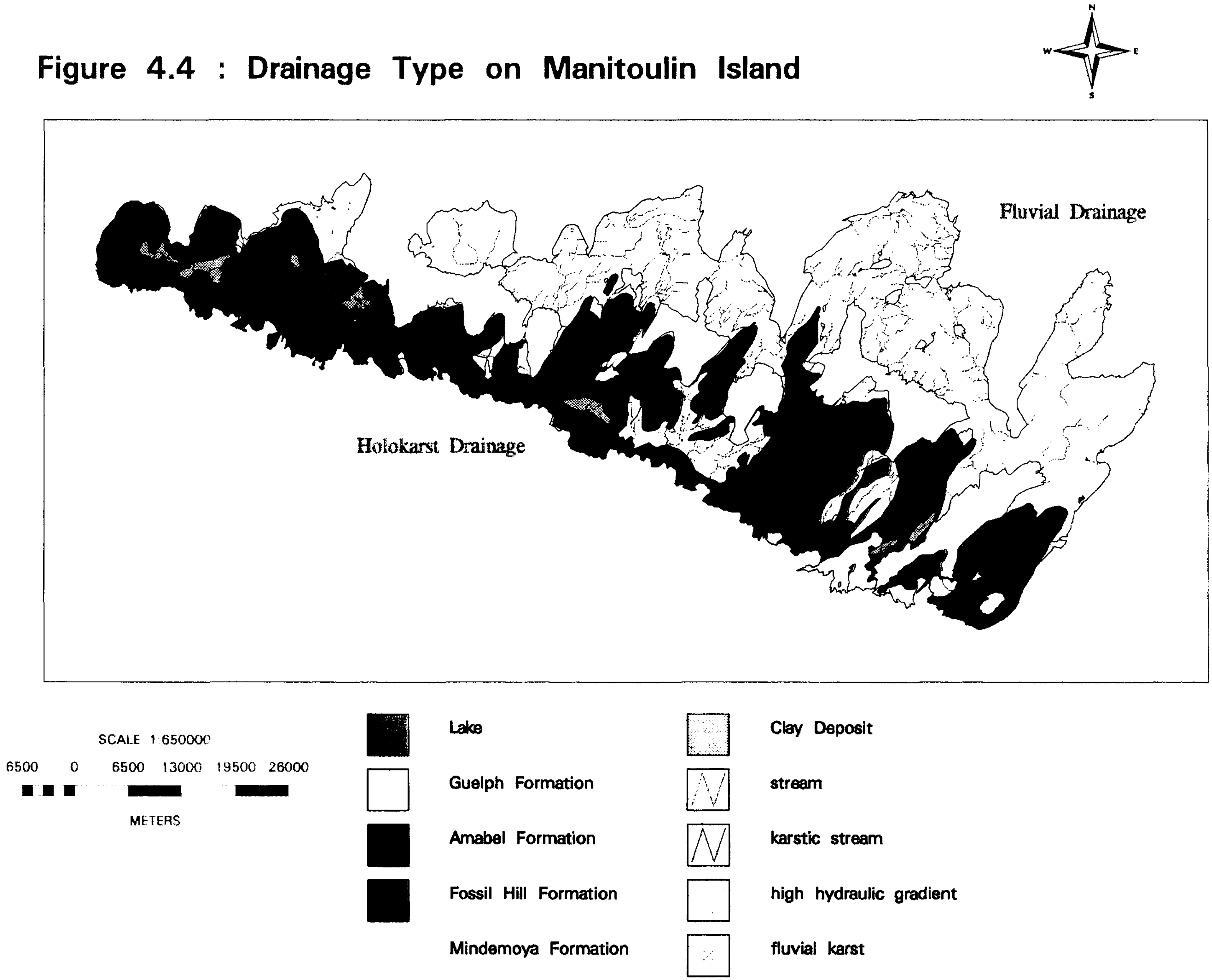


Figure 4.4 : Drainage Type on Manitoulin Island



equipotentials and streamlines) may be parallel to the hydraulic gradient of the water table and converge to the valley floor or coast, resulting in emergence of springs. This is often seen on Manitoulin Island.

However, due to the heterogeneity of karst aquifers, a large conduit intersecting the flow net will cause flow to converge to it. Thus micro-structure (occurrence of solutionally enlarged joints and fractures) have great influence on the orientation and transmissibility of primary flow paths. Bedding planes link joint-dominant routes of downward percolation in the vadose zone and provide recharge routes if laterally continuous. Regional structure controls flow since joints are more penetrable if under tension. Thus domes and anticlines are often recharge zones and at synclines flow converges, creating groundwater recharge zones (Ford and Williams, 1989). Therefore it is difficult to predict groundwater movement direction from maps, calculations, theory and field observations of sinks and springs alone. A dye trace is the only method to definitely establish the link between input points and output points in karst areas. Unfortunately, this was beyond the capabilities of this study, so groundwater flow will be estimated using the above approximate methods.

4.2 - Field Methods

This research is a preliminary survey of the drainage for the entire area of Manitoulin Island. Air photos and maps were used to determine stream density, hydraulic gradient, and occurrence of karst features (sinkholes, karst lakes and springs) which also suggest directions of underground drainage. These were verified in the field and are mapped in GIS to discriminate areas with different drainage types. Karst occurrence and extent of development will be related to geology, Quaternary deposits, soil type and vegetation.

Ford and Williams (1989) classify drainage in karst areas into four categories which will be applied to Manitoulin Island :

1) holokarst - wholly subsurface, with no record of surface channels.

2) fluvial karst - complete capture of surface channels.

3) immature fluvial karst - partial underground drainage of surface channels.

4) normal fluvial - wholly surface or non-karstic.

There are three types of drainage present on Manitoulin Island, although two are most common. These are fluvial (normal, or non-karstic) and holokarst drainage (wholly subsurface flow). The third is a combination of immature and mature fluvial karst. However, only approximate divisions can be made between regions and stream divides since there is certainly groundwater interflow across topographic divides; often groundwater basins are not coincident with surface basin divides. All of the study area will be classified into the above types, and the most important findings on each will be summarized.

4.3 - Fluvial drainage

Normal surface drainage may be found in dominantly karst regions given certain conditions. On Manitoulin Island, the distribution of this type of drainage corresponds to the location of shales, impure dolomites and limestones or the location of thicker glacial sediments and soils (especially clays).

The northern aquifer is dominated by a normal drainage pattern. The host geologic formations include the Lindsay, Whitby, Georgian Bay (Meaford and Kagawong), and Cabot Head Formations as well as most of the Manitoulin Formation. Everywhere these lithologies outcrop, there are greater surface channel stream densities. Where the more soluble Amabel, Fossil Hill, Guelph, Mindemoya Formations and the Manitoulin bioherm are mantled with clay-rich deposits and soils, these areas will also feature normal drainage. Occurrence of sand deposits does not appear to hinder karstic drainage since they are highly permeable, and water may still be able to infiltrate into the underlying carbonate bedrock (Cowell, 1976). Other deposits, such as tills, dictate drainage according to their composition; where they are carbonate, they allow penetration of water but with inhibited corrosion potential. Clay-rich tills inhibit infiltration. Mucks, usually surrounding marshes, indicate poor therefore non-karst drainage.

Figure 4.4, created by GIS overlay illustrates how closely the occurrence of less soluble formations and clay-rich deposits coincides with the extent of normal surface drainage. The surface channels form dense stream networks on areas with normal drainage and flow as dictated by topography. Where directed towards the North Channel, the streams cross the northern scarps via waterfalls. If the streams draining the major lakes are able to breach the central scarp barrier, they flow down the dipslope of the Amabel and Fossil Hill formations south to Lake Huron (eg. Mindemoya and Manitou Rivers). Lake Kagawong, the lakes east of Sheguindah, Silver and Maple Lakes have outlets to the north since their rivers are unable to breach the barrier. Swampy areas are common in the regions with normal fluvial drainage, occurring where hydraulic gradient is very low, (on the south shore) as well as on the northern headlands such as near Gore Bay, Kagawong and West Bay. In the south and west, fluvial drainage areas closely coincide with location of clay deposits, and possibly very low surface gradients or high water tables. All of the larger lakes are perched on the Cabot Head shales, which are highly impermeable.

The only large rivers on Manitoulin Island are those draining the major lakes mentioned above. Discharge data are only available for Blue Jay Creek at Tehkummah, which is fed by multiple springs. Discharge data from 1985 to present are given in Appendix 6.

From the GIS analysis, it is estimated that areas with normal drainage cover an area of 1280 km^2, or approximately 50 % of the island's surface area.

4.4 - Holokarstic Drainage

4.4.1 - Overview

Holokarst areas have a pronounced lack of surface channels with vertical drainage directly into bedrock. Precipitation and snowmelt almost immediately pass down into grikes or small sinkholes. On Manitoulin Island, dispersed drainage via grikes on pavement is dominant in the holokarst areas. They coincide with areas of karstic bedrock (mainly Amabel and Fossil Hill, minorly Guelph, Manitoulin and Mindemoya formations), and areas with no surface deposits (minor sand) as well as thin soils (Farmington series). These areas are found in western and southern Manitoulin, south of the central scarp. From this scarp, the holokarst zone appears to extend south to the Lake Huron shore wherever there are no inhibiting surface deposits. This type of drainage is best seen on Amabel uplands which are completely devoid of surface lakes and streams. Where the hydraulic gradient is greatest, at the edges of scarps (eg. Cup and Saucer), grikes become very deep (greater than ten meters), and eventually separate and fall away, the scarp eroding back from the edge (Figure 4.5). In some pavement areas such deep grikes may become more focused input points in the dominantly diffusely drained areas.

Holokarst is very rarely found north of the central

Figure 4.5 Deep grikes (> 10 m) at edge of the "Cup and Saucer" scarp. On high hydraulic gradient sites such as this, more developed grikes may serve as concentrated input points for groundwater flow.

escarpment. With exception of the Manitoulin bioherm, it is limited to the high hydraulic gradient zone along the edge of the northern scarp on the Manitoulin and Kagawong strata. There are only a few shallow open grikes none more than ten meters back from the scarp, although other grikes exist under the thin soils in some regions on the Manitoulin Formation. Since these lithologies have greater impurities and are more thinly bedded, water seepage is very slow, resulting in frequent ponding. The presence of numerous springs emerging at the scarp base along the whole island is the only evidence of underground drainage.

In the central island, scarp promontories such as the Cup and Saucer, High Hill and Jerusalem Hill do not display extensive pavement even though the hydraulic gradient is very high. However, there is no fluvial drainage thus they must be internally drained. They are heavily forested and pavement is thought likely to exist beneath shallow soils and deep forest litter. Likely input into the groundwater is diffuse and results in a number of smaller springs emerging at the bases of the scarps to the north, east and west.

At the edges of the holokarst zone, there may be some surface runoff as thicker sediments or less permeable bedrock is encountered. There are also pockets of normally drained areas (featuring swamps, ponds and surface streams) within the holokarst areas, which coincide with the locations of very low hydraulic gradients or high water table levels near the south

Lake Huron shore, or areas with thicker clay deposits. Surface streams appear five to ten kilometres south of the holokarst zone on the central scarp area. These streams are common in the south but almost non-existent in the west.

Very little is known about internal drainage of holokarst regions on Manitoulin Island. Due to a lack of concentrated runoff (such as large sinkholes or sinking streams), this has inhibited development of large conduit/cave passages of explorable size. Likely some may lie at greater depths although the individual carbonate units are not very thick. The depth to the Cabot Head shales is at maximum 99 metres (325 ft) from the top of the Amabel Formation, restricting the area for development of passages. Karstic drainage on Manitoulin is dominated by autogenic recharge (from precipitation onto karstic rocks). In this case it is quite diffuse, down many fissures over a large area, resulting in many intermittent small springs rather than large perennial springs, as on the Bruce Peninsula (Cowell, 1976).

4.4.2 - Spring Systems

There are two main systems of springs on Manitoulin Island which drain the two main aquifers. The more significant system drains the southern aquifer which includes the highly karstic formations above the Cabot Head Shales. These blocker beds prevent groundwater from infiltrating into the lower aquifer. Groundwater flow emerges in the form of springs at many points around the central escarpment into the large lakes, as well into the North Channel from the scarps in the west and south. Streams also emerge at the south shore where the water table becomes very shallow. The northern aquifer located in the formations below the Cabot Head Shales, although largely drained by surface streams, also features spring seepage. Here the Basal Beds or the water table at lake level act as barriers driving springs to emerge from the northern scarp. Groundwater flow routes would develop according to hydraulic gradient (determining direction of drainage), but occurrence of solutionally enlarged fractures and bedding planes would largely control conduit develop thus direction of flow. Therefore the local drainage across the island is much more complex than described above. Springs were found to emerge outside of the above patterns. For example, south of the large lakes many springs, such as that feeding Blue Jay Creek, emerged from the base of isolated Amabel headlands. Some emerged far from the scarp bases (Figure 4.6). Spring locations found in this research are mapped in Figure 4.7.

Not much is known about these springs. Most are very small from dispersed inputs and likely represent shallow underground drainage. Flow most likely occurs through solutionally enlarged fractures. There may be a few larger conduits, such as those which emerge at larger perennial springs such as one north of Bidwell (Figure 4.8) and the springs that feed Blue Jay Creek. Smaller springs are

Figure 4.6 Spring seepage from the Manitoulin Formation on top of scarp south of Little Current. The spring does not emerge from a scarp base, but from a very gradually sloping field several 100 m downslope from scarp.

Figure 4.6 : Spring locations on Manitoulin Island

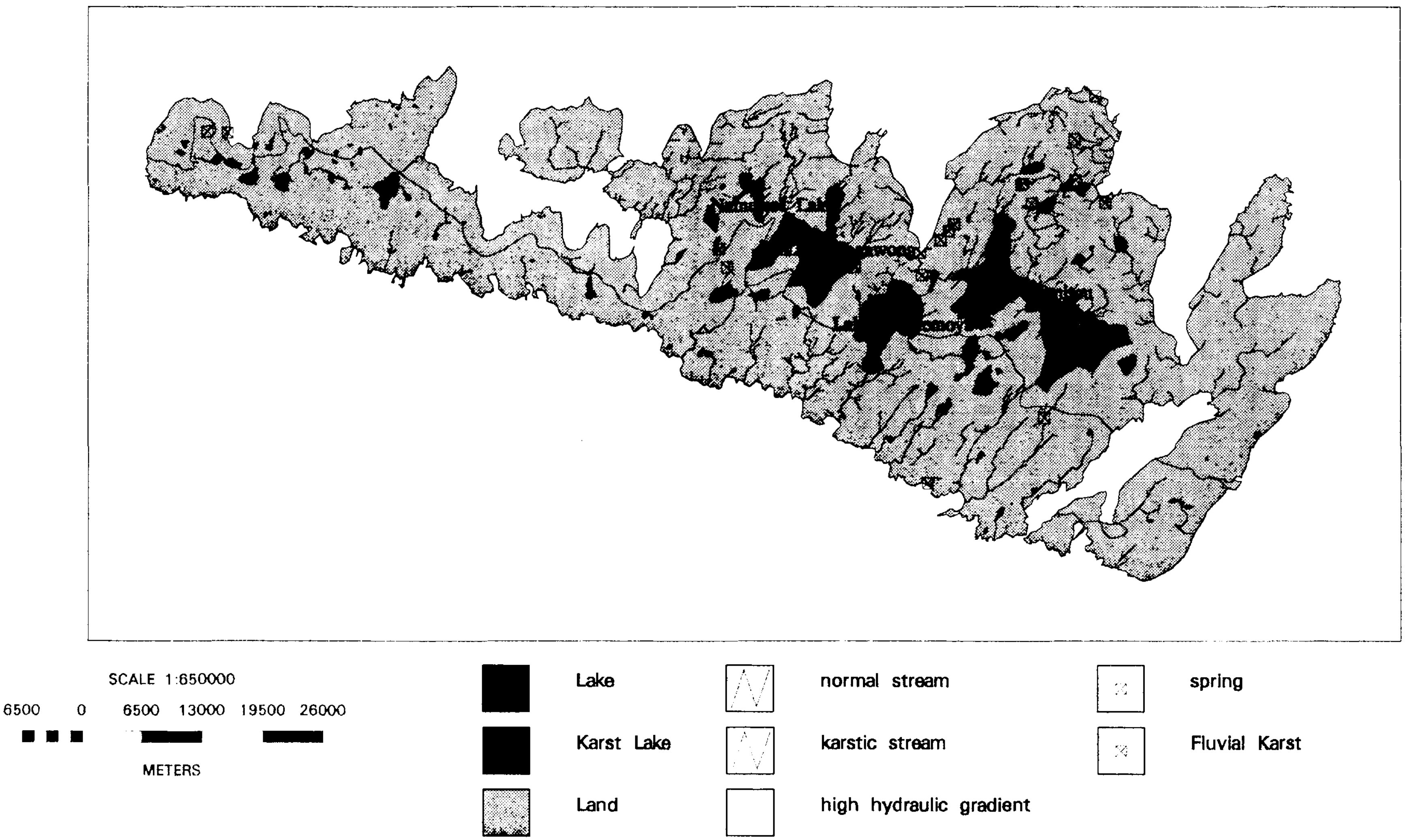


Figure 4.8 Large spring emerging from scarp north of Lake Manitou. This spring was observed to flow throughout the field season, thus likely is a perennial spring serving as an outlet for a large drainage basin. Here flow is greater due to recent rain.

probably fed by many small inputs that become integrated within the bedrock, are characterized by less variable flow, a slow response to precipitation and snowmelt events, and a high carbonate hardness with less variation. In contrast, conduit springs, fed by a single major input usually into a cave passage, show greater variations in flow, rapid response in precipitation and snowmelt, low but highly variable hardness (Quinlan, 1990). Further study on the springs of Manitoulin Island, including dye traces to link inputs to outputs and spring hydrograph analysis, would be required to confirm this tentative classification.

4.4.3 - Karstic Lakes

Many lakes on Manitoulin Island act as sinking points for surface flow (59 lakes, or 39 % percent of the total number). These were identified from maps and air photos as closed depressions that are not externally drained. Several were verified in the field. Most are found in the west and south regions of the island. They range in size from larger ones such as Windfall Lake (surface area of 4.322 km^2) to smaller ponds less than 3.5×10^{-3} km^2. In total their surface area covers 17.2 km^2, only 6.85 % of the surface area of all lakes, indicating they are relatively small. The direction of groundwater flow is thought to be downdip towards the west and south, where numerous springs emerge near the shoreline. Dye traces will be needed to verify these presumptions. Traces will be difficult at these ponds, however, since most do not have outlet channels draining to distinct sinkpoints, it appears water seeps slowly into the bedrock through muddy lake bottom sediments. The lakes present problems in where to inject the dye while the sediments could absorb the dye. This presents a challenge for future research in this area.

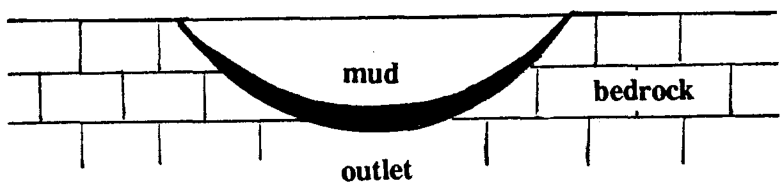
Most of these karstic lakes (especially the larger ones) are situated on the Fossil Hill Formation. Thirty are located near the Amabel contact. It appears that the Amabel itself has too great a permeability to support lakes; the extensive pavement areas effectively drain all surface water collecting on the surface. The Fossil Hill bedrock thus has less effective permeability than the Amabel. Also it is further from the Lake Huron shore where the hydraulic gradient is very low; this may allow for more concentrated recharge to develop such as these lake - sinks.

Several possible scenarios may explain the existence of these lakes (Figure 4.9). The input and output of water must be balance in order to maintain their presence. They may develop where the volume of water at the recharge point is too great to be completely drained at the sink. A few of the lakes exist on top of clay or muck deposits, which plug their sinking points ponding up the water. Slow seepage still may occur into the karst groundwater system, either through the deposit itself, or the outlet may be above the plug on bedrock. Alternatively, lakes exist in bedrock depressions which extend beneath a shallow water table (D. Ford, personal

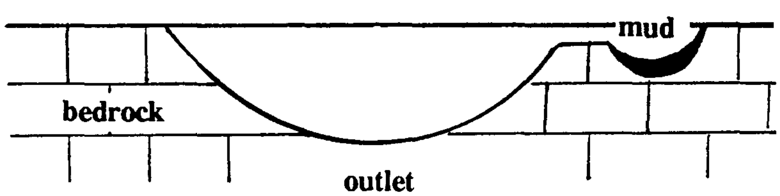
Figure 4.9

Possible explanations for the occurrence of karstic lakes (D. Ford, personal communication).

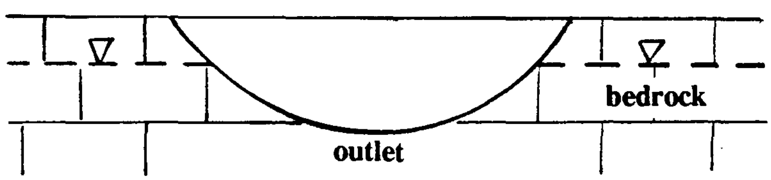
1. Mud and sediments plug outlet at lake bottom, through which slow seepage into karstic bedrock occurs.



2. Lake has a separate outlet plugged by clay or mud deposits.



3. Lake bottom is situated beneath shallow water table, resulting in ponding of water.



communication); many of these lakes likely have an outlet at the bottom also. There are many such sinking ponds in Western Newfoundland (Karolyi, 1978), due to incomplete development of sinkholes.

Nameless Lake

As an example, this lake is located in central Manitoulin and is 0.614 km^2 in surface area, 0.46 km by 2 km in size. It is very shallow from (Figure 4.10) and is situated in a closed depression on top of bedrock at 220 m (722 ft) a.s.l. on the dipslope of the Mindemoya Formation. To the west it is ponded up against a large promontory of the Amabel 228.6 to 259.2 m (750 to 850 ft) in height. To the north is Tobacco Lake at 222.9 m 731 ft), with the dipslope to the south. Nameless Lake is also fed by several small springs emerging from a minor scarp in the Mindemoya Formation on the east side (Figure 4.11), which ascends into a higher scarp of the Fossil Hill (maximum 266.8 m or 875 ft).

Nameless Lake has one outlet, in the form of a small stream (approximately 3 m wide and 0.5 m deep) flowing out of the south end of the lake for a distance of 10 m. Velocity of the stream was estimated at 0.1m/s when observed in spring 1993. The stream flows into a large shallow swampy area approximately 65 m in length and 10 m in width (Figure 4.12). In spring the water level was approximately 0.5 to 1 m higher than in summer. At this sinking outlet there was no visible drain, likely the water does not drain down through one point

Figure 4.10 Nameless Lake, a shallow karstic lake in central Manitoulin Island. Photo is facing north, opposite from outlet at the south end of the lake.

Figure 4.11 Spring emergence from bedrock by Nameless Lake. Water is seeping from between bedding planes to right of person.

Figure 4.12 The sink of Nameless Lake, a large muddy area approximately 65 m in length and 10 m in width. The outlet stream flowing in from the lake is located in the far rear, left side of the photo.

but through a multitude of smaller points in the mud floor. The estimated discharge emptying into this sink is estimated to be 0.15 m^3/s (15 litres/second) or $1.3*10^6$ l /day.

The outlet of Nameless Lake could be a series of small springs found to drain into Mud Lake 2.5 km to the southeast. Mud Lake is situated on the Fossil Hill Formation at 213 m or 700 ft. This yields a hydraulic gradient of 0.003 between the two points, which is enough for flow through narrow fissures in dolomites. This connection cannot be made from observation alone since there is no point source of emergence: the springs appear from a marshy area which feeds the lake. There is also the possibility that Tobacco Lake (at 222.9 m or 731 ft with no outflow streams) could drain into Nameless Lake but there is no visible sink for it. It is questionable if this larger lake (surface area of 2.378 m^2) drains into Nameless Lake, although given the direction of the hydraulic gradient it is possible. It is difficult to estimate drainage basin size for this system since it is unknown how many springs flow into it. There is another possible karstic lake (area 0.144 km^2) to the northeast of Tobacco Lake situated on the Cabot Head - Mindemoya Formation borders. It appears marshy but has no external drainage. It is located above 228.65 m (750 ft) thus may drain underground into Tobacco Lake.

Young-Wickett-Falls Lakes

These lakes are situated in the west end of the island on the dipslope of the Fossil Hill at less than 198.2 m (650 ft) elevation. There was no external drainage or sinking points visible at the time of the field season. However, a local resident claims that they drain underground to the south. Furthermore, with higher water levels from snowmelt and precipitation in the spring, Wickett Lake drains on the surface to the north as does nearby Loon Lake, while Lily Lake drains on the surface to the south. There are many karst lakes in this area of the island.

4.5 - Fluvial Karst and Immature Fluvial Karst

These two types of drainage are discussed together because they are limited on Manitoulin Island. Systems with fluvial karst have surface channels for an entire drainage basin feeding through sinking points into the groundwater system (complete capture of surface channels). Immature fluvial karst is incomplete capture of surface channels, where only some flow may feed into the groundwater system from a drainage basin, or sink only along some of the channel length (Cowell, 1976). These usually result from allogenic recharge: surface streams, generated by runoff off neighbouring non-karstic rocks, are captured into the groundwater system when they flow into regions with carbonate rocks. The sinking points are concentrated and well developed, such as stream sinks or sinkholes.

On Manitoulin Island, a small stream system off Highway 6 (south of Sheguindah) is a typical example of such a system.

The small stream flows east towards the scarp on the Kagawong Formation, where the hydraulic gradient is very high. The stream is 55 cm wide, six cm deep and flow is estimated at 0.20 m/s (discharge of $6.6*10^{-2}$ l/s). It sinks at a distinct point (with a small whirlpool) ten metres back from the scarp edge (Figure 4.13). It emerges at the scarp face by the roadcut (scarp height here two to three metres) (Figure 4.14). This is a very small fluvial system in a formation that exhibits little other karst. However, even though the Kagawong is thinly bedded (10 - 15 cm), with many shaley interbeds, water is able to infiltrate. Since water soon encounters blocker beds, flow emerges shortly. This creates a system isolated from general groundwater seepage flow.

Other such small fluvial systems exist on Manitoulin Island. One is along the Kagawong River at the Bridal Veil Falls near the town of Kagawong. A tributary stream (2 m wide and 0.2 m deep) of the main river slowly sinks along a channel of fractured bedrock filled with debris; within five metres, the water completely disappears. No springs were seen to emerge at the falls. The water may emerge in the riverbed below their base. This effect was only observed in spring 1994; in 1993 the stream flowed over the scarp edge as a surficial waterfall.

There is a lack of mature fluvial karst (capture of complete or larger drainage basins) on the island. As on the Bruce Peninsula, there is the potential to capture many small

Figure 4.13 Small sinking stream on the Kagawong Formation, at a roadcut south of Sheguindah. The streams sinks at a distinct point (whirlpool in lower right of map) 10 meters back from the scarp edge.

Figure 4.14 Emergence of flow from sinking stream in Figure 4.13 on Kagawong Formation. Water slowly seeps out at several points from between bedding planes 0.5 m above scarp base.

surface channels since many areas lack surface drift cover. However, south of the central scarp, where there is more permeable bedrock along high hydraulic gradient zones, there were no sinking systems found along the major stream channels that were investigated. It is possible that some of the numerous small streams sink. Map investigations and field work reveal some features. Firstly, most surface streams emerge a good distance (five to ten kilometres) south of the holokarst region and flow away from it, south to Lake Huron. These have little potential for capture since the channels flow where hydraulic gradient is very low (calculated to be less than 0.003). Few streams cross the central scarp (where the high hydraulic gradient zone is located), since it redirects flow north to the central lakes. Thus, topography imposes a major limitation on the occurrence of fluvial karst, since it prevents most streams from crossing the normal to holokarst boundary for capture. Secondly, although the whole southern region features Amabel and Fossil Hill bedrock which are highly karstic, many of the surface channels (Blue Jay Creek, Manitou and Mindemoya Rivers) flow over clay and till deposits. This inhibits the potential for stream capture, and if the streams finally pass onto bedrock the hydraulic gradient is too low to allow capture (within two to three kilometres of the Lake Huron shore). An additional point is that most of the southern area features autogenic recharge, which results in more dispersed inputs into the groundwater system (through extensive fractured pavement areas) rather that concentrated inputs.

Despite these restrictions, fluvial karst, as shown by two sinking streams on the Kagawong formation, does occur. More extensive fieldwork may reveal that a greater number of small streams in the process of partial or complete capture. Possible systems to check include those flowing on bedrock such as Hughson, Timber and Dewars flowing south to Lake Huron. Jenkins Creek is indicated on maps as disappearing. For small systems the link between sink and spring could be more easily investigated but larger systems would require a dye trace. The karstic lakes may be considered as forms of fluvial karst, since they represent capture of drainage basins which flow into the closed depression of the lake. Nameless Lake, for example, has a small stream which first flows out of it for a short distance before sinking.

4.6 - Meso and Macrokarst: Subsurface features

Mesoforms (ten to 1000 metres) and macroforms (greater than 1000 meters) may be present as both surface and subsurface karst forms. Surface forms include sinkholes, disappearing streams and sinking lakes already discussed. Subsurface forms include caves and their phenomena.

On Manitoulin Island, a very limited number of mesoforms were found. Sinkholes are rare. There were a few apparent sinkholes on till in fields east of Gore Bay. They were mostly small (few metres in diameter) forms found on bedrock in forested regions, such as around Nameless Lake. This absence of sinkholes is because they require a concentrated link to a conduit or proto-cave in order to become enlarged. On Manitoulin Island recharge is more diffuse, channelled into many smaller inputs such as grikes on exposed pavement. Thus few concentrated input points can develop.

The only explorable passageway known on Manitoulin is Mindemoya Cave, although it is quite likely other caves of enterable dimensions exist.

Mindemoya Cave

This cave, previously known as Skeleton Cave, is situated in the western scarp of Lake Mindemoya. The cave was discovered in 1888 and today is owned by the proprietors of the Rock Garden Terrace Motel and is accessible to tourists. In 1978 P.J. Whittaker mapped the cave, giving some of the following details. Figure 4.15 is his survey map of the cave and Figure 4.16 shows the main passageway.

The cave is formed in the dolomite of the upper Mindemoya and lower Fossil Hill Formations. The passage form is dominantly phreatic and its direction is strongly controlled by jointing. It seems oriented in two main directions: the entrance of the main passageway at 90 degrees, with the back passageway oriented at 45 degrees. A secondary blocked passageway is oriented along 120 degrees. The total surveyed length of the system is 63.7 m (209 ft). The main passageway is approximately 23 m (75.5 ft) in length, 1.8 m wide and 1.5

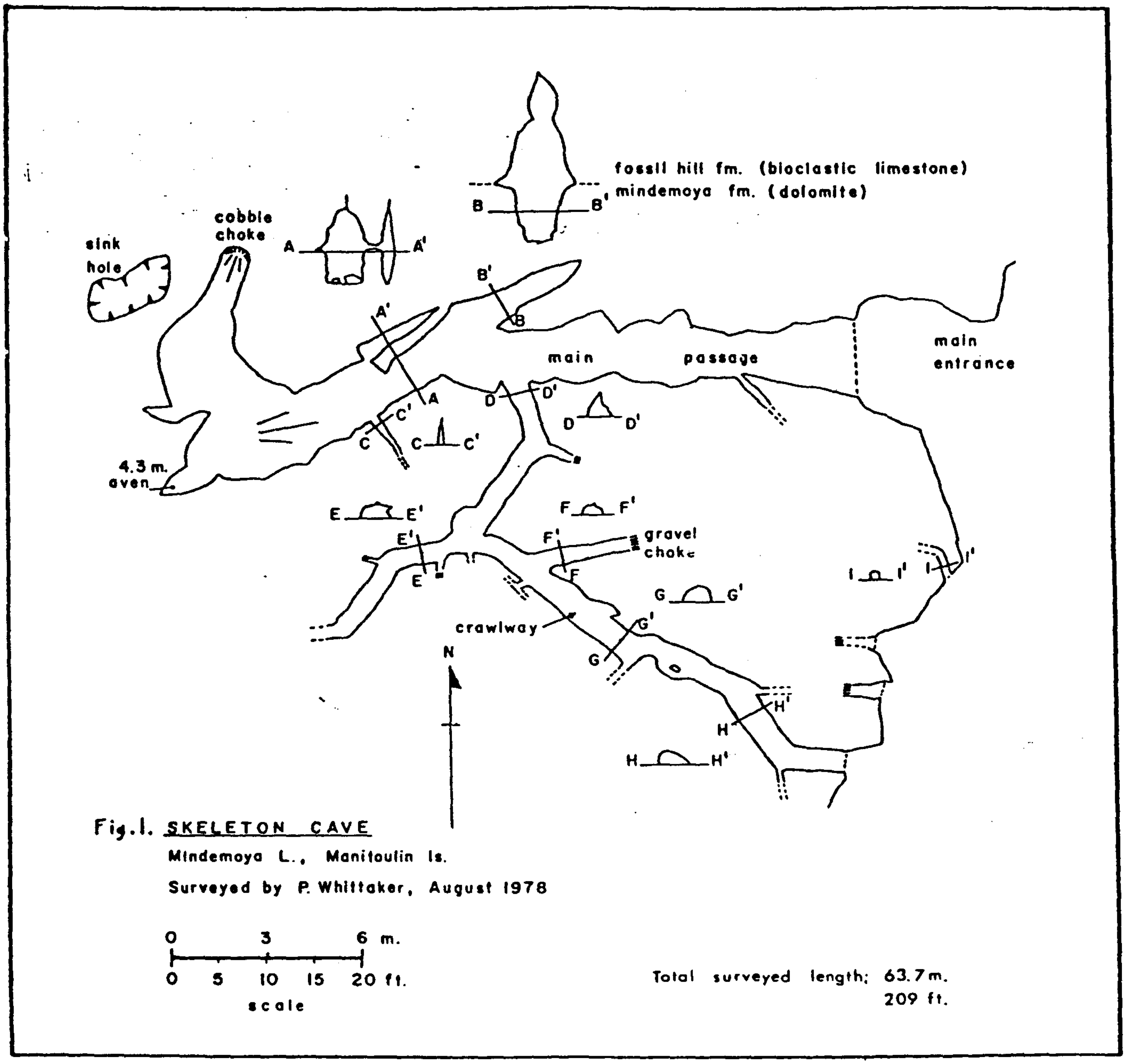


Figure 4.15

Survey of Mindemoya Cave (Whittaker, 1978).

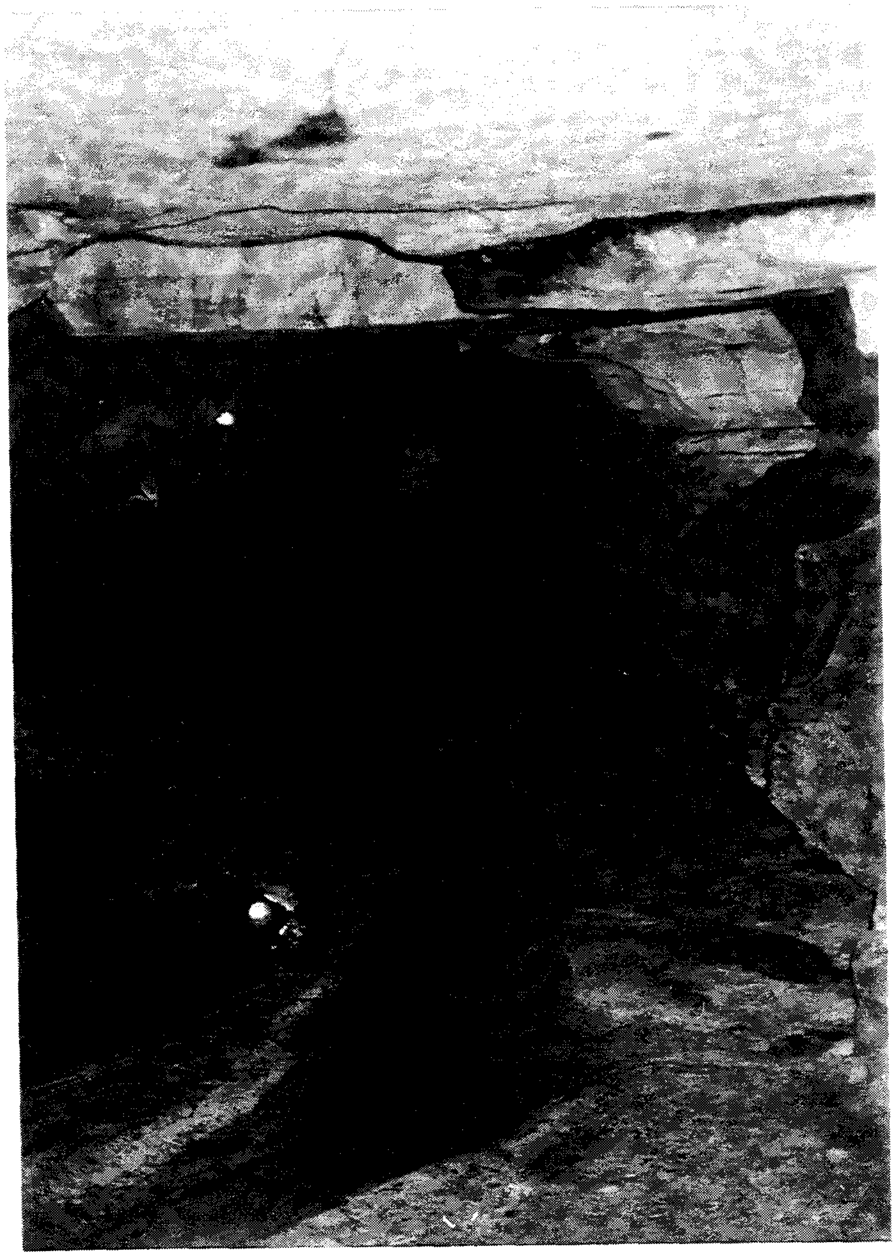


Figure 4.16 Main passageway of Mindemoya Cave, showing phreatic nature of passageway with the polished floor. This passage extends for only 23 m.

to 1.8 m high. The ceiling is a flat bedding plane at maximum 2.1 m in height in the main passageway, to a maximum of 6 m in a side room. Breakdown and sand-gravel till covered the original floor; this was removed artificially to reveal a smoothened rock surface today. Solution scalloping marks the walls of the main passageway, especially in the Mindemoya Formation. The rear passage is more vadose in form, with two avens (4.3 and 5.8 m). A cobble choke to the north of this side passage may be linked to a sinkhole located 3.1 m away on the surface. Slowly dripping water is observed at this point and throughout the cave. The remaining passages are 1 m by 0.4 m silt floor crawlways extending from the main passage to another entrance 11.2 m north of the main entrance. These feature sponge-like solution features and an ox-bow channel with a 0.3 m pillar near the entrance (Whittaker, 1978).

The joint-oriented passages correlate with those mapped on the surface above the cave which are shallow, filled with soil and vegetation and with joint set measurements across the island. The cave is situated on a scarp 213.4 to 228.7 m (700 - 750 ft) in height, with the lake level at 197.6 m (648 ft). Closer to the lake level a series of small springs are emerging.

Whittaker believes the cave is post-glacial in age due to absence of stalactites and because of similarities to other caves such as Bonnechere in southern Ontario. However, given the nature of the bedrock (dolomite), flowstone may take much longer than 10,000 years to develop. It is possible that the cave is pre-glacial in origin, but this cannot be confirmed due to absence of datable speleothems. It is also not certain how the cave connects to the karst drainage system since it a perched, inactive outlet today. Possibly it drained the large scarp of the Amabel to the west (213.4 to 266.8 m or 700 to maximum 875 ft). Today there are no concentrated inputs in this area. Although no evidence was found, these may have existed pre-glacially but were stripped away by iceflow or filled with till. Inputs today are diffuse through a large area of permeable, fractured pavement, which could feed the small springs below the cave (area of pavement is 14.92 m^2). If the lake existed in its present position pre-glacially the cave stream may have drained into the lake. Or the cave may have continued on in bedrock which was stripped away when the ice scoured out the lake basin. Thus today the cave is a relict, perched feature. If the cave developed post-glacially, the lake level would have been high following deglaciation, with the result that the cave stream came out at lake level.

Although Mindemoya Cave is the only explorable passage known on Manitoulin, it is likely that more exist. They have yet to be discovered due to the size of the island and density of forest along the central escarpment, where caves would most likely be found (because bedrock is most permeable and hydraulic gradient is greatest). If concentrated input sinks could have existed in the past, development of larger conduits is possible, despite constraints of the bedrock. Since the bedding units are not very thick, caves would be small in size such as Mindemoya Cave. Their outlets would likely be along the escarpment, at various levels depending on date of formation (higher for older when lake levels were higher, or lower for more recent caves with lower lake levels). Outlets for cave streams would have to emerge at the base of the escarpment where the Cabot Head Shales are located (15.2 m or 50 ft below the Mindemoya and St. Edmund Formation). Caves such as St. Edmund Cave on the Bruce Peninsula have formed from drainage through fractures on the bottoms of relict depressions (sinks). Their date of formation is unknown, of Nipissing Age (6,000 to 7,500 B.P.) or from the Algonquin phase (up to 12,000 B.P.) (Cowell, 1976).

4.7 - Discussion

The hydrogeologic setting of Manitoulin Island provides the physical constraints which determine the characteristics and flow patterns of the main aquifers. The lithology of the outcropping formations determines drainage for Manitoulin Island; it is either fluvial on the non-karstic bedrock areas, or holokarstic, on the most karstic bedrock. The hydrogeology is complicated by stratigraphy: the presence of the Cabot Head Shales divides the regional carbonate aquifer approximately in half, in terms of both the vertical section and the geographic distribution. The northern aquifer is dominated by normal fluvial drainage although there is slow groundwater seepage into the carbonates. Stream networks are quite dense and they drain relatively flat-topped uplands dominantly towards the north channel. The headlands are not heavily dissected, since the impure dolomite and limestone bedrock is quite resistant to mechanical erosion. The southern aquifer is highly karstic, with drainage being dominantly diffuse through extensive pavement. Recharge and discharge zones are dictated by topography: recharge is through the pavement on the uplands while discharge occurs at the scarp base above the shale blocker beds. Flow in this karst aquifer is likely through solutionally enlarged fractures. The zone of highest hydraulic gradient along the scarp edge is where greatest potential for groundwater drainage is found for both scarps. Fluvial karstic drainage, which is expected to occur in transition areas between non-karstic and karstic rocks, is relatively limited on Manitoulin Island, being confined to a number of small systems on scarp edges.

However, since it is known that most formations (including those displaying little karst such as the Manitoulin, Kagawong and Lindsay Formations) have groundwater flow, with time more concentrated input points may develop. Potential for holokarst expansion away from the high hydraulic gradient zone bordering the escarpment through stream capture was examined by Cowell (1976) for the Bruce Peninsula. On Manitoulin Island, this could occur, but most streams flowing into high hydraulic gradient zones are found on the northern scarp, where karst potential is limited. Thus many streams cross this escarpment as waterfalls, without being captured underground. Possibly rivers such as the Kagawong River could be losing flow along the way like the Crane River on the Bruce Peninsula. Since there are no discharge data this requires further investigation.

CHAPTER V: THE CHEMISTRY OF KARST WATERS

5.1 - Introduction

Examining the geochemistry of karst waters may yield important information on solution processes in an area. This is a preliminary study of the surface and subsurface waters on Manitoulin Island. The main focus was to examine the relationship between two significant variables: hardness and specific conductivity. Since limestones and dolomites form the dominant bedrock on the island, they produce simple bicarbonate waters when they dissociate in the presence of water. The main ions formed are calcium (Ca^{2+}), magnesium (Mg^{2+}), and bicarbonate (HCO_3^-) Thus, by studying the concentration of these dissolved ions in solution, information on $CaCO_3$ uptake is obtained. This gives insight into solution rates as well as on the rates of karstification.

This study attempts to create regional equations to characterize the relationship between hardness and specific conductivity, as was done by White (1988) for the limestones and dolomites of central Pennsylvania. Analysis of concentrations of dissolved cations and anions is expensive and time consuming. As an alternative, once a relationship has been established, specific (electrical) conductivity may be used to approximate water hardness because it is directly proportional to the concentration of charged ions in solution. This study aims to derive this relationship so that hardness can be predicted from the two simple field measurements of conductivity and temperature.

This relationship is explained with equations from White (1988). Specific conductance (conductivity) defines the conductance between faces of a 1 cm metal cube in a solution at 25 C:

$$K = d/aR \tag{1}$$

where d = distance between plates in cm

a = area of each plate in cm^2

R = resistivity in ohms

Resistivity is:

$$R = E/I \tag{2}$$

where R = resistance in ohms

E = electrical potential in volts

I = current in amperes

Conductivity is directly related to the ionic strength of the solution. Ionic strength is the sum of the concentration and ionic charges of each species which dissociate in solution. For calcium carbonate in water it is calculated by:

$$I = m_{Ca2+} + m_{H+} + m_{CO32-} + m_{HCO3+} + m_{OH-} \tag{3}$$

For dolomite the equation is:

$$I = m_{Ca2+} + m_{Mg2+} + m_{H+} + m_{HCO3+} + m_{OH-} \tag{4}$$

Where m = ion concentrations in moles/litre

z = ionic charges of each species

Thus, the ability of a solution to conduct a current is a function of the concentration and charge of the ions released in dissociation and the rate at which they can move under the influence of the potential (Hem, 1982). A field conductivity meter measures the electrical resistance of a solution, thus it can be directly related to ion concentrations.

White (1988) obtained the regression relationship between specific conductivity and total hardness expressed as calcium carbonate hardness for Pennsylvania wells and springs shown in Figure 5.1. A Ca/Mg ratio < 1.5 (solid dots) suggests that the water has passed through dolomite, whereas a ratio > 1.5 suggests that it has mostly encountered limestone. Although Pennsylvania is geologically similar to Manitoulin Island (limestones and dolomites), differences in depositional environment mean there could be differences in the SpC : hardness trend from White's. Thus his equation cannot be assumed for Manitoulin Island, and must be tested. White's equations are:

$$Hd(mg/L \text{ as } CaCO_3) = -29.6 + (5870*SpC) \quad (5)$$

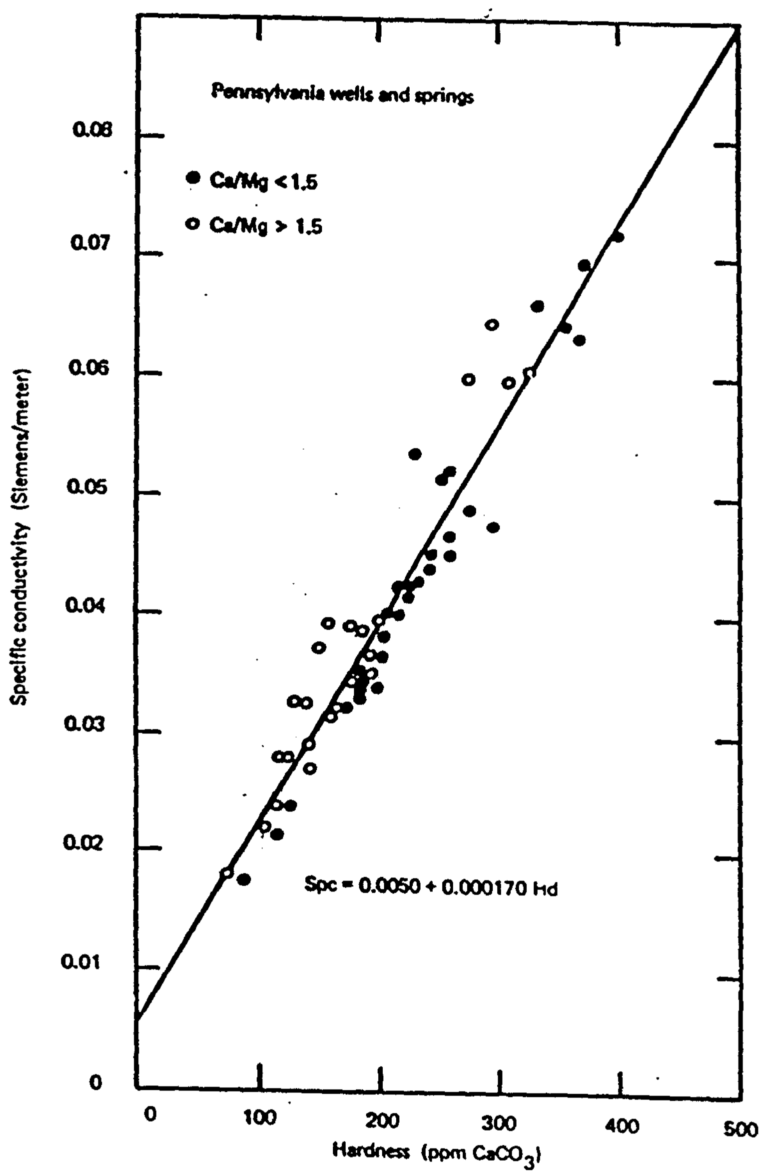
or reversed to find Spc =

$$SpC = 0.005 + (0.00017*Hd) \quad (6)$$

The $CaCO_3$:$MgCO_3$ ratio is an additional measure of bicarbonate waters. It is derived from measured concentrations as follows (White, 1988):

Figure 5.1

Regression plot of Specific Conductivity vs. Hardness used to obtain White's equation for Pennsylvania waters (White, 1988).



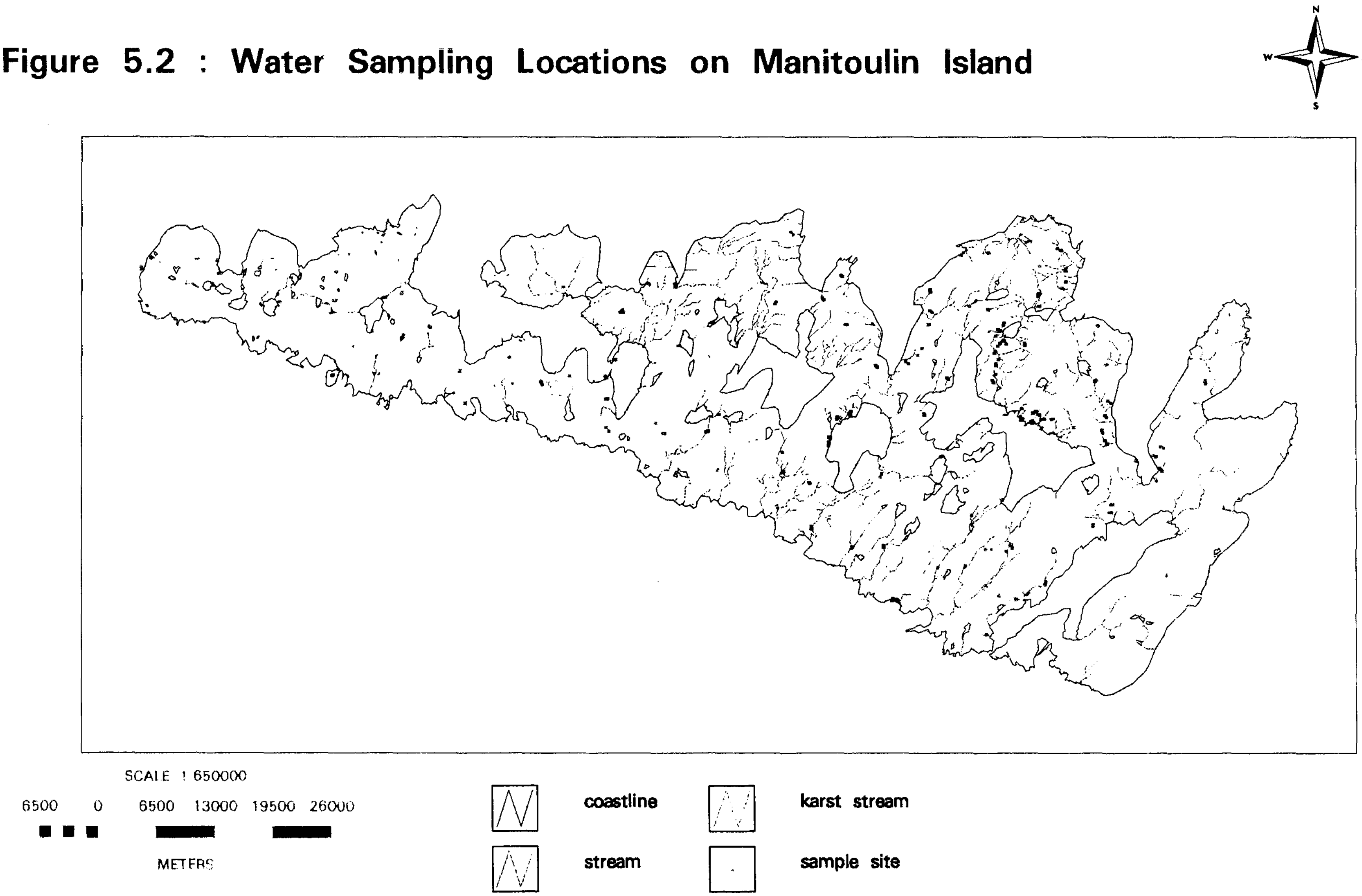
$$Ca/Mg = [Ca_{2+}]/[Mg_{2+}] \quad (7)$$

This ratio varies according to the type of bedrock the water is in contact with, thus may be used to derive such information without analysing the rock itself. Ideally, the ratio is 1 for dolomites, and ranges from 2 to 10 for limestones with 6 being the most common (White, 1988). Cowell (1976) determined that most Ca/Mg ratios for Niagaran dolomites in southern Ontario were greater than 1.5, with the general formula of rock composition being $Ca_{1.2}Mg_{0.8}(CO_3)_2$. From total hardness, calcium hardness may be subtracted to obtain magnesium hardness. These equations explain the relationship between conductivity and hardness, and why they are useful measures to characterize carbonate waters.

5.2 - Sampling Methods

A wide range of water samples were collected on Manitoulin Island. Streams, rivers, lakes, springs, wells and water flowing in roadside ditches provide a wide range of water types across the island. Figure 5.2 maps the location of sampling sites. There were two time periods of data collection. Between June 9 and June 29, 1993, 107 samples were collected to create Set 1. Specific conductivity was measured in the field and the samples were titrated for total and calcium hardness in the lab. This part of the study was done by Tanya Kohler as her B.A. thesis. A second set of measurements were collected later to test the equation derived from Set 1. Set 2 was collected between May 1 and May 7, 1994,

Figure 5.2 : Water Sampling Locations on Manitoulin Island



with a total of 41 samples. Some of Set 2 samples were from the same sites as Set 1 while others were new samples. For this set only specific conductivity and temperature were measured on site. The linear relationship between conductivity and hardness derived from Set 1 was used to calculate the total hardness for Set 2.

For both data sets specific conductivity had to be temperature corrected using Jacobsen and Langmuir's (1974) formula:

$$SpC\ (25^0\ C) = 1.81\ SpC(T)e^{-.023T} \tag{8}$$

where T is the temperature of the original sample. For data Set 1 temperature was estimated from semi-diurnal air temperature records (available in Appendix 7) since it was not measured on-site. Using the above equation, all conductivity values for both data sets increased, since field temperatures were all lower than the standard lab temperature of 25^0 C. Colorimetric titration techniques for total and calcium hardness are described in Appendix 8.

5.3 - Data Analysis

For data Set 1, xy graphs of total hardness (and calcium hardness) vs specific conductivity, as well as calcium hardness vs magnesium hardness, were created. This was to determine the linear relationship between the two variables to derive an equation similar to White's. Regression analysis was performed to predict the dependent variable (SpC) from the independent variable (Hd). The regression line was calculated using the formula: "constant + x-coefficient * independent variable". This "line of best fit" allows for visual comparison of this relationship.

Once a few outliers were removed from Set 1 a good relationship was obtained. For both data sets, outliers were removed to produce the final sets. For Set 1, outliers were data points too far from the regression line on the plots of conductivity vs. total or calcium hardness. These could be affected by various factors which will be discussed in 5.5. Outliers in Set 2 were points with unusually high SpC for their temperature. Figures 5.3 shows the graph for Set 1 of Hd vs SpC. Appendix 8 presents the results of the regression analysis and the raw data.

The equation obtained from the regression was only slightly different from White's:

$$SpC\ (s/m) = 0.0017852 + 0.000176Hd \qquad (9)$$

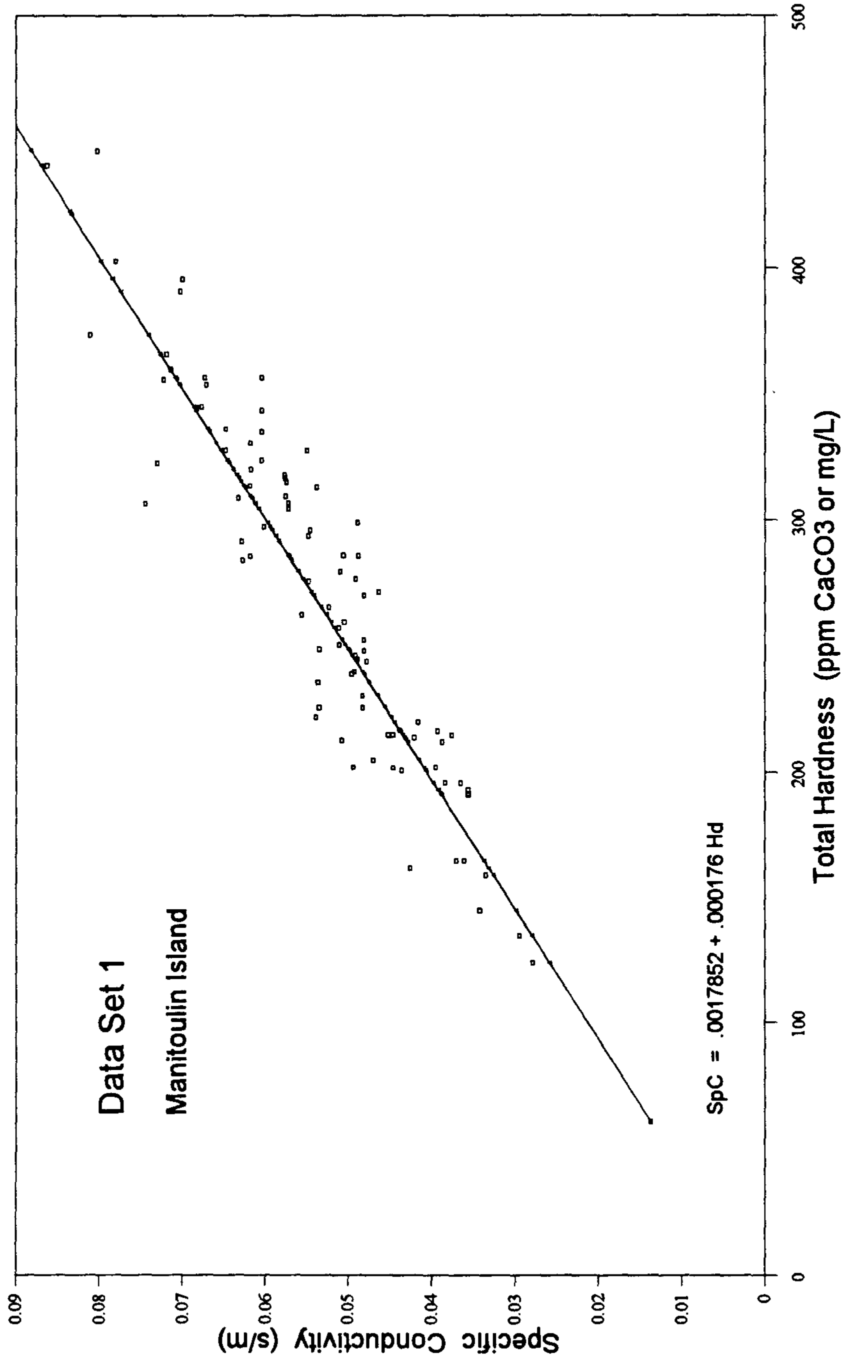
It was reversed to find hardness:

$$Hd = -29.4 + (5882 * SpC) \qquad (10)$$

For Set 2, values for total hardness were calculated from the regression equation (10) (Figure 5.4). The line of best fit on the graph appears perfect, since hardness was calculated with the formula. However, it is likely that there would be more variation as with data Set 1, if these water samples were titrated for hardness.

The mean total hardness (ppm or mg/L) for Set 1 is 280, and 252.7 for Set 2, while the ranges were 487 (Set 1) and 477

Figure 5.3
Specific Conductivity vs Total Hardness



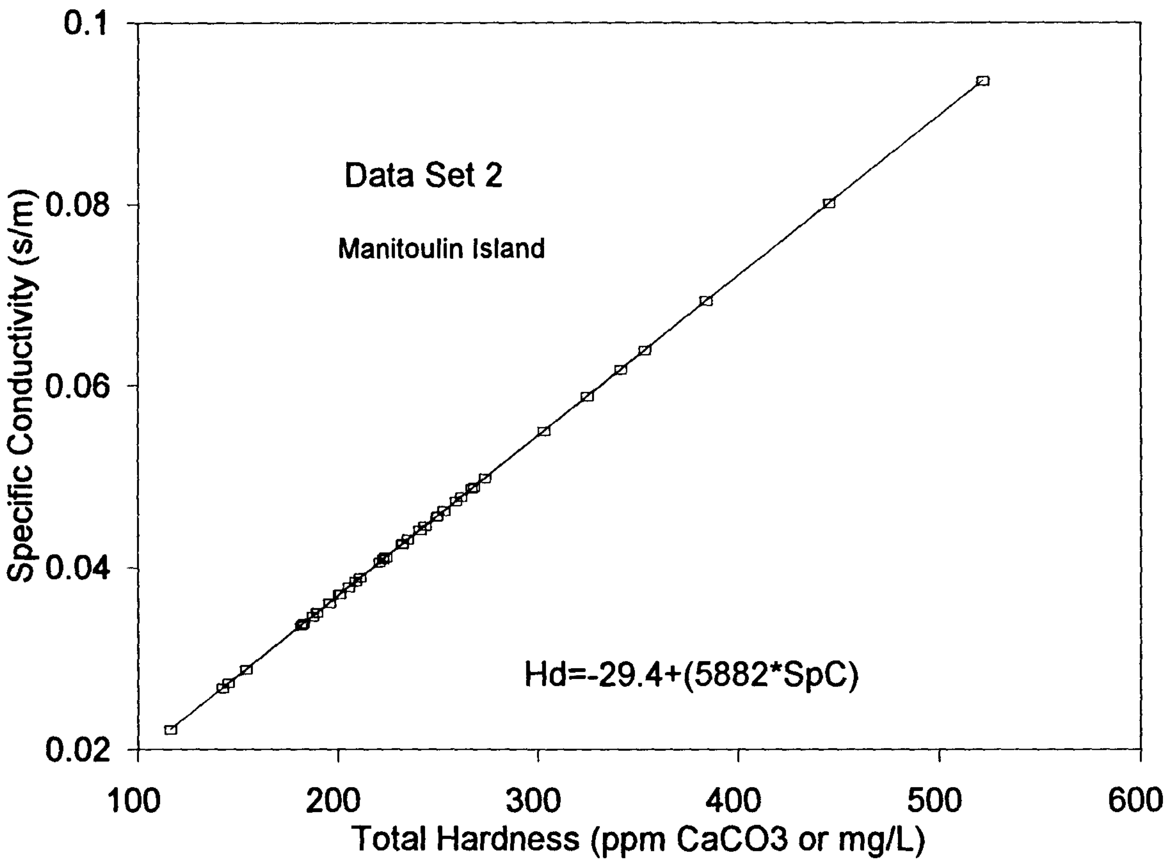


Figure 5.4
Specific Conductivity vs Total Hardness

(Set 2). The means for specific conductivity (in us/m) were 511.31 for Set 1 and 462.62 for Set 2. The ranges for SpC were 927.58 for Set 1 and 1016.03 for Set 2, including the outliers. The means and ranges are similar for both data sets, as expected since the both sampled similar waters. Conductivity and hardness may vary between the two due to: time of year the measurements were taken, the number of sites differs in Set 1 and 2, temperature was not taken for set 1 but estimated, and due to errors in analysis.

The $CaCO_3$: $MgCO_3$ ratio obtained from Set 1 was 1:0.57 (Figure 5.5), once outliers were removed. This indicates that the dolomites on Manitoulin Island are calcium-rich.

5.4 - Sources of Error

The main problem with Set 1 was that temperature was not taken on-site. It had to estimated from the published semi-diurnal air temperatures. The samples were warmed during transportation to the lab, where they were titrated. With measured temperatures there may have been a closer line of best fit and the equation derived would be more accurate.

Outliers were removed from the sets if they had unusually high SpC for their hardness. This implies that ions other than the Ca, Mg and HCO_3^- that were measured were present in significant quantities. Some outliers were from wells where they may have been affected by home water softeners (addition of salt). Ditch waters may have had residual road salt in them which would raise conductivity values. In Set 2, a sample from

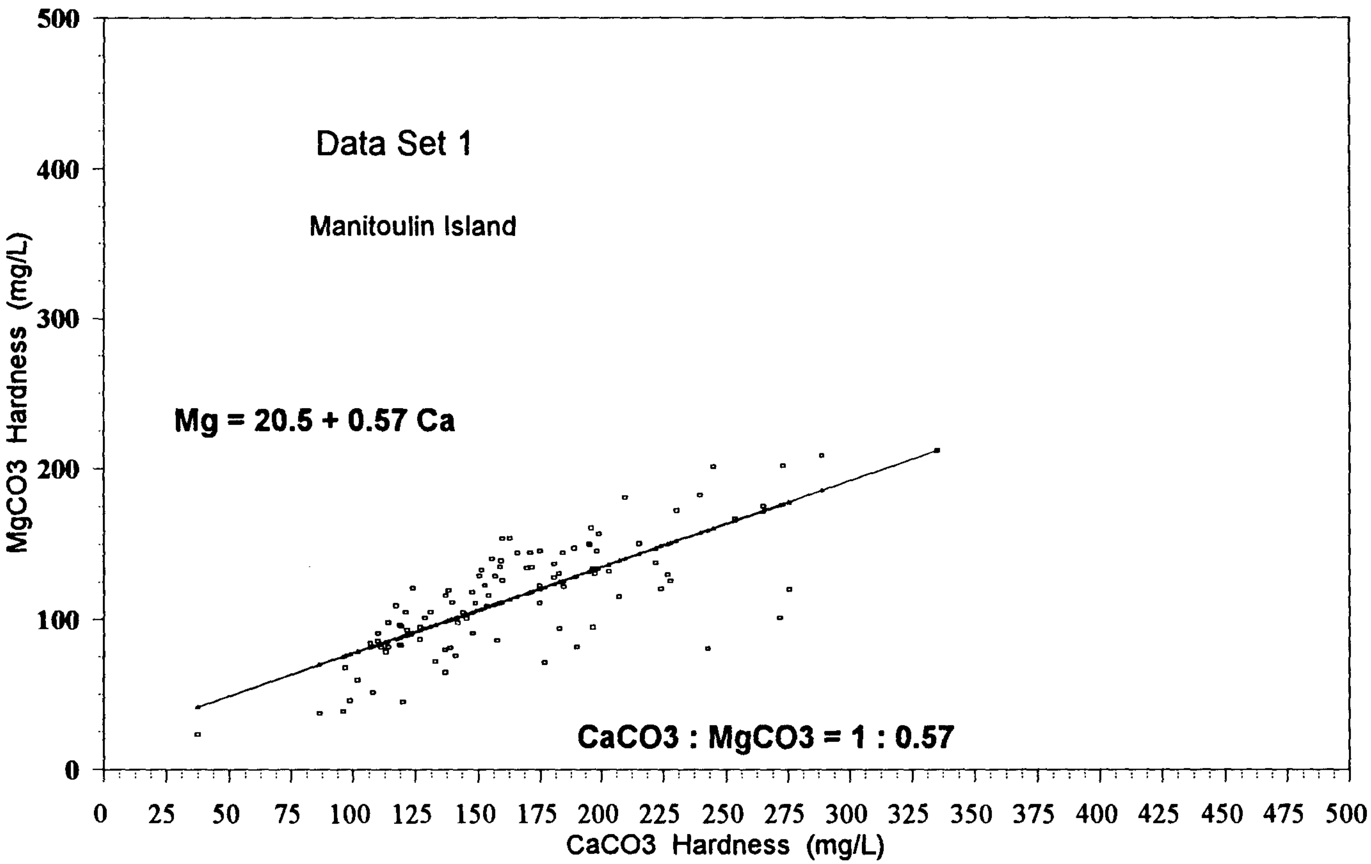


Figure 5.5
CaCO3 : MgCO3 ratio

a spring in Little Current had an SpC value of 0.124 s/m, which is unusually high for a temperature of 4^0 C. This may be due to pollution from a nearby sewage lagoon in the south of the town. Potential pollution problems indicated by this study will be discussed in 5.6.

5.5 - Discussion

Overall, the waters of Manitoulin Island display high hardness values, with means between 252 and 280 ppm or mg/L. This is typical for carbonate terrains. Now that an accurate relationship between Hd and SpC has been established, only measurement of the latter is required in the future.

White's regional equation was closely reproduced. However, there is overall greater linear correlation between SpC vs Hd for the Manitoulin Island data. In comparison to White's equation, his y-intercept (at 0.005) is greater, implying that a certain amount of ionic charge is present in the Pennsylvania waters before any Ca, Mg, etc. have dissolved (or these are added during dissociation). The waters in Pennsylvania will cross more sandstone and shale (with Si, SO_4 available to dissolve) and are more highly modified by human impact than the Manitoulin waters. This implies that the water chemistry is more complicated, thus the intercept value is higher. Because the Pennsylvania waters are more complex, the linear correlation is weaker than on Manitoulin. The Manitoulin set represents a more homogenous, simpler environment, despite the "noise" introduced by failing to measure field temperature in 1993. Thus, equation (10) is believed to offer a fairly accurate estimate of the SpC : hardness relationship for Ca-rich dolomite and limestone waters of northeast North America. It could be extended with additional data sets from karst areas such as Newfoundland, Kentucky and Florida (D. Ford, personal communication).

Overall the Manitoulin Island water chemistry results show a modified set of Cowell's measurements, but a similar regional water signature. This was expected due to similar rock type, vegetation and climate. Cowell found karst waters with typically greater than 300 ppm total hardness for subsurface waters and greater than 150 ppm for surface waters. This indicates that a lot of dolomite is being removed by solution, a result of high seasonal biotic activity operating on calcium-rich dolomites. This was also indicated by the insoluble residue analysis of Manitoulin Island bedrock in Chapter 3.

Cowell's data offers a more complete study of the water signature of the Bruce Peninsula. Although he did not measure SpC, he measured pCO_2 in soils. He was also able to sample over a much larger field season and a greater variety of water types than possible for this Manitoulin Island study. Cowell also noted that different types of waters have specific chemical signatures on the Bruce Peninsula. Springwaters had lower summer temperatures and greater hardness than other types of waters. Ford and Williams (1989) suggest that variation in total hardness may be a better index for aquifer type than actual values. For diffuse springs it is relatively constant (< 5% variation), while for conduit springs it is more variable. More data would be needed for Manitoulin Island especially on spring systems to use such an index. The springs on Manitoulin did show a greater SpC (thus total hardness) than other waters. The mean was 383 us/m, ranging from 210 to 750. The temperature was also overall lower for springs, with a mean of 5.7^0 C, ranging from 4^0 to 9^0 C. Thus, it appears many trends found by Cowell for Bruce Peninsula waters would be expected to be present on Manitoulin Island, given similar bedrock type and climate.

The $CaCO_3$: $MgCO_3$ ratio is very similar to that obtained by Cowell for the Bruce Peninsula at 1 : 0.51 (Figure 5.6). This is due to similar rock composition. Although the Guelph formation is more dominant on the Bruce and the Amabel more common on Manitoulin Island, Cowell obtained similar composition ratios for the two. The Ca/Mg ratio for the Guelph formation ranged from 1.39 to 1.43. The range for the Amabel was 1.40 to 1.52, indicating the Amabel is slightly more magnesium rich (Cowell, 1976).

Since this study is a very simple one which looks only at two variables, much more work on the water chemistry of Manitoulin Island waters may be done. More variables need to be examined once the routes of underground flow are well

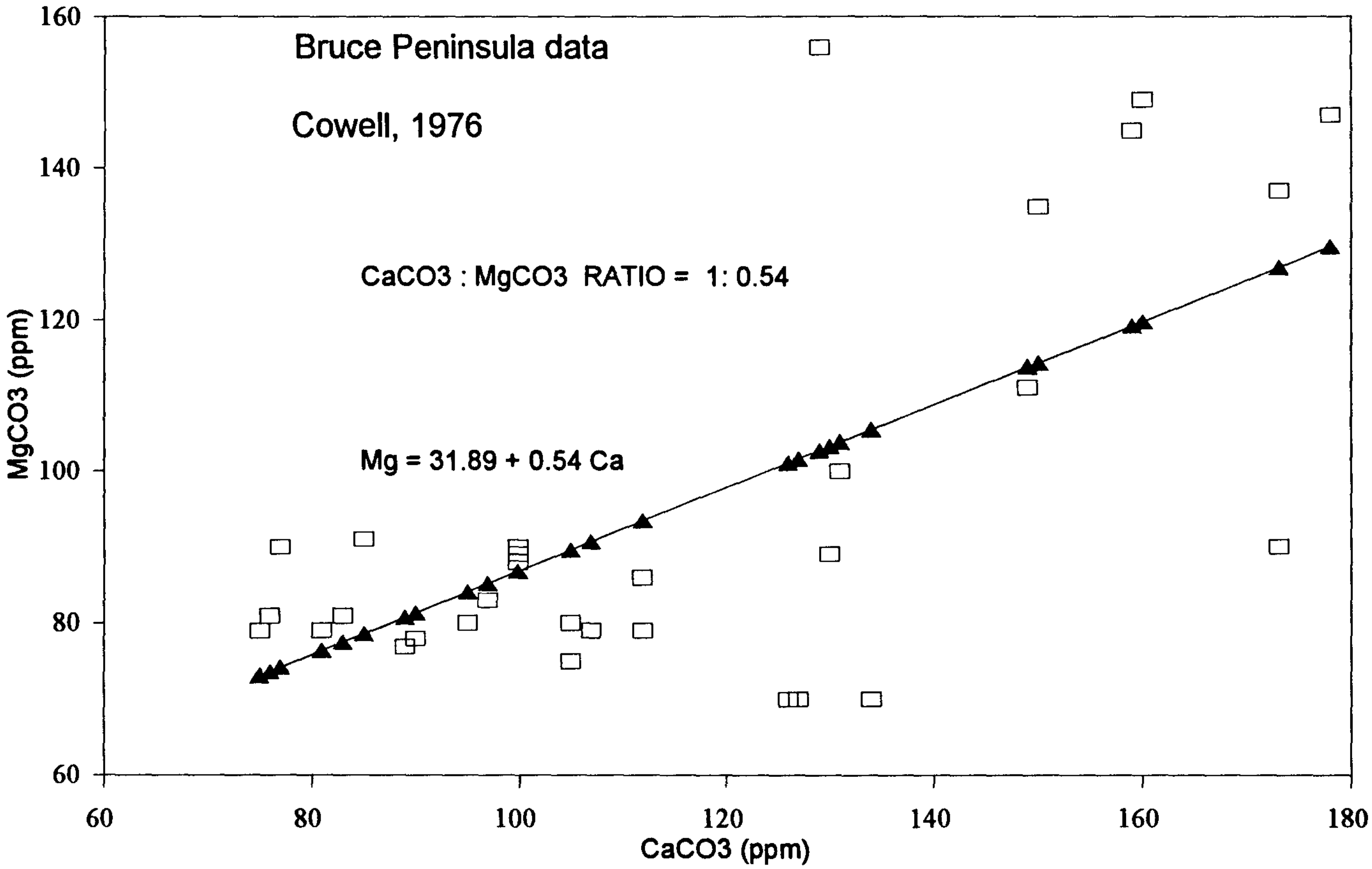


Figure 5.6
MgCO3 vs. CaC03 Concentrations

established through dye traces. A good guide is Cowell, who looked at pCO_2, T , SIc in addition to total, calcium and magnesium hardness to characterize Bruce Peninsula waters and to deduce much on karst development.

This reconnaissance may have established important sampling sites for a more thorough study of the Manitoulin Island waters. The steps for such a study, with an emphasis on subsurface waters but sampling all types of surface waters, may be carried out as follows. First, the linkage between recharge and discharge areas must be established to determine routes of groundwater flow. This must be done by a dye trace, which may prove challenging for Manitoulin Island since there are few concentrated sinking points; most recharge is diffuse seepage through pavement. Once this is established and a number of perennial springs are located, water chemistry data needs to be seasonally collected, perhaps using Cowell's measures plus SpC. This procedure would yield a complete set of water data on Manitoulin Island, to tie in with other data on the island's karst development.

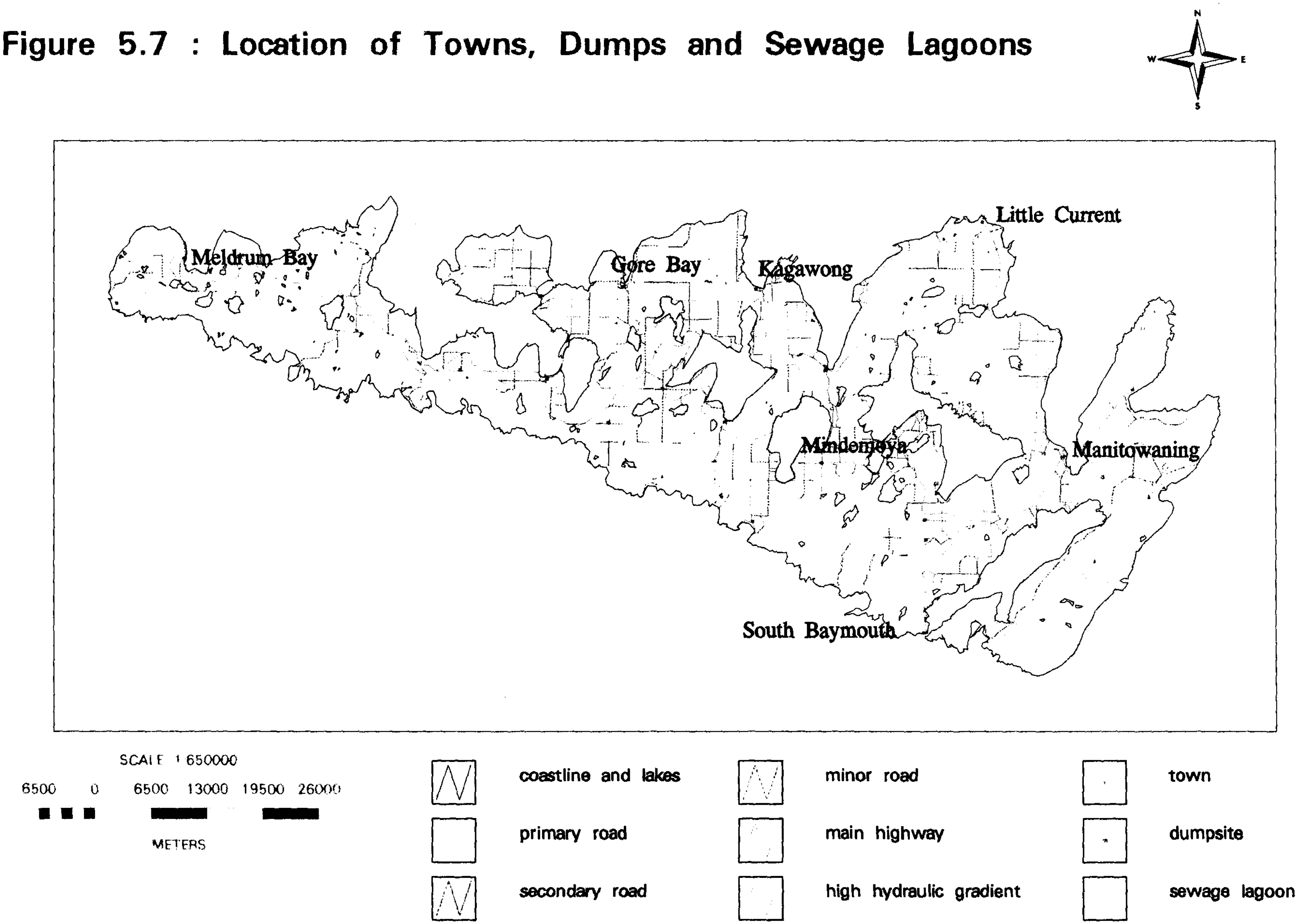
5.6 - Pollution Potential

Due to the limited field season, examination of dissolved pollution in the waters of Manitoulin Island was beyond the scope of this study. However, this is an important area for future study. This research gives evidence that potential environmental problems exist on Manitoulin. Such a study could be undertaken one a more complete set of sampling procedures is established, as described above.

Some evidence was obtained from field observations. A certain number of sampling sites yielded outliers that could indicate contamination. The likely pollutants include road salt and leachates from the sewage lagoon. It was observed that many local dumps and sewage lagoons are located on karstic rocks, several of them at high hydraulic gradient sites. In addition, many of the major towns are in areas where there is good potential for karst. Figure 5.7 maps these across the island. Thus there is potential for leachate to be directly input into the groundwater. From discussion with local residents, it was found that the dumps are not lined, many are on gravel beds and that many homes use septic tanks for their sewage disposal. Since many homes are directly on pavement, this could be a greater problem in the future, especially with increased tourism resulting in cottage development. Additionally, many residents obtain their drinking water from wells or lake water. Treatment often consists of a stercil filter (charcoal, no bacterial treatment). Thus if surface and subsurface waters become polluted it would affect local water supplies. Residents have suggested that pollution problems already exist in some areas such as Mindemoya Lake. At present, only Little Current and Gore Bay have advanced sewage treatment.

The samples from this simple chemistry study were

Figure 5.7 : Location of Towns, Dumps and Sewage Lagoons



weighted towards groundwaters rather than surface waters. Groundwaters are more susceptible to pollution, especially in karst areas, where conduit flow can rapidly spread dissolved pollutants far from their source. Groundwater pollution also makes remediation much more complicated since clean up is very difficult. Therefore, a future study which would help identify potential problems and possibly prevent them would be very useful for Manitoulin Island.

CHAPTER VI: ALVARS ON MANITOULIN ISLAND PAVEMENTS

6.1 - Methods

The main purpose of this research was to examine the occurrence and distribution of alvars on Manitoulin Island. Alvars are unique associations of vegetation found on limestone and dolomite pavements. These landscapes are believed to be products of enhanced mechanical erosion on carbonate bedrock following deforestation. The original forest cover has little possibility of full recovery due to the barrenness of the resultant surface (Koningsson, 1968). Most dissolution of the limestone and dolomite occurred under forest cover, which created the karst forms exposed today. Alvars are characterized by dominantly xerophilic (adapted to dry conditions) and calciphilous (adapted to calcium rich soils) vegetation associations and a humus-rich soil type (Tsobel, 1985).

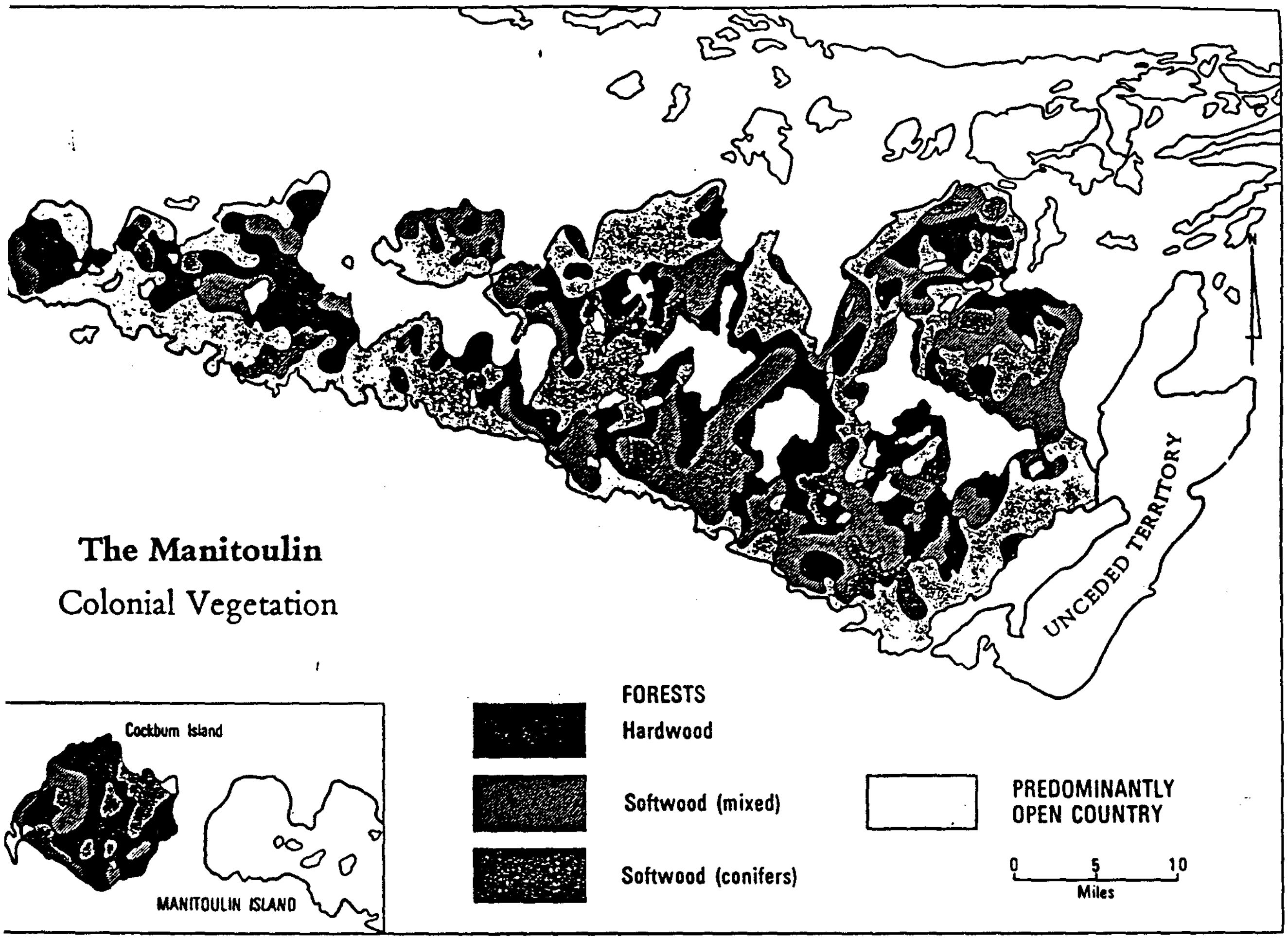
This research surveyed alvar vegetation to determine variation between types of pavement on Manitoulin Island. This was done by recording the presence or absence and relative density of major vegetation species at alvar sites. The following controls on alvar location and variety are examined : lithologic (rock and formation type), botanical (regional and local plant type and successional stage) and hydraulic gradient (drainage from karstic to normal, droughty to wet). Classification of alvar flora was not a focus of this thesis; Morton (1977) provides a detailed description of Manitoulin's vegetation.

Through the above methods, this research examines how changing land-use, from forested to agriculture to bare pavement (largely due to human influence), has altered the biological processes creating karst landforms. The history of changing vegetation on Manitoulin Island may be important to understanding the development and morphology of many karst features present today. Vegetation, through enhancing the concentration of CO_2 and organic acids in percolation waters, has enhanced karst processes on the dolomite pavements. Thus changes in vegetation through landuse will affect karst forms in their continuing development.

6.2 - History of Vegetation on Manitoulin Island

In prehistoric times a complex and varied mix of softwood and hardwoods forest was dominant on Manitoulin Island. Hardwoods included maple, oak, ash and beech and were common on uplands and in areas with thicker glacial deposits and soils. These were areas around Lakes Manitou, Mindemoya, Kagawong, Ice Lake, as well as on the northern headlands and central escarpment. Softwoods, dominantly cedar, birch, spruce and pine, could be found on droughty to swampy to fertile sites. Mixed softwoods were common in the central and southern areas of Manitoulin. By the time of the first surveys, there were also open areas, a result of earlier burn (it may be assumed most areas were forested prior to burn, except on the droughtiest sites). A reconstruction by Wightman (1982) from the detailed colonial surveys is shown in Figure 6.1. Table 6.1 shows the initial breakdown of forest type according to the original surveys. The first detailed survey was the Dennis Report of 1862, and surveys covering most the ceded territory continued between 1864 to 1879, (a total of 22). These were completed before most of the forest clearance by white settlers.

However, surveyors noted that many areas appeared to have undergone intense burn at the time of the surveys. Prior to white settlement Indians had practised small scale slash and burn agriculture. This resulted in locally hot conditions which stripped away all soil in areas with thin soils to begin with. The burns ranged in seriousness and permanence; sometimes the burn was intense enough to expose barren patches of bedrock, other times only the humus and upper layers were removed. Extensive burned areas were noted west of Lake Wolsey, in the southern townships of Burpee, Allan, Billings, Tekummah and on Barrie Island. The burns also ranged in ages,



<u>Figure 6.1</u>

Map of Wightman's reconstruction of pre-settlement vegetation on Manitoulin Island. Information from first colonial surveys (Wightman, 1982).

Table 6.1

Colonial Vegetation on Manitoulin Island

Categories	Acres	Percent
FORESTS hardwood	162,126	28.6
softwood - mixed	142,694	25.1
softwood - conifer	60,923	10.7
OPEN COUNTRY	202,543	35.6

(Wightman, 1982)

Table 6.2

Historical Landuse Change
(for ceded territory)

Class of Land	1931 acres	1931 %	1951 acres	1951 %	1971 acres	1971 %
farmland	264,746	45.5	282,995	48.6	242,125	41.6
bush	264,080	45.4	299,145	51.4	340,015	58.4
total land held	528,826	90.6	582,140	100	582,140	100

(Wightman, 1982)

older sites with much fallen, burned timber already had regrowth of shrubs and trees (mostly birch, poplar and evergreens) at the time of the surveys. It was reported that several regenerating areas were repeatedly swept by fires. Surveyors noted that in the eastern townships of Gordon and on Barrie Island, the frequency of fires resulted in prairie-like conditions. These older burns were likely caused by natural fires or from early Indian activity. However, later fires were purposely set by white settlers to clear the land for agriculture and road development (Wightman, 1982). These changes had important effects on the way pavement and karst features appear today.

Much of the remaining colonial forest cover was felled for timber to allow development of agriculture when white settlement began around 1867 (Wightman, 1982). Heavy harvesting in the early years have left the forests of the island in poor condition. Table 6.2 illustrates the changes in the natural vegetation with timber harvesting. The original forest occupied 64.4 % of ceded territories on the island, (28.6 % hardwoods and 35.8 % softwoods), with open areas (in various stages of regrowth) occupying 35.6 %. By 1931, agriculture accounted for 45.5 % of Manitoulin's landuse, and exploitation forestry of secondary growth used 45.4 % of the land, which left less than 10 % of initial forest in its natural state (Wightman, 1982). By 1971, 41.6 % of Manitoulin's land was used for agriculture while 58.4 % was bush. The latter refers to immature secondary forest in various stages of regrowth, although small-scale logging continues to the present. Today only in small patches does the rich forest growth remain, since most of the island is characterized by thin soils and rocky terrain, which does not allow the climax forest to regrow. In these regions poorer Boreal forests of the north are found. In open areas with very little soil cover, often only infilling grikes, mainly low shrubs including junipers, honeysuckle (*Virburnum rafinesquianum*), soapberry *(Sheperdia canadensis)* and dogwoods (*Cornus canadensis*) dominate (Morton, 1977).

6.3 - Impacts of Vegetation on Karst

One of the main environmental factors which controls karst solution processes is CO_2 availability. Here is where vegetation exerts a strong influence. Soil air CO_2 may increase up to 1 - 3 %) from a standard pCO_2 in the atmosphere of 0.033 %. Increased temperature and moisture increases the rates of CO_2 production, thus increases pCO_2. Highest CO_2 production is also found in the deepest soils, where there is greatest dry mass of litter and roots (usually in forests). Bacterial and microbial decay in ground air (in zone of percolation below soil) could also contribute to increased CO_2 concentrations in solution.

There are two sources of soil CO_2: respiration of roots and soil organisms and the decomposition of organic matter. The decomposition of organic matter, through microbial transformations, releases CO_2 in addition to creating organic acids which further react on the carbonates (Trudgill, 1985). Soil fungi also synthesize organic acids, releasing more CO_2 than bacteria. Plant tissue (the roots, canopies and stems of trees, shrubs, grasses) provide the original source of the soil organic matter. Secondary sources are from bacteria which attack the original plant tissue, their waste products and bodies becoming part of the organic residue (Brady, 1990).

These organic substances fall under the general category of soil humus, which includes humic substances (mainly humic and fulvic acids). These substances are dark brown in colour, amorphous and occur in cave deposits through precipitation (Thurman, 1985). Humic and fulvic acids are stable in soil and very resistant to microbial attack. They may remain in soil up to hundreds of years, thus are available to percolating groundwaters to influence the karstification process.

Additionally, plants growing on carbonates tend to create pockets of increased acidity around their roots (Jones, 1965). Acid stemflow is an additional process that can cause small-scale dissolution on limestones and dolomites. Deeply etched micro-runnels are often found at bases of trees, where bark drainage water runs over the bedrock (pH ranges from 3 - 5) (Trudgill, 1985). If extremely acid waters flow over carbonates, the result may be chemical polish (surface smooth from even dissolution). Weak organic acids produce etching.

Therefore, where the densest and heaviest vegetation is present, the karst solution process will be the most enhanced.

6.4 - Vegetation Change and the spread of Alvars in Historic times

Since the composition and distribution of vegetation strongly influences karst development, changes in vegetation cover also have important effects. On Manitoulin Island, the most significant land-use change has been deforestation. The early effects on the dolomite pavement may be evaluated from the conclusions of an extensive study on the limestones of Vancouver Island by Harding (1987). Harding found one of the greatest impacts of deforestation to be hydrological. This resulted in increased mechanical surface erosion and sediment yield from increased surface runoff. As on Manitoulin Island, the soil tends to be thinner on carbonate bedrock, thus more susceptible to erosion (Harding, 1987). Nutrient loss, a second consequence, occurred from removal of forest vegetation. Initially, the decomposition of organic matter increases from loss of forest cover and enhanced CO_2 concentration (Trudgill, 1985). Although at first this may be beneficial to karst dissolution, increased runoff soon removes organic matter which is often washed into grikes (Harding, 1987). Harding's study showed that limestone surfaces were far more sensitive to the above effects than other bedrock types that were used as controls (volcanics in her study). Soil depth decreased by 60 % and the percentage of bare rock increased by 20 % on the limestone surfaces. On newly exposed, bare outcrops smooth karren forms which had developed under soils and forest cover became enhanced by solutional micropitting. Flaky shattered pavement surfaces were common on intensely burned sites. From field reconnaissance such pavements were found to be very common on Manitoulin Island (Chapter 3). Since the deforested surfaces are usually colonized by mosses, lichens and other acid-forming vegetation, enhanced dissolution may continue, but to a lesser degree than before deforestation. Species which flourish in dry soils were found by Harding to increase in comparison to wetter loving species on the cut and burnt limestone areas. Harding's study showed that on land cleared in 1911, only an estimated 15 to 19 % volume of wood had been able to grow again, even on ideal sites with gentle slopes and well developed epikarst (Harding and Ford, 1993).

The result of such changes on Manitoulin Island is that a particular vegetation association, alvars, have become much more widespread. Alvar landscapes spread from their natural occurrence to normally forested areas due to increased mechanical erosion following deforestation. This is since recovery of the forest is minimal and very slow, and full regrowth is unlikely. Most karst forms presently exposed developed prior to deforestation. The term originates from the Great Alvar on Oland Island, Sweden. On this island, in addition to other areas in northern Europe, historical deforestation and overgrazing of limestone terrains since Neolithic times have resulted in development of alvars. Studies in Estonia and Great Britain show that the intensity of landuse is correlated with the severity of the resulting alvar form and vegetation type (Tsobel, 1985).

Alvar ecosystems in southern Ontario have been surveyed by Caitling et al. (1975). They are found where the Quaternary deposits are very thin and limestone and dolomite bedrock is exposed. This is most often along escarpment crests or on contacts between the Ordovician and Precambrian bedrock (Figure 6.2) (Catling et al, 1975). Alvar vegetation is not found on all limestone outcrops. For example, uplands on Manitoulin often are covered with hardwood forests. Caitling et al. (1975) reported that the richest alvar flora in the province is found on Manitoulin Island, although the actual study site was to the north on La Cloche Island limestones, as well as on Pelee Island and along the contact lines. Woods in the more open areas were composed principally of red and white cedar, white spruce and white pine along with spreading juniper, all species common on the pavement on Manitoulin Island. All sites had similar native species but with some regional variations. The characteristic species found on alvars were classified into several groups, including "alvar vegetation" (most abundant and widespread on alvars), prairie and dry ground species (native to western Canada), a mixture of northern (evergreens) and southern species (hardwoods), as

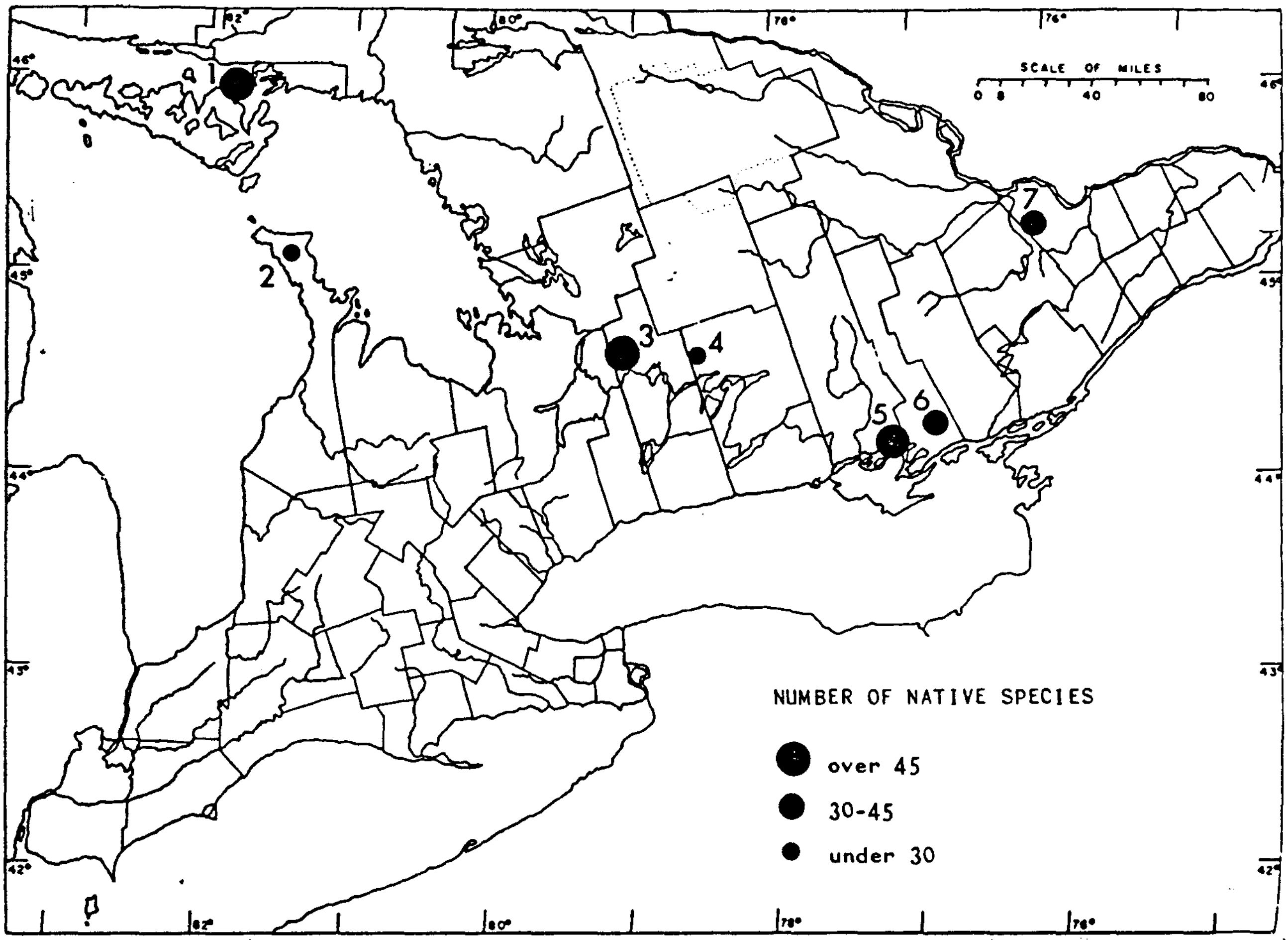


Figure 6.2

Location of alvars in southern Ontario (Caitling et al., 1975).

well as littoral species (on coasts) and weedy species. A main characteristic of these alvars is that vegetation usually forms a mosaic of the above communities, in a pattern linked to local conditions such as droughtiness, soil depth and moisture content. Often low herbaceous vegetation grades into parkland type vegetation with conifers.

One of the most important results from the study by Caitling et al. (1975) is the conclusion that the alvar vegetation in Ontario is predominantly natural. Largely alvar occurrence is not human-induced as documented in the European cases. This is deduced from the presence of the prairie species. These needed time periods longer than the span of human influence to colonize Ontario from the west. Colonization may have occurred during the warmer hypsithermal interval between 8000 and 4000 B.P. that is recorded by fossil pollen (Caitling et al, 1975). At this time forests retreated while prairie vegetation could spread and flourish in the ideal warmer and drier conditions found at most sites. As cooler conditions resumed, forests replaced the prairie vegetation except in areas where prairie species were favoured. These areas included the drier conditions found on thin soils with frequent fires in some open areas on limestone and dolomite. However, historic land-use change may have helped to spread conditions favouring alvar vegetation, as will be examined in this research.

6.5 - Vegetation Density on Manitoulin Island Pavements

6.5.1 - Field Research

For the purposes of this thesis, the definition of alvars is extended to all sparsely forested pavement sites on Manitoulin Island. This study does not attempt a detailed examination of the distribution of all major and minor alvar species on the island. It focuses upon the variation of major vegetation species found on different types of the karst pavement.

The field programme consisted primarily of vegetation identification and density measurements at eleven Amabel Formation pavement sites and five Fossil Hill sites. Since there was no extensive, well-developed pavement on the other karstic formations (Manitoulin and Kagawong), their characteristics are only briefly described. Density of the most common tree species provides the basic data for a comparison of alvar vegetation on the different lithologies, hydrologic locations and pavement types. Kolmogorov-Smirnov significance testing is used to determine whether there are differences between vegetation densities on the sites that can be attributed to control by the above factors. However, the very important control of history of natural vegetal colonization can only be examined in general terms because the majority of vegetation on Manitoulin is secondary regrowth.

Table 6.3 lists the tree species which are most common on the Manitoulin Island alvars and those which were used for

Table 6.3
Major vegetation species present on Manitoulin Island Alvars

white cedar - *Thuja occidentalis L.*
white spruce - *Picea glauca*
white pine - *Pinus strobus L.*
jack pine - *Pinus banksiana*
ground juniper - *Juniperus communis L.*
paper birch - *Betula papyrifera*
sugar maple - *Acer saccharum*
silver maple - *Acer saccharinum*
red oak - *Quercus rubra L.*

(Morton, 1977)

density counts in the research. Lower plants were principally mosses and lichens. These were not counted, but the amount of cover was estimated on a scale of three: slight, intermediate or heavy. Other minor plants were frequent but not included in the counts because of identification problems. The number of each type of tree was counted in a 100 m^2 plot at each site. Next, the sites were grouped for each formation according to location and pavement type for the Amabel sites (as categorized in Chapter 3). Refer to Figure 3.1 for site locations, which correspond to pavement locations.

6.5.2 - Alvar Vegetation Density

AMABEL ALVARS:

Table 6.4 illustrates tree densities at each site. The mean density of all trees was 222/100 m^2. The range was from 105 (site 2) to 380 (site 3). Cedar was the most common species, on average 89/100m^2 (range 0 to 300), followed by juniper (mean of 42/100m^2). However, the junipers often appear to be the dominant cover species because individuals spread over areas up to ten metres in diameter. Cedars were present at all but one site, junipers at all but two. Other common species included birch ($\bar{x}$ = 34/100m^2), spruce ($\bar{x}$ = 28/100m^2) and pine ($\bar{x}$ = 23/100m^2). Hardwoods were far less common, with only stunted maples and oaks being found on two out of the eleven sites, on average 2 to 3 m in height and 15 cm in diameter. Four sites had slight moss and lichen cover, five displayed intermediate cover and there was heavy cover on only

Table 6.4
Amabel Formation Alvar Sites:
Vegetation Density

Density of species per 100 m2
NOTE: for mosses and lichen: s = slight cover (< 50 % of surface),
m = moderate cover (50 % cover), h = heavy cover (>50 % cover)
NOTE: pine denotes P. strobus, unless * = P. banksiana

Species Vegetation	#/100m² Site 1	Site 2	Site 3	Site 4	Site 5
cedar	17	80	300	188	25
spruce	0	10	20	13	50
pine	63	5	0	0	16
juniper	60	0	0	30	50
birch	15	10	60	63	34
maple	6	0	0	0	0
oak	20	0	0	0	0
moss/lichen	m	h	m	s	m
total trees	181	105	380	294	175

Site 6	Site 7	Site 8	Site 9	Site 10	Site 11
44	27	0	30	173	100
30	133	0	0	27	30
0	0	170*	0	0	0
57	133	50	40	47	0
37	27	50	50	33	0
0	34	0	0	0	0
0	0	0	0	0	0
s	h	s	m	m	s
168	354	270	120	280	130

two sites.

There are numerous trends according to variation in type and location across the island (Table 6.5). The western sites (Sites 5, 6, 7 and 8) had higher total tree densities but lower densities of cedar and oak. The central sites (1, 3 and 9) had close to average tree density, with greater than average cedar and oak, close to average pine, birch and maple and less than average spruce and juniper. Southern sites (2, 4, 10 and 11)had the lowest tree densities, but the highest number of cedars, with birch close to average and all others less than average. Moss and lichen cover was moderate on all central sites, but in the south and west moss and lichen cover ranged from slight to heavy.

However, there is much variation between sites in a given geographical area. Central sites all have lower than average numbers of cedar, except Site 3 which yielded 300, the highest number of any site. Some species, such as pine, juniper, maple and oak only occur on one out of three sites. Mean densities range from very low to very high. Southern sites show more consistency; all have less than average cedar and spruce, although maple and oak are absent. The total tree densities vary from very high to very low values. Western sites all have low numbers of cedars, but Site 7 shows greater spruce and juniper densities. All sites have low pine numbers except Site 8. Total numbers also vary from very low to very high in the west.

Table 6.5
Amabel Formation Alvars:
Vegetation Density According to Location and Type

Density of species per 100 m^2
NOTE: for mosses and lichen, indicates most common extent cover: s = slight cover (< 50 % of surface), m = moderate cover (50 % cover), h = heavy cover (>50 % cover)

LOCATION:

Species Vegetation	#/100m^2 Central	Southern	Western
cedar	116	135	24
spruce	7	20	53
pine	21	1	47
juniper	33	12	73
birch	41	35	37
maple	2	0	8
oak	6	0	0
moss lichen	m=3	s=2 m=1 h=1	s=2 m=1 h=1
total trees	226	203	242

TYPE:

Type 1	Type 2A	Type 2B	Type 3	Total
111	61	14	190	89
24	20	67	15	28
0	20	85	3	23
29	50	92	0	42
50	33	39	35	34
0	2	17	0	4
0	5	0	0	2
s=3	m=3	s=1 h=1	m=1 h=1	s=4 m=5 h=2
214	192	314	243	222

In conclusion, gross densities do appear to vary according to geographic location. Western sites may have had greater burn, with the result that more xerophilous species such as pine and juniper are common. Furthermore, this area has remained more isolated, perhaps there was less land development since deforestation. Therefore regrowth potential has been greater, resulting in greater number of species and diversity.

Comparing vegetation to pavement type, Type 1 sites (4, 6 and 11) showed lower tree density but greater than average cedar and birch. There are no pine, maple or oak present. Type 2A sites (1, 5, 9 and 10) have closer to average tree density but with less than average numbers for all species except junipers. Type 2B alvars (7 and 8) have the highest mean density, with greater than average numbers for all species except cedar and oak. The maxima for spruce, pine, birch, juniper and maple all occur on this type. Type 3 pavements have a very high number of cedars, close to average birch and less than average densities for all other species. Type 1 sites have only slight moss and lichen cover. Type 2A and 2B moss and lichen cover is moderate, while on Type 3 it ranges from slight to heavy.

Examining the number of different species present at each site, the range was from all seven species present (Site 1) to only two (Site 11). Most sites had four to five. There are few other trends. Central and western sites had all seven while southern sites had at least five species present. Type 1 pavement had the lowest variety of trees (four species). Type 2A displayed all seven species, Type 2B had six while Type 3 had only four in total.

Pavement type definitely appears to affect tree density. The very flat, regularly jointed Type 1 pavement has the lowest density of species, followed by undulating Type 3 pavement. Types 2A and 2B, the most fragmented, support the greatest density and variety of trees. This suggests that on smooth pavement, due to less debris infilling grikes, the potential for trees to take root is lessened. On fragmented pavement, debris in grikes can support greater densities and varieties of trees. Another condition influencing alvar vegetation density appears to be droughtiness. On Type 1 pavements, with little moss or tree cover, most surface precipitation rapidly flows underground through exposed grikes, thus these sites are droughtier. However, hardier species which thrive on a wide variety of conditions, especially cedar and birch, are more common. Furthermore, sites with a very "clittered" appearance likely underwent heavy harvesting and burning. They are presently very droughty, supporting only tolerant species such as juniper and pine. The numbers of other species are lower, such as cedar. Therefore it appears that the degree of pavement fragmentation, which determines the amount of debris in grikes for trees to root, controls the number of species and total vegetation densities that are found on these sites.

On pavements with shallower but wider grikes, more soil and vegetation debris may be trapped. Thus greater densities of trees are found on these pavements. Tree sizes also appear to be related to the above factors: on pavements where greater densities of trees are present, their sizes are be greater. Trees are much more stunted on the droughtier sites.

FOSSIL HILL SITES:

Overall, tree densities are greater on the Fossil Hill Formation than the Amabel, with approximately 140 more trees per $100m^2$ (average approximately $362/m^2$) (refer to Table 6.6). Cedars, spruce, birch and maple are found in greater densities while pine and juniper are in lower densities, and there are no oak present. Moss and lichen cover is also more extensive, being heavy on four out of five Fossil Hill sites. Overall, the Fossil Hill is a more fragmented pavement with more debris for vegetation to grow in, thus greater densities are to be expected. Since they are less barren and less droughty, junipers numbers are lower than on Amabel sites.

Examining data site by site (Table 6.7), the central Site 1 has greater than average cedar and pine and total trees, while density of other species are less than average. There are no junipers, maple or oak present. Southeastern sites (2 and 3) have greater than average cedars, birch, maple and total trees, but spruce, pine, juniper are less than average. All sites except one in the south (with intermediate cover)

Table 6.6

Fossil Hill Formation Alvar Sites:
Vegetation Density

Density of species per 100 m2

NOTE: for mosses and lichen: s = slight cover (< 50 % of surface), m = moderate cover (50 % cover), h = heavy cover (>50 % cover)
NOTE: pine denotes *P. strobus*, unless * = *P. banksiana*

Species Vegetation	**#/100m^2 Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**
cedar	250	67	268	0	0
spruce	60	200	6	150	130
pine	20	13	6	40	0
juniper	0	27	0	70	40
birch	40	150	30	50	80
maple	0	19	67	0	20
oak	0	0	0	0	0
moss/lichen	h	m	h	h	h
total trees	370	476	377	310	270

Table 6.7
Fossil Hill Formation Alvars:
Vegetation Density According to Location

Density of species per 100 m^2
NOTE: for mosses and lichen, indicates most common extent cover: s = slight cover (< 50 % of surface), m = moderate cover (50 % cover), h = heavy cover (>50 % cover)

Species Vegetation	**#/100m² Central**	**Western**	**Southeast**	**Total**
cedar	250	0	168	117
spruce	60	140	104	110
pine	20	20	9	16
juniper	0	55	14	27
birch	40	55	92	71
maple	0	10	43	21
oak	0	0	0	0
moss lichen	h	m = 1 h = 1	h	m = 1 h = 4
total trees	370	270	430	362

display heavy moss and lichen cover. Western sites (4 and 5) have no cedars or oak, less than average birch and maple but greater than average spruce, pine and juniper. The total number of trees is less than the formation average.

In the central region, Site 1 on the Fossil Hill is located very close to Site 1 on the Amabel in the Nameless Lake area. Both display very high numbers of cedar and birch, with close to average spruce. In contrast to the Fossil Hill site, the Amabel site does not have any pines, but nevertheless the density of other species and total trees (both are above average) suggests that proximity is an important determinant: sites in the same local area have similar vegetation. This is likely a result of local vegetation history as well as uniformity of local physical conditions such as droughtiness, hydraulic gradient, etc.

6.5.3 - Significance Testing

Kolmogorov-Smirnov (K-S) testing was used to measure these qualitative trends on the alvar vegetation of Manitoulin Island pavements. The K-S test determines whether two independent samples are drawn from the same population or populations with the same distribution. The test considers the maximum difference between the cumulative frequency of the two samples and compares it to a tabulated value to determine if the difference is too large to attribute to mere chance (Roscoe, 1969). In this research, the difference between tree density for alvars on the two formations is first compared, then intra-formation difference according to geographical location and morphologic type is tested. The null hypothesis is that there are no significant differences between vegetation distributions on the different pavements. This implies that any measured differences are chance and all sites are members of the same population. Where differences between the two cumulative distributions of the samples are greater than the critical value for the test, the null hypothesis is rejected and the differences may be attributed to other factors, such as lithology, location or pavement type within a formation

Table 6.8 presents the results of the K-S tests. The significance levels are in Appendix 10. The null hypothesis was tested for significance levels between 0.20 and 0.01 The lower the level of significance at which the null hypothesis can be rejected, the stronger is the presumption that the two samples are significantly different.

Results:

Test 1 compared tree densities on the two formations, Amabel and Fossil Hill, considering all sites on each. Test 2 compared the two most different types of Amabel pavement (Type 1 and Type 2B). Test 3 looked at variation between the two geographical extremes (south and west) for Amabel alvars. Intra-site variation between Fossil Hill alvars appears low, so it was not tested.

The most important finding of the K-S tests is that all

Table 6.8
Significant Differences between comparable Alvar sites based on K-S two sample test

Test 1 = Amabel vs. Fossil Hill
Test 2 = Amabel Type 1 vs. Type 2B
Test 3 = Amabel west vs. south

Grouping	T	C	S	P	J	B	M	O
Test 1	***	-	***	-	*	*	***	-
Test 2	**	***	**	-	-	-	-	-
Test 3	*	***	*	-	-	*	-	-

(All significance levels are given in Appendix 9)

NOTE:

T = all trees
C = cedar
S = spruce
P = pine
J = juniper
B = birch
M = maple
O = oak

*** = < 0.01 significance
** = < 0.1 significance
* = < 0.2 significance
(denotes that the sites being compared are signifcantly different at the above level)

tests revealed significant differences for the total number of trees between the different types of alvars. The impressions gained from the raw field data are thus confirmed. Test 1 showed significant differences at the lowest significance level of 0.01. Tree densities at most Fossil Hill sites are greater than for the Amabel, chiefly reflecting the fact that there are more debris for trees to root in. Test 2 also showed at level 0.01 a significant difference, again from the fact that Type 2B pavements are much more fragmented. Test 3 confirmed a significant difference at level 0.2. The conclusion for different densities between western and southern Amabel sites is not as strong, perhaps since there are various types of pavements at each location (noise).

The second most important was spruce density variation. It was found to be significantly different at level 0.01 for Test 1, at level 0.1 for Test 2 and at level 0.2 for Test 3. This may be related to more droughty conditions on the Amabel pavements, Amabel Type 1 and southern alvars. Spruce needs fairly deep soils to thrive in, thus more fragmented pavements may be needed for it to be found in greater densities. Spruce distribution may also be related to local conditions such as local vegetation history, etc. Spruce is also a tree which does better in heavier forest conditions, thus thrives where total tree densities are greatest.

Tests also revealed no significant differences for cedar according to lithology, but a significant difference at level

0.01 for the Amabel according to location and type. Because cedar is so widespread, it is found on most pavements (similar means for Amabel and Fossil Hill alvars). There are greater cedar densities on Type 1 alvars and in the south. The reason is not known for certain. It may be related to tree physiography or pavement morphology. However, in general it seems cedar is the most robust colonizer. It gains first footing on the harshest sites but it is comparatively easily displaced by other species on more favourable terrains.

The distribution for the remainder of species sampled is fairly similar for all types of pavements. The greatest differences show up between the Amabel and Fossil Hill; again lithology is an important control. Birch, juniper and maple were significantly different here (birch also for Test 3). Oak numbers were very low (typically 0) on most pavements, so there were no significant differences.

6.5.4 - Alvars on other formations

On the Manitoulin and Kagawong Formations, most high hydraulic gradient sites (top of scarps) are known to have karstic drainage. However, they are typically covered with very thin soils of the Farmington series (13 to 25 cm in depth). Bare pavement is rare, being limited to a few shallow grikes by the roadsides or to five meter zone along the scarp edges. The characteristic vegetation consists of flat, grassy fields that are used for pasture even on the high hydraulic gradient sites. Occasionally there is heavier forest along the scarp, often including hardwoods (scrubby maple, ash and oak, mostly birch). Junipers and cedars are scattered sparsely throughout pasturelands. This lack of typical alvar vegetation on these formations is a result of landuse practices. These areas are suitable for grazing and their treeless state has been maintained. The forest could not regrow once initially cut and/or burnt. Alvars on the Manitoulin Formation consist of grasses covering most of the bedrock and soil filled grikes. The Manitoulin bioherm does not have alvar vegetation similar to that on other pavements, although pavement is well developed on it. This is because it occurs in a limited area adjacent to a house and has been kept cleared except for a few scattered cedars and herbaceous plants. Since it is situated on a scarp top, likely the natural vegetation would be forest resembling secondary growth on the Amabel pavements. There is much pitting on the bioherm which is filled with mosses and lichens (intermediate cover).

Therefore, the northern escarpment on Manitoulin Island does not feature the characteristic vegetation of the other alvars. Since there is no real pavement, these areas are usable as pasture and have remained treeless since deforestation.

6.6 - Discussion

6.6.1 - Interpretation

The natural vegetation on the Manitoulin Island dolomite pavements was a mixed hardwood and softwood forest, as described by original Crown surveys. However, since these records are now more than 100 years old, it is difficult to reconstruct the original vegetation at a particular site. Wightman's general reconstruction is the only guide available (Figure 6.1). As a consequence this study had no true control sites (good pavement known never to have been cut and burnt). Today, such natural forest may survive on the most elevated and remote sites the island, such as on the "Cup and Saucer" Hill. This location has no access roads and is on the highest point on Manitoulin Island. Some of its forest was likely never cut. Today, the vegetation is predominantly deciduous forest that grows nearly to the edge of the scarp. The edge is the only place when grikes are exposed but large trees are able to root directly in them. Maple comprises approximately 35 % of the forest, oak 30 %, spruce 20% and cedar 15%. There is heavy underbrush and moss cover on all exposed bedrock. This site has holokarstic drainage (no surface streams), but soil depth in grikes is sufficient to maintain the heavy, optimal forest growth. This is an observation also made by Harding (1987); before they are clear cut limestone (or dolomite) areas can maintain heavy forest growth even with very thin soils.

Using the Cup and Saucer as an example of a probably unaltered site, it is found that deforestation and burning of the natural forests has had a significant affect on pavement. The present vegetation is much more sparse than original due to changes from the land use (cutting and burning). However, due to reliance on old surveyors reports, the exact history of a particular site is not easily determined. Thus the conclusions on alvar development should only be applied generally.

6.6.2 - Conclusions

The patterns of tree occurrence on Manitoulin Island alvars are complex. Many factors influence species density and distribution. An important one is pavement type. The degree of fragmentation ("clitter") on a pavement, determines the number of trees which may root in grikes. Extra debris allow more trees to root and grow to larger sizes. Pavements which have wider and shallower grikes also have greater vegetation densities since they trap more debris and offer developing roots more space to grow. This factor of "clitter" varies according to lithology. The Fossil Hill is more fragmented than the Amabel and thus has greater numbers of trees. It also varies according to pavement type. Type 1 Amabel is much less fragmented than Type 2, which is reflected in the number of trees that may root in them. This factor resulted in significant differences between the total number of trees, spruce and maple for Amabel vs. Fossil Hill, and total trees, cedars and spruce for types of Amabel pavement. However, since there is much intra-formation variation in the densities, there are other factors controlling tree distribution. One could be droughtiness. On very droughty sites, especially in the south and west, the most common species are junipers and stunted birch. Cedars and spruce which are less drought tolerant are less common. Successional stage is also important. The western (more isolated) sites were left alone following their first cutting and burning, thus denser forest could regrow.

Reviewing the revegetation of Manitoulin Island following deglaciation may offer some insight to the post-settlement regrowth pattern. However, initial revegetation was quite different from that since 19th century deforestation. Due to the long time span the forest was able to fully regrow on limestone and dolomite bedrocks where most previous surface karst had been stripped by ice scour. Little soil or surface deposits remained, most being washed away by the post-glacial lakes. Freshly exposed, immature joints were open but not significantly widened by solution. When lake levels fell and Manitoulin Island emerged, mosses and lichens were the first to colonize. Along with herbaceous plants, this vegetation formed a natural alvar on the developing karst pavements on early Manitoulin Island. However, over time as organic matter accumulated, thin soils were formed. Succession by a climax forest followed since these trees could root in developing grikes filled with deeper soils. Karst dissolution was enhanced from organic acid input; and grikes continued to be widened and other subdued karst forms developed. On areas with thicker glacial deposits, the heaviest forest (greater numbers of hardwoods) could develop.

An exception to the above situation was along escarpment edges and similar extremely droughty sites. Here alvar vegetation was naturally favoured. These were likely very limited given the extent of forest reported by Crown surveys. However, due to human land-use change, the natural vegetation was altered so that most pavements on Manitoulin were stripped of their forests. This resulted in a second phase of historical recolonization.

One can examine recolonization in the Holocene to attempt to determine how particular species recolonized since historical deforestation. Initial forest succession on Manitoulin Island following deglaciation began approximately 11,000 B.P. with a spruce parkland type vegetation dominated by *Picea* (spruce), *Artemisia*, *Cyperaceae* and herbs, reflecting a cool, dry climate (Warner, Hebda and Hann, 1984). Between 10,500 and 10,200 B.P. *Pinus banksiana* (jack pine) and *P. resinosa* (red pine) became more important, along with *Populus* (poplar) in an open pine woodland reflecting warmer, dry climate. From 10,000 to 8,000 B.P. *Picea* again became dominant, and near the end of this time *Abies* (fir), *Larix* (larch) and *Betula* (birch) increased although the *Picea/Pinus* forest was still dominant. By 8,000 B.P. *Pinus strobus* (white pine) largely replaced *P. banksiana*, and *Tsuga canadensis* (hemlock) became important, persisting to present day. The hypsithermal maximum was reached at 6000 B.P. on Manitoulin when more prairie species invaded the island.

These patterns were a result of both climate and colonization characteristics of a particular species. Modern recolonization following deforestation is a result of local conditions (such as droughtiness), presence of seed local source and degree of soil cover available for growing plants. These may be results of the severity of cutting and burning at a site (Cotlam, 1981). Favourable species characteristics for recolonization include which ones are the most rapid invaders. Typically, spruce, tamarack and jack pine are the first to colonize. Over time with increased humus levels hardwoods such as oak and maple can be established (Warner, Hebda and Hann, 1984). This is observed on Manitoulin Island pavement. The dominant species present on most pavements (except the driest) is cedar, which seems to be the most robust colonizer and is found on the widest variety of sites (Morton, 1977). However, if present in greater densities the size of spruce will be the largest. The majority of maples and oaks present are very small saplings even though these are in lower densities. Today on Manitoulin Island pavements the immature forest is only at the first stage of succession. However, due to the characteristics of the bedrock, it may not reach full climax stages for a very long time, if it ever can.

The previous vegetation enhanced development of the karren forms on pavement visible today. Heavier forest vegetation resulted in enhanced dissolution, forming a well - developed pavement with widened grikes. Because the pavement developed under forest vegetation, the karren forms are very rounded and subdued. These include rinnenkarren and rundkarren. There is also much pitting because of mosses and lichens colonizing the pavement. To what extent the vegetation and vegetation change influenced pavement is unknown.

When human impacts altered the environment, the alvar vegetation could spread due to the expansion of favourable conditions created by deforestation and burning. On Manitoulin Island, the spread of fires, both natural and human induced following Indian and white settlement, likely allowed alvar vegetation to spread to more extensive areas of occurrence beyond natural areas. These are seen today on extensive plains even with low hydraulic gradients, especially in the west end. In the future karren forms that will likely develop include micro-pitting, which may be enhanced on exposed surfaces. Chemical weathering rates may overall decrease (less CO_2 input from vegetation) while mechanical weathering rates may increase. Since many pavements are on flat, open plains, likely there will not develop many more forms from surface flow (only on Type 3 pavement may have more rillenkarren). Mosses will continue to enhance dissolution in the pits and pans they colonize. Litter will be washed into grikes. Eventually they may fill in and some surface soil may develop.

There are differences between the alvars found in North

America and Europe. European alvars reflect much greater intensity of human land use for thousands of years longer than found on Manitoulin Island. The outcome of forest clearing followed by intense grazing was that full forest vegetation could never regrow due to loss of already thin soils. On Manitoulin, landuse mainly involved clearing and burning of trees, with less intense grazing continuing locally to the present. Many karst pavement areas were too barren for any cultivation or grazing, so were mostly left alone following the initial deforestation 150 years ago. Full vegetation has yet to recover upon them. There has not been enough time for vegetation to reach climax communities on the thin soil and droughty conditions. However, in some regions fairly dense forest, mostly conifers and few hardwoods, could regrow.

Manitoulin Island's alvars have more in common with other alvars in southern Ontario concerning appearance as well as types of species. However, alvars on Manitoulin's dolomite pavements have more a parkland type vegetation with sparse juniper-cedar forest because of deep grikes which trees may root in. The main factors influencing alvar development are the time scale and intensity of land use, which effect the type of alvar vegetation present on a site and the extent it is found, along with the rate of recovery for original vegetation.

For the future, some type of preservation may be needed to protect these unique assemblages of vegetation. The

Ministry of Natural Resources has such a preserve in the Misery Bay area, although this is very shallow pavement (Pearen, 1992). Other more well developed pavements should be protected as well, as was done in areas of England to protect pavements from quarrying, waste disposal, grazing, housing development etc (Goldie, 1988).

CHAPTER VII: GEOGRAPHIC INFORMATION SYSTEM ANALYSIS

7.1 - Why use Geographic Information Systems ?

Geographic Information Systems (GIS) are valuable tools in the study of geography. As in the other branches of science, geographers study real-world processes by the development and analysis of models. GIS enhances this process by providing meaningful sequences to design new models, and by offering advanced computer functions for rapid analysis. Once the geographic database is completed, information for each layer (coverage), containing specific details needed for analysis, can be manipulated in many ways. Since GIS can handle large amounts of complex data, it may identify new relationships between data sets and therefore increase understanding of the real world.

This thesis is the first known attempt to use GIS for a regional karst study. It was hypothesized that the use of a GIS for analysis would be useful for Manitoulin Island because many factors influence karst development and these might be combined and analyzed more efficiently in GIS. GIS is used as a tool to examine the karst geomorphology for the entire area of Manitoulin Island. Since this is a very large area and the field season was limited, a GIS could perform the analysis more quickly, easily and accurately. In this study, GIS work was undertaken after the field work was completed. However, in the future, it may be more useful if the analysis is done before fieldwork. This would pinpoint important sites for detailed study and allow information to be verified in the field.

In this thesis the vector-based GIS package ARC/INFO (by Environmental Systems Research Institute) was used to create the database for analysis and display. As in other GIS packages, information is stored for each coverage as map features (points, lines and polygons) with corresponding information in a table (on size, id number, and other). This package is the most popular commercial program and is advantageous to use. It is compatible with many other programs, has many functions in the PC version and can handle very large databases. It presents problems because it is command-driven thus not very user friendly. Other difficulties and sources of error in GIS use for this analysis will be discussed in 7.4.

7.2 - Steps in the Database Creation

Before any analysis can be done, there are many steps in the creation of a geographic database. This section summarizes those issues in database creation and analysis in GIS which are relevant to this project.

7.2.1 - Deciding on needs of the analysis

The initial decision-making process is an important one when using GIS. The objectives and criteria for analysis must be established from the beginning. The problem and sequence of operations needed to produce meaningful results must be defined. Each selection criterion must be looked at to see how it contributes to the final result.

The first step is to decide what maps and/or information one wishes to put into the database and decide which coverages are most important for the analysis. For this thesis, the purpose of using GIS was to gain information on the occurrence and distribution of karst for the entire area of Manitoulin Island. The nature of the problem is that karst development depends on a number of key criteria which act in combination. On Manitoulin Island, it is affected by: bedrock geology, presence, depth and type of Quaternary deposits and related soils, groundwater hydraulic gradient and topography. These factors lend themselves to GIS analysis since they can be mapped. They may each form separate coverages which can be looked at individually or combined to determine areas of potential karst development.

Each coverage provides important information about karst occurrence. The bedrock geology identifies where the carbonate units are, and which are more pure thus more susceptible to karstification. The location of Quaternary deposits identifies where there may be a barrier to karst because these deposits may slow or block groundwater flow into the carbonate bedrock. The corresponding soils have similar characteristics to their parent material (bedrock or deposit), which also may indicate karst potential in an area. Hydraulic gradient, as dictated by the combination of bedrock, cover and topography, indicates areas where there is greatest potential for rapid groundwater flow, thus karst development. It also suggests directions of groundwater flow. The location and type of surface waters in karst areas are also important. They are often present where karstic drainage is slowed or blocked, thus may indicate non-karst conditions. Sinking streams, rivers and lakes may indicate fluvial karst regions.

These factors are important to each aspect of karst examined on Manitoulin Island. They dictate the location of pavement, and how well developed it may be. For hydrogeology, they locate areas of high hydraulic gradient, and where the three different types of karst drainage are likely to be located (holokarst, fluvial karst and normal). For biogeography, they indicate where alvar vegetation will be most likely found, as it is related to occurrence of pavement in holokarst areas. For water chemistry, GIS can be used to identify patterns in conductivity and hardness across the island. GIS may also be used to identify areas potentially sensitive to land development and pollution, since karst areas are more vulnerable. The location of major towns, dumps and sewage treatment plants with respect to holokarst areas will give some insight to future environmental problems.

7.2.2 - Creation of the database

Once the analytical needs are identified, the appropriate database is created by digitizing the relevant information from source maps. This process encodes information in digital form so it can be used by the computer for analysis. Topology is later added to define the spatial relationships between the features. Each layer of information (contours, streams, geology etc.) forms a separate layer, or coverage, which can be later combined with others by overlay.

For each coverage first tic points need to be digitized. These are points with known latitude and longitude that serve as references. All future coverages for a particular map sheet are referenced to the original file containing the tics, known as a clip coverage. This process allows for greater accuracy when adding or editing features from a map. Tics must be registered within a maximum RMS error (root mean square error) of 0.003. This allows the tics to be registered as closely as possible to the original, thus accuracy is greater.

Next, the map features for each layer are input as arcs (lines) or label points. In ArcInfo every map feature is represented by them or the relationship linking arcs to form polygons. Locational and topological information are stored separately. Only one coverage can be digitized at a time. Initially, all units are in digitizer units (inches). Later, it will be explained how they may be projected into other units.

When all relevant features are digitized, coverages are checked for errors. ArcInfo has a command known as "CLEAN" which automatically performs some error correction. First, it calculates the intersection point between arcs. Then it "snaps" together any pair of coordinates within the preset "fuzzy tolerance". This joins some arcs which may not meet at their intersections. It also deletes arcs which "overshoot" their intersection points, within the "dangle length". CLEAN assumes that such arcs (known as overshoots and undershoots) are errors, thus corrects them. However, the coverages must still be checked manually since there may be errors which are larger than the set tolerances. CLEAN also creates topology to define the relationship between features on the coverage and information stored in the corresponding tables.

Next "BUILD" must be used. This works on a clean set of arcs to create and update topology. It must be used also if any changes are being made on a coverage, since it updates coverage information with that stored in the tables. BUILD creates either line coverages (information stored for lines) or polygon coverages (information stored for areas between lines).

The following step is to add attribute information about the features, such as length and name of a river, type of soil, etc. ArcInfo stores basic information such as length of arcs, perimeter and area of polygons, and various identification numbers for each feature. Information on what is important to each coverage needs to be added by the user. Table 7.1 lists the attributes for each coverage in the Manitoulin Island database. This information identifies areas of karst and includes names or descriptive terms for display and user query purposes.

Once all attribute information is correct, the coverage must be transformed from digitizer units (inches) into real-world units (meters in UTM). Latitude and longitude for tic locations are entered into the tic file. This file, using the "PROJECT" command, is then transformed into UTM.

There may be several adjoining maps forming the total coverage. At this stage they must be joined to form the complete map. For Manitoulin Island, there were seven OBM maps to join, and six geological maps. The command "EDGEMATCH" is first used to make sure that the features at the edge of each coverage will link. This visually joins nodes and arcs that must link from one coverage to the next. It must be done for all sides of adjoining map sheets. Once all coverages are edgematched, the coverages must be joined for both features and attribute information. Two functions in ArcInfo may be used. "APPEND" merely brings together features without building new topology. "MAPJOIN" does both in one step.

The final step in creation of the database is to check all features and attributes to make sure they are correct. If there are polygon borders along the individual map borders, "DISSOLVE" is used to remove them.

Table 7.1
List of Selected Attribute Information for Manitoulin Island GIS database

Geology coverage

Attribute: Formation
CODE:

1	Guelph
2	Amabel
3	Fossil Hill
4	Mindemoya
5	Cabot Head (and St. Edward)
6	Manitoulin
7	Kagawong (and Meaford)
8	Basal Beds
9	Lindsay
11	other (quartzites)
10	normal lake
20	karstic lake

Attribute: Type
CODE:

1	dolomite
2	limestone
3	shale and shaley limestone
4	other
0	lake

Attribute: Karst features
CODE:

1	good
2	few
3	none
0	lake

Physiography coverage

Attribute: Deposit
CODE:

1	limestone or dolomite plain
2	clay
3	sand
4	drumlinized till plains
5	beveled till plains
6	esker
7	peat and muck
8	bare rock (quartzite)
10	lake

Attribute: Karst potential
CODE:

1	likely
2	possible
3	inhibited
4	lake

Lakes and Coastline coverage

Attribute: class
CODE:

1	normal lake
2	karstic lake
3	land

Rivers Coverage

Attribute: class
CODE:

1	normal
2	karstic

Roads Coverage

Attribute: class
CODE:

1	primary road
2	secondary road
3	minor road
4	large highway

Attribute: name
(Highway or road number)

Dumpsite Coverage

Attribute: Class
CODE:

1	tcwn
2	dumpsite
3	sewage lagoon

Other Coverage

Spring locations
Pavements study site locations
Water sampling site locations
High hydraulic gradient line

7.3 - Sources of data

At the present time, there are no other digital maps of Manitoulin Island available; thus the database created for this thesis may prove to be a useful general resource in the future. All the information had to be digitized. Basic source maps were the 1:50,000 Ontario Base Maps, which provide data on contours, shoreline, lakes and rivers, roads, township boundary lines, town and dump locations. In addition, geology maps and physiography maps from the Ontario Geological Survey were used. The complete list of maps is provided in Table 7.2.

7.4 - Analysis

In modern GIS work the various types of analysis are typically performed in a set order. First, spatial operations are performed, which involve overlaying coverages on top of each other to create new polygon coverages. This maintains their spatial locations and attributes and joins them to derive new relationships. Some types of operations include buffers, erasecover, clip, update etc. Tabular analysis is performed next. This uses logical and arithmetic equations to select and remove features from attribute tables. This is from the "reselect" module, which selects a subset of the current records in a coverage according to an equation.

The final step in analysis is to evaluate and interpret the results. The initial analyses are examined to see if they are valid and reasonable. The validity of the criteria and need for additional analysis must be addressed. Errors in

Table 7.2
Source Maps for GIS Database

1. Ontario Base Maps

1 : 50,000 scale (centimetres)
Surveys and Mapping Branch, Department of Energy, Mines and Resources

41 G/9	1976
41 G/10	1976
41 G/13	1976
41 G/14	1976
41 G/15	1976
41 H/11 & H/12	1990
41 H/13	1990

2. Geology Maps

1 : 63,360 scale (inches)
Ontario Division of Mines
(based on geology by B.A. Liberty, 1954 - 1957)

2244	1972
2245	1972
2246	1972
2247	1972
2248	1972
2249	1972

3. Physiography : Northwest Portion, Southern Ontario

1 : 243,077
Ontario Department of Mines and Northern Affairs
(Based on "The Physiography of Southern Ontario, 3rd Ed." edited by L. J. Chapman and D. F. Putnam).

2224	1984

database creation and analysis are examined. The analysis may need to be refined. Certain steps may need to be adjusted and repeated, alternative approaches may need to be used. Finally, if the results are suitable, maps are prepared for both graphics and hardcopy display. Written reports are usually produced as well.

For Manitoulin Island, the following types of analyses were performed. First, appropriate karstic bedrock formations were selected from the geology coverage. Then, the karst-inhibitive or clay rich Quaternary deposits were selected from the physiography coverage. These areas were erased to create new coverage containing only karstic units. This produced a map of areas which are potentially karstic due to favourable bedrock and lack of inhibiting surface deposits.

Groundwater hydraulic gradient was calculated manually, and the boundary then digitized in. It determines where the greatest potential for karst drainage exists, although pavement is common throughout the entire karstic area, regardless of gradient. The method is explained in Appendix 5. This line was overlayed onto the previous map to isolate karstic uplands within the high hydraulic gradient zone. In the new coverage this line represents the distance from the edge of the central scarp where karst potential is greatest. Figure 4.4 is the output of this analysis.

Additional analysis involved overlay of locations of pavement, karstic lakes and rivers. These maps show how these pavement locations correspond to areas of greatest karst potential; that there are few surface rivers in the karstic zone and that most lakes in it are karstic.

GIS was also used for display purposes in this thesis. Water sampling sites and location of towns, dumps and sewage lagoons (potential pollution sources) were mapped for the map in Chapter 5, and general maps of physiography and geology were also created. Maptools was used to create the maps.

7.5 - Sources of Error

Although GIS offers a more accurate and sophisticated method of data analysis, it is not without sources of error. Some of these errors are inherent to geographic information systems itself, while others depend on the specific project.

Those which are inherent to GIS use at this time are briefly reviewed in Table 7.3. They must be accepted as margins of error.

There were numerous errors that were specific to this project. First, it was very time consuming to enter all data from base maps and edit all coverages for such a large area. There were several problems with the availability and quality of source maps. For the topological maps, much of the data was taken from air photos, and when checked in the field some features were misrepresented, particularly the presence and types of roads, and, more important, some streams and small lakes. Not all could be verified in the field. An additional source of error lies with the contour coverage.

TABLE 7.3
Errors Inherent to GIS use

1. In the transformation of spherical coordinates (latitude and longitude) to Cartesian coordinates, there will be some distortion.

2. There is question of accuracy of the measurement of the features on Earth which are represented by the source map.

3. When digitizing, there will be a certain degree of interpretation by the analyst, such as interpolation of a boundary.

4. If data need to be converted from vector to raster or raster to vector, further error is introduced.

5. The process of analog to digital conversion also depends on the accuracy of the digitizer.

6. The stability of the input document may also introduce errors, since paper maps can shrink from humidity or become folded and torn.

7. The accuracy of the human eye sets the limit for digitizing accuracy (maximum 0.5 mm resolution).

8. There may be error when new coverages are registered by their tic points.

9. Machine precision may create errors, since the computer may need to round off numbers, or when data must go through a series of calculations and transformations. The use of computers may create a false sense of accuracy, since they can store numbers in greater precision than possibly represented on the source map.

10. Errors in digitizing from the source document may be related to the pen size used to represent features on the source map.

The effect of these errors may be cumulative. There also may be errors in accuracy of attribute information, whether due to mistakes on the map or because information changes with time. Soil classifications, etc. are subject to the surveyors interpretation. It is useful to check the accuracy of random points on a coverage, and to decide whether the amount of error is acceptable of if there is need to re-survey, depending on the application.

(Laurini and Thompson, 1992)

This could have been more accurate if every contour on the basemap (25 ft) was digitized. However, due to the complexity of the topography, and time constraints, only every 100 ft contour was entered. With respect to physiography, the only map available was very small scale (1:243,077). Accuracy could be improved if a larger scale map was available. The soils map for Manitoulin was very complex and the source document was in poor condition. Thus physiography, closely related to soils, was used instead. A larger scale soils map would yield greater accuracy. The most detailed geology map was old, and based on Liberty's 1954 stratigraphic classification. More recent classifications exist, which may be more accurate for karstic purposes. There was no suitable map of modern forest distribution, which would allow for additional analysis of alvar distribution. An additional source of error from the digitizing stage is that two persons digitized the base maps. There may have been different interpretations of the source map during digitizing. One digitizer did not use the "SPLINE" function, which automatically creates a curve out of a series of vertices while digitizing. For these coverages this was done during editing, which may be an additional source of error.

Other problems arose in the process of editing. By having to use CLEAN, many contours and geology boundaries were accidentally snapped together. These errors were manually corrected, not re-digitized. This could also reduce accuracy.

However, they were all along steep scarps, where the location of contours is largely interpreted by surveyors. There were also problems with analysing hydraulic gradient by GIS, which led to it being done manually. At this time GIS cannot handle the vertical difference which is needed for this calculation. The gradient lines were digitized in, thus less accurate. It was also only done for the southern scarp, although for the northern scarp it is known there is less well-developed karst. Calculating hydraulic gradients via GIS will be an important area for technical development because it will be applicable throughout hydrological regional flow studies and for pollution problems.

7.6 - Discussion of results

The first stage of analysis determined that the karstifiable bedrock on Manitoulin Island covers 60 % of the total area of the island. These are the Amabel, Guelph, Fossil Hill and Mindemoya formations, which show the best pavement development. In the next stage, removal of inhibiting deposits reduced the karst area to 50 % of the total surface area of the island. This revealed that in many lowlands presence of clay deposits inhibits karst in the south and west. Overlay of the lakes and river coverage determined that karstic lakes occur in these areas, mainly on the Fossil Hill Formation near the Amabel contact. Surface streams flow outside of these areas, thus differentiating the defining zones of holokarst and normal drainage. Overlay of the Lake Nipissing shoreline shows that all pitted pavement occurs within this zone. Alvar locations coincide with pavement locations. Pollution potential is great due to dumps and sewage lagoons being located in zones of high hydraulic gradient and/or on highly karstifiable units.

7.7 Conclusions

The GIS analysis confirms the findings from the field work. Although some problems may lead to reduced accuracy, for an overall look at karst occurrence on such a large area as Manitoulin Island, it proved to be a very useful tool. The major drawback of this GIS project was that it was extremely time consuming. Several months were spent digitizing and editing. For a large area as Manitoulin Island with no digital data already available, it is recommended that GIS be used only if it is very important to the final analysis. For this thesis, as a first attempt at a regional karst study, the GIS work proved to be a learning process. However, with digital maps becoming more available for many areas, future projects should be done much more quickly and efficiently. This research is a start at using GIS for karst studies. Various improvements, given more time, could take it beyond the preliminary stage. There are also many capabilities of GIS that were not used in this thesis, such as hydrologic modelling. There is much potential for mapping groundwater flow routes and rates in karst areas, which would be useful for modelling pollution flow routes. Mapping the density and distribution of smaller features such as sinkholes would help pinpoint recharge areas and possible routes of flow. The use of GIS for karst studies is virtually unlimited, given ingenuity and advancement of the present capabilities of the system. The digital database created in this research could be used for future studies of the island, with applications such as locating new sites for landfills.

CHAPTER VIII: CONCLUSIONS

8.1 - Review of the Karst landforms on Manitoulin Island

This research has revealed that Manitoulin Island has a great extent and variety of karst features. However, they are of immature type. The most important influences on karst development on the island are reviewed here.

The first factor is lithology. Although on the global scale limestones have greater solubilities and therefore greater potential for karst development than dolomites, on Manitoulin the opposite happens to be true. The limestones, which outcrop on the north side of the island, are composed the Simcoe Group, Georgian Bay and Kagawong Formations. They are characterized by a high percent of impurities (including clays and silica), thin beds and frequent shaley interbeds. Thus, the overall porosity and permeability of the rock is decreased, and with it the potential for karstification. However, it is known that water slowly penetrates into these units because there are numerous springs seeping out at their bases. Even though there are very few surface karst features (limited to a few shallow grikes) and no widespread pavement (not even at highest hydraulic gradient sites such as scarp edges), under thin soil and vegetation cover some karstic drainage has evidently developed.

On Manitoulin Island the best karst is found on the purest dolomite, the Amabel Formation. The Fossil Hill Formation is second, the Guelph and Mindemoya Formations are limited in extent of their outcrop and thus difficult to compare, but they display some karst forms. However, the Manitoulin Formation has too many insolubles and thin beds for good karst to develop, except on the bioherm. It is likely that since dolomite is the main karstic rock found on Manitoulin, the karst is less mature and less widely found than on more pure and massively bedded limestones (such on the glaciated Carboniferous strata of Yorkshire or Western Ireland).

The most important factor affecting the karstification potential of the Manitoulin Island dolomites is the Quaternary history of the island. Erosion by glacial ice has stripped away previous surface deposits, leaving exposed areas where the bedrock can be attacked by solution. Post-glacial history was important in this process because post-glacial lakes flooded most of Manitoulin, removing most till and glacio-fluvial deposits except in some lowlands. This situation is unlike that in southern Ontario, where a thicker and more extensive till cover has inhibited postglacial karst development.

The end of Wisconsin glaciation and the emergence of Manitoulin Island from the post-glacial lakes (approximately

11,000 to 9,000 B.P.) sets a time limit on karst development. In most situations mature karst (including cave development) needs longer time periods than this, thus many glaciated areas such as Manitoulin Island lack it. Furthermore, for well - developed conduits and caves to form, concentrated inputs are needed, such as large sinking streams or large sinkholes. On Manitoulin groundwater input is dominantly through pavement orifices (dispersed). Additionally, all the large rivers on Manitoulin flow on non-karstic bedrock or on clay-rich deposits thus have little potential for underground capture.

The most important findings from this research are reviewed:

1) GEOMORPHOLOGY

This research forms one of the most complete studies on dolomite pavement. Pavement was the most extensive karst form found on Manitoulin island. The most common karren forms were those which exploit structural openings, such as grikes which are present on all pavements. Other karren were more rare, but included pit-and-tunnel karren, rinnenkarren, solution pitting and kamenitzas. Pavement was best developed on the Amabel Formation, which outcrops on much of the southern and western island. Pavement was present at all hydraulic gradients on this formation, although at lower gradients it tended to be very shallow and not well developed. Excellent pavement was studied on 11 sites, and could be differentiated into three types. Type 1 were the very smooth and flat pavements with regularly intersecting grikes, with few karren forms such as pit-and-tunnel karst. Type 2 pavements had very roughly pitted surfaces, with Type 2B featuring more fragmented, clittered surfaces than Type 2A. These appeared to be the most common type of pavement and karren development was limited to pitting. Type 3 pavements were found on whalebacks and had the widest variety of forms include rinnenkarren and, more rarely, rillenkarren. On all the Amabel pavements grike width ($\bar{x}$ = 12.3 cm) increased while depth ($\bar{x}$ = 76.7 cm) and length ($\bar{x}$ = 316.6 cm) decreased as the pavement became more fragmented.

The Fossil Hill Formation pavements featured wider ($\bar{x}$ = 13.7 cm) but shallower ($\bar{x}$ = 59.8 cm) grikes, since they were much more fragmented than Amabel pavements (mean length = 390.7 cm). However, pavement was more limited in its occurrence, mostly exposed only by roadcuts. These pavements were very pitted, which seemed partly due to solution of the carbonate bedrock around siliceous fossils, with few other karren forms.

Well developed pavement on the Manitoulin Formation occurred only on the bioherm, which resembled the Amabel type of pavements ($\bar{x}$ = 13.5 cm for width, 113.7 cm for depth and 394.7 for length). On the normal bedded Manitoulin Formation, pavement were very shallow (grikes filled with soil to surface) with no other karren forms.

Pavement type and lithology appeared to be a more important control than geographic variation on pavement form.

Coastal pitting was observed on the Amabel Formation along the southern Lake Huron littoral zone. It was similar to that on the Bruce Peninsula and was best developed on Providence Bay whalebacks. Similar pitting found several kilometres inland (Misery Bay) give evidence of pit development under the Lake Nipissing shoreline.

Joint orientation patterns were studied on all pavements. The trends on Manitoulin Island appear to be related to those reported elsewhere in the Michigan Basin (Holst, 1982). However there is much variation across the Manitoulin Island pavements. The dominant trend is the 90^0 east - west set, which likely represents a regional force since the complementary 180^0 set which would result from tensional forces is very weak on the island. Other prominent regional sets on Manitoulin of 60^0 and 120^0 are offsets of 52^0 and 134^0 sets found in the Michigan basin. This could be because many joints are curved on Manitoulin, or that more data are needed.

Trends according to geography or type are very complex. The 90^0 set seems less common in the west, the 120^0 set less common in the central regions, the 30^0 set less common in the south and the 150^0 set less common in the west and south.

2) HYDROGEOLOGY

The most striking finding is that the two extreme types of drainage; normal fluvial and holokarstic, are each dominant in close to equal proportions. There is very limited immature fluvial karst. The two types correspond with locations of the two main aquifers on the island. They are separated by the Cabot Head shale aquiclude. The southern aquifer is formed of highly soluble dolomites and is dominated by holokarst drainage. The northern aquifer is formed of more impure dolomites and limestones thus features normal fluvial drainage, although there is slow seepage into the bedrock. The main spring systems draining these aquifers emerge at the bases of the central and northern scarps as well as on the down dip sides of the scarps.

The holokarst areas are found across all the Amabel, Fossil Hill, Guelph and Mindemoya Formations where there are no clay-rich surface deposits mantling the surface. This drainage is common on most uplands and many lowlands in southern and western Manitoulin. There are very few rivers in this region but there are numerous internally draining lakes which act as sinking points for underground drainage. Not much is known about the internal drainage conditions of the holokarst zones, since most inputs are quite diffuse (through large areas of highly fracture pavement) and outputs are via many small springs and seepages. The zone of highest hydraulic gradient (greatest potential for groundwater drainage) is on top of the central escarpment and was calculated to extend several kilometres back from the scarp edge.

Normal fluvial drainage is found along the northern headlands on the Manitoulin and Kagawong Formations, as well as the shaley Ordovician limestones. It is also found on the southern karstic bedrock if there are clay deposits. These surface stream networks flow according to topography: many drain either to the central lakes or over flow the scarp to the North Channel. Most streams are relatively small since the area where they can flow is limited to that between the two escarpments.

The fluvial karst systems are very small with two systems being found on scarp edges on the Kagawong Formation. This form is immature and limited because most surface streams do not cross the high hydraulic gradient zone in the central scarp. Streams either flow north of the central scarp or farther south. This results in little potential for stream capture but, given time, more mature fluvial karst may develop.

The existence of Mindemoya Cave shows that although they appear to be more limited, mature karst macro-forms can exist on Manitoulin. Probably these would have to be initiated pre-glacially in order to develop. The optimum location for such forms would be the high hydraulic gradient zone of the central scarp, but none have been there found yet.

Manitoulin Island has many similarities to the related karst regions of the Bruce and Door Peninsulas. Both have widespread dolomite pavement, but other larger scale forms are limited on Manitoulin. This may be because it emerged later from glaciation.

3) ALVARS

Alvar vegetation was found to occur on most Manitoulin Island pavements. It is a parkland type of vegetation dominated by relatively few tree species. These are cedar, spruce, juniper, pine and birch. Hardwoods are rare on alvars. Species occurrence and density seems tied into pavement type. More fragmented pavements with infilled grikes are able to support greater densities of trees. These include the Fossil Hill pavement and Type 2 Amabel pavements. Individual species densities are more complex, related to site droughtiness, local vegetation type and landuse history. Colonial surveyors' records suggest that most of the island was heavily forested, since over time thin soils on pavement could support greater tree densities. Since all sites studied feature secondary growth, a likely result of deforestation is that a much poorer forest is only possible once soil is lost down grikes.

4) WATER CHEMISTRY

From the analysis of the relationship between water hardness and specific conductivity a linear correlation was obtained which can be used in the future to predict Hd from SpC. The equation was close to White's (1988) obtained on Pennsylvanian carbonates, indicating a common regional water signature. Although this was an initial study, variables of total and calcium hardness, SpC and temperature suggest similarities to the water signature of the Bruce Peninsula. Springs have lower temperatures and higher SpC and Hd. This study also revealed potential of groundwater pollution problems on the island, although they were not analyzed for in detail.

5. GIS ANALYSIS

The GIS package ArcInfo was used as a tool to analyze karst occurrence across Manitoulin Island. It was used to determine where karst potential was greatest and to map location of karst features. It proved to be very useful but time consuming for such a large area, although the database created may be valuable to future studies on the island.

8.2 - Future Research Needs

Due to the limited field period, there are many areas for future research on the Manitoulin Island karst. This pavement study is believed to be a fairly complete one, as it examined a variety of characteristics at numerous sites. However, more sites could be examined between those studied here to see how different types of pavement change from one type to another. More sites are needed across the island to obtain a better pattern of geographic variation. The sites used in this research were all accessible (along roadways) but from airphotos, appear to extend across trackless areas of many kilometres. Although it may be difficult to gain access, such sites would yield useful data on changes over pavement in one area. More Fossil Hill sites need to be sought out, to better characterize this type of pavement. Additional study on the pitted littoral zone could examine variation in pitting form and density from the littoral zone back to the Lake Nipissing shoreline. However, even with more study sites. It is likely the pavement of Manitoulin Island will remain a complex landform which cannot be easily characterized due to a great range of variation in karren type and distribution.

The hydrogeology of the island needs much more study. Since it is a karst area, underground drainage cannot be deduced from surface observation alone because conduit development is complex. Dye tracing is required to positively identify connections between inputs and outputs, flow routes and flow rates. This may prove to be a very challenging aspect of the research because most drainage on the island is input diffusely through pavement, and outputs are small springs dispersed over wide areas. Dye traces work best if injected in point source inputs, such as sinkholes or swallets. Karstic lakes, which act as more concentrated inputs into the groundwater system, also create difficulties since few lakes have distinct sinkpoints and sediments at lake bottoms would absorb or slow the passage of dye. However, this study has identified many important sites for any such detailed work. A better understanding of the hydrogeology will be necessary to initiate a general study of pollution on the island, which almost certainly exists due to the siting of unlined dumps and residences directly on holokarst areas.

A water chemistry study could be carried out similar to that done by Cowell on the Bruce Peninsula. A wide number of variables important to karst waters should be analyzed. Once the important sites such as perennial springs, etc, are established, seasonal testing would be in order. However, use of the SpC:Hd relationship derived in this research could simplify need to determine hardness in most samples.

The study of alvar vegetation on the island could be expanded upon by examining vegetation density on unaltered sites such as on the Cup and Saucer scarp. A more detailed vegetation study could be modelled after Harding (1987) to include other variables such as tree girth and densities of minor species.

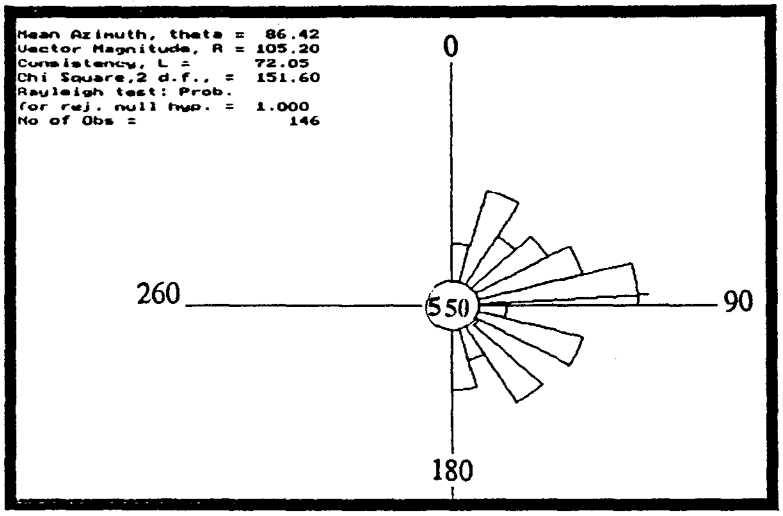
Finally, the GIS analysis could be improved upon if more accurate and detailed source documents were available (larger scale and better quality). More information may be input into the database such as more detailed contours, soils, vegetation type and density for more useful analysis. In the future development of a package which can estimate hydraulic gradient and map routes of groundwater flow would be very useful for karst hydrogeology studies.

APPENDIX ONE

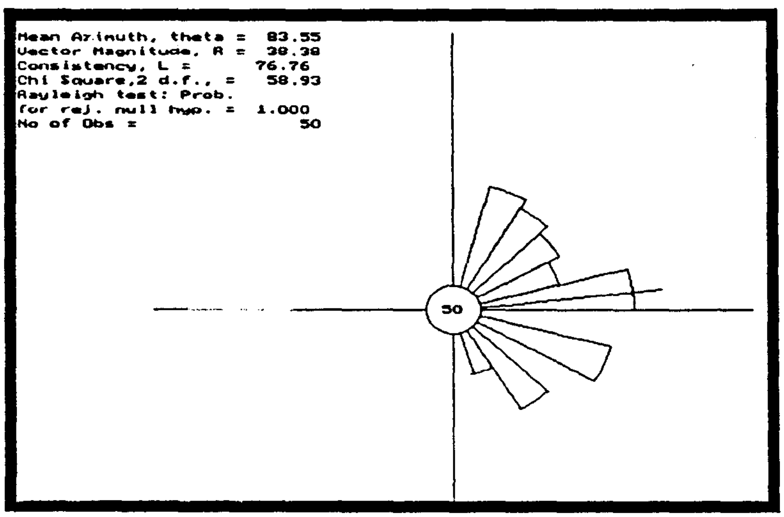
ROSETTE DIAGRAMS FOR INDIVIDUAL PAVEMENT SITES

(Data plotted in program Vecstat3 developed by G. Middleton, McMaster University)

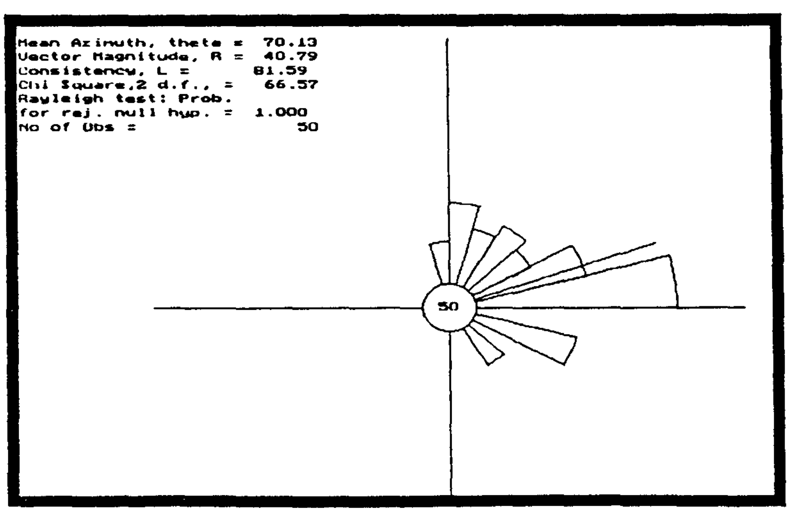
Amabel: All Sites



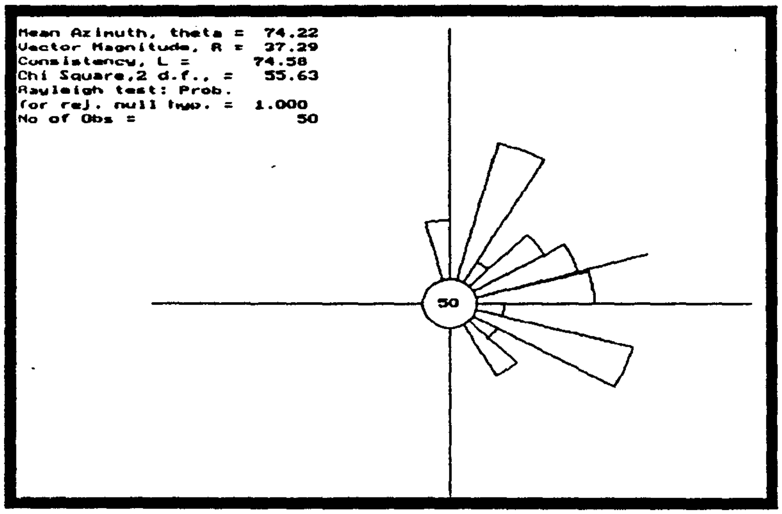
Amabel Site 1



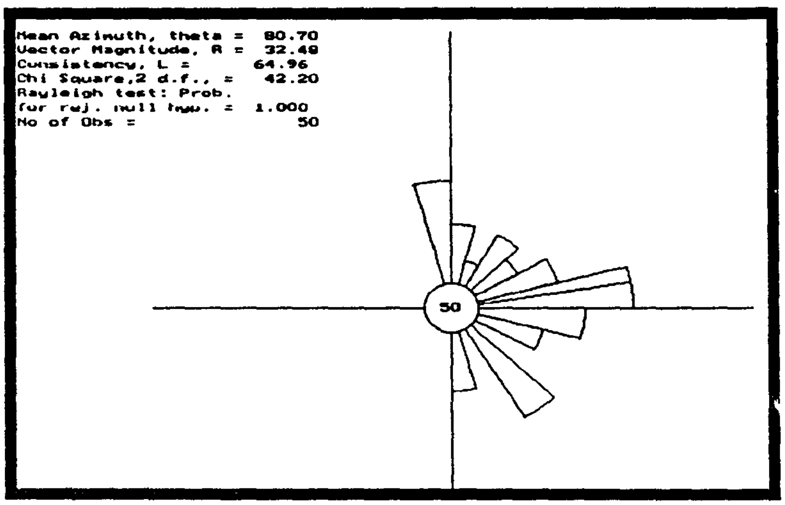
Amabel Site 2



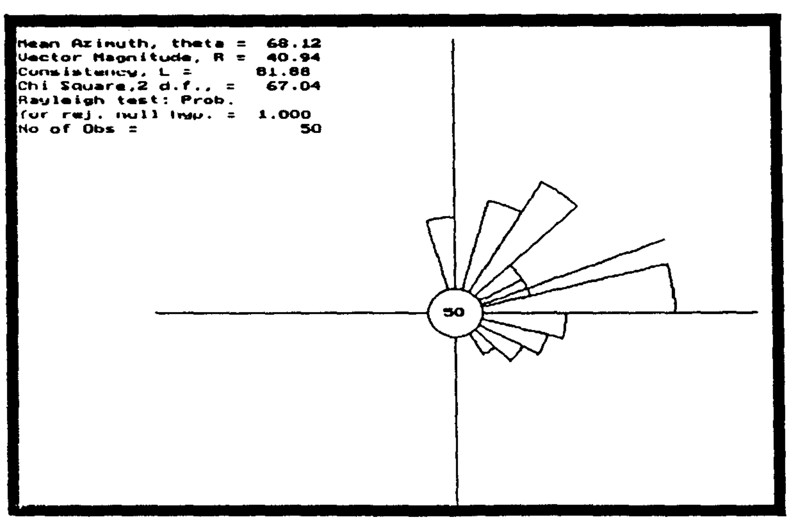
Amabel Site 3



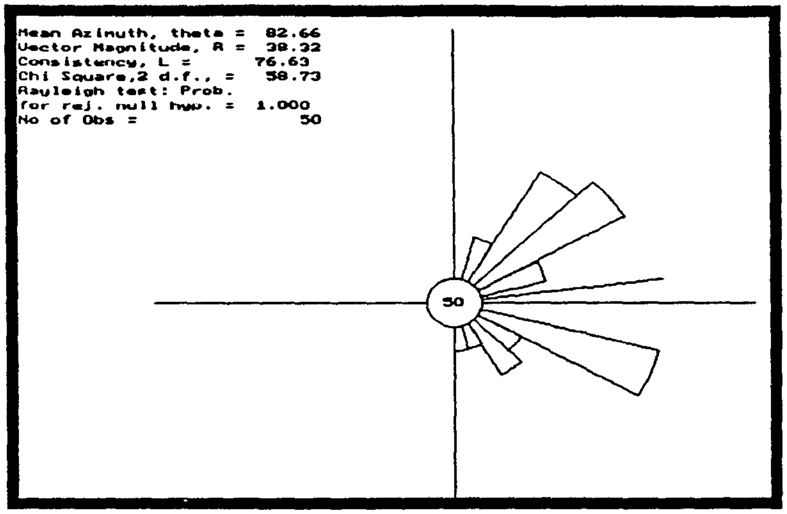
Amabel Site 4



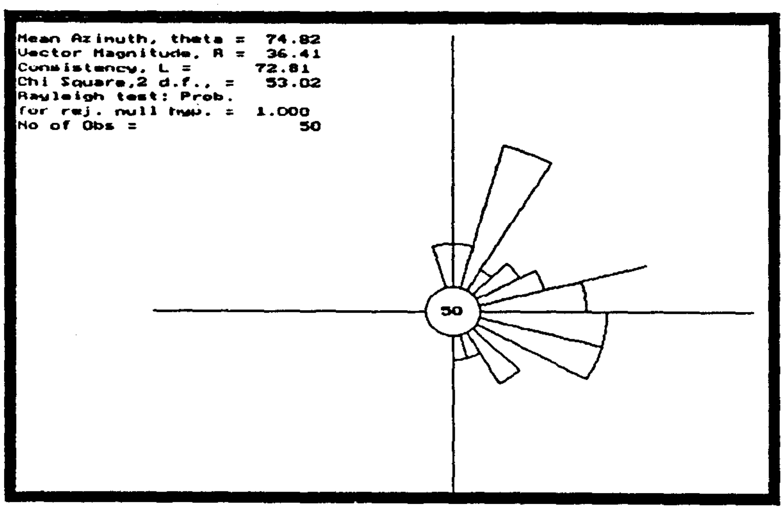
Amabel Site 5



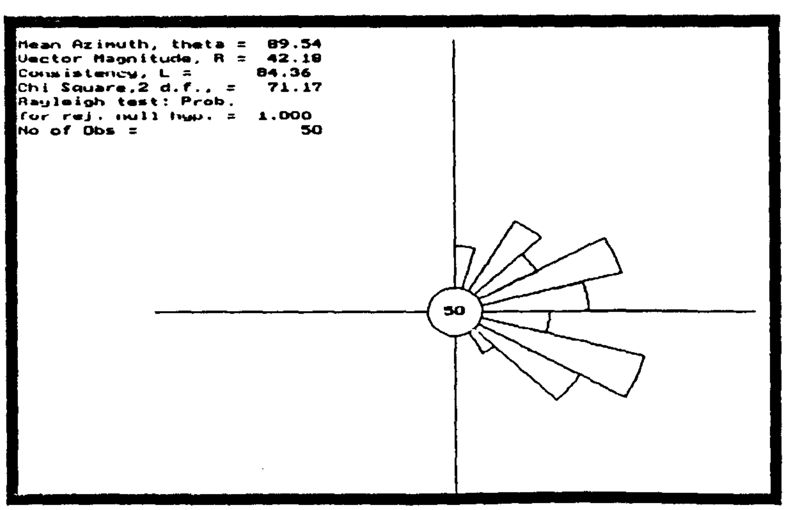
Amabel Site 6



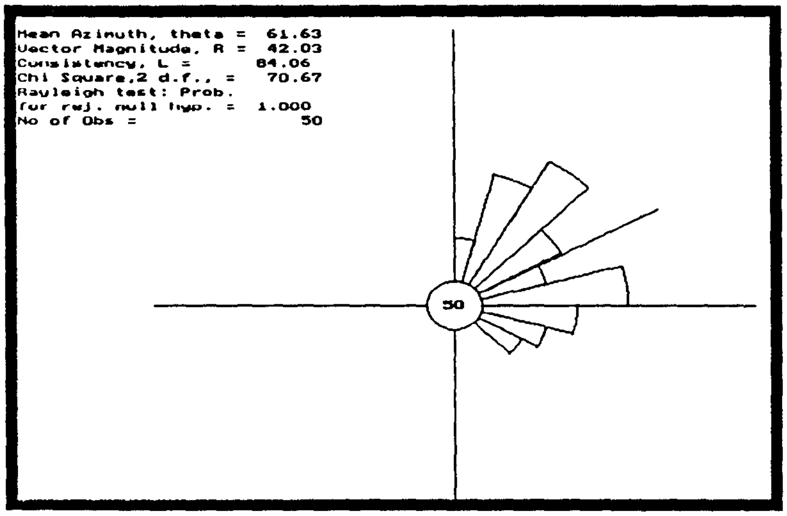
Amabel Site 7



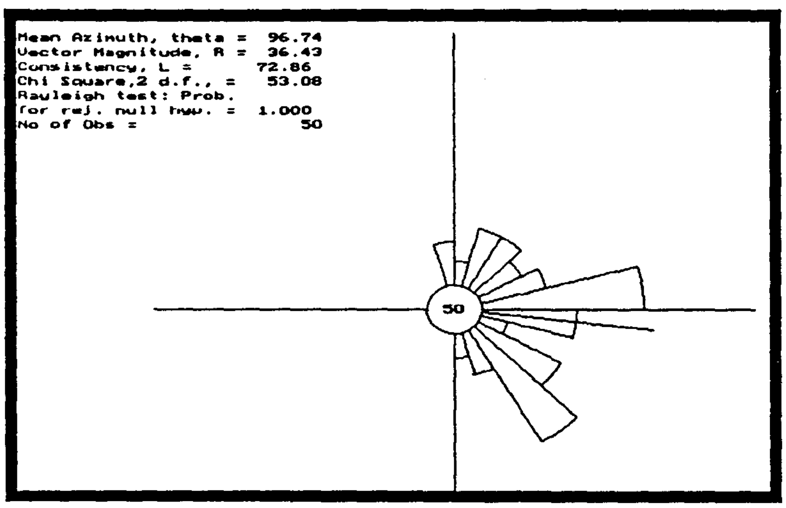
Amabel Site 8



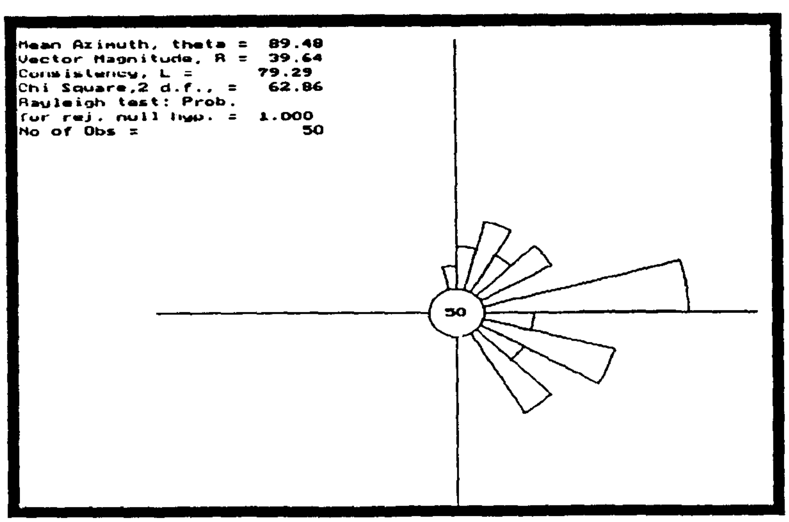
Amabel Site 9



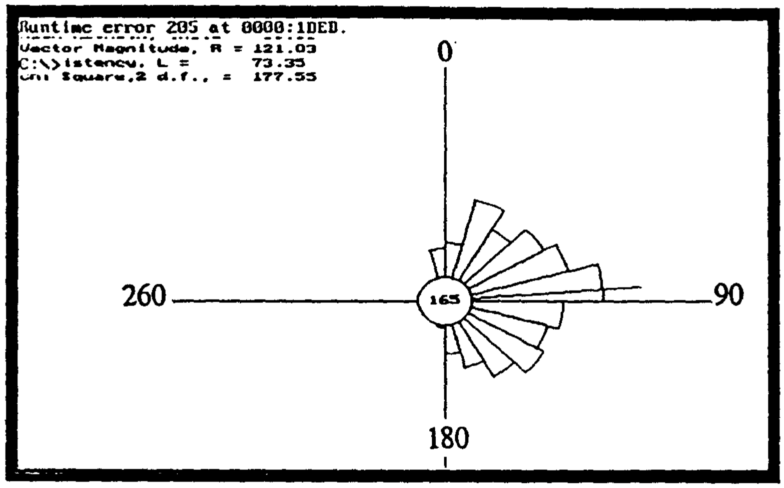
Amabel Site 10



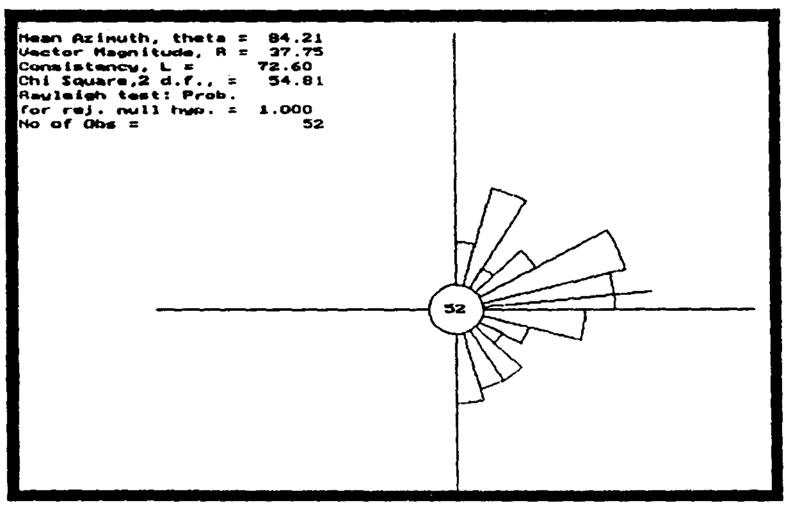
Amabel Site 11



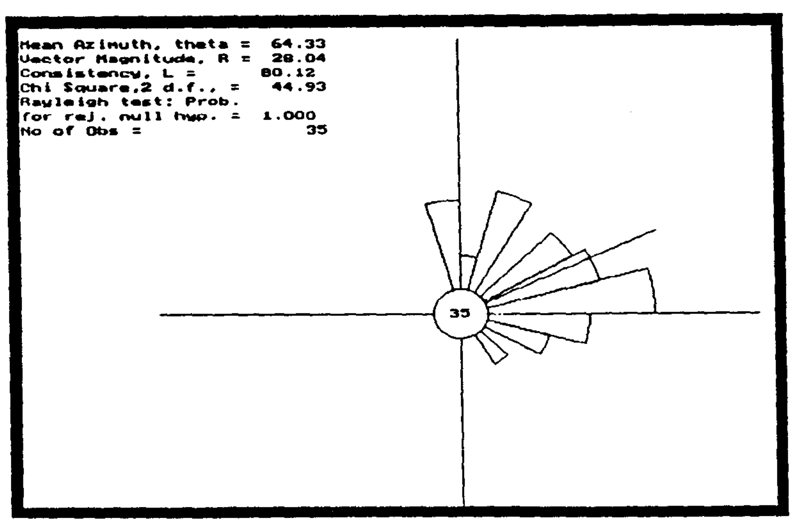
Fossil Hill: All Sites



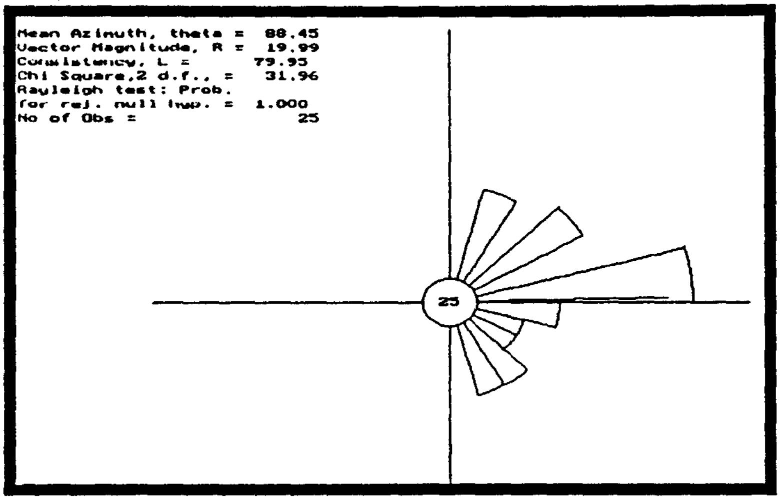
Fossil Hill Site 1



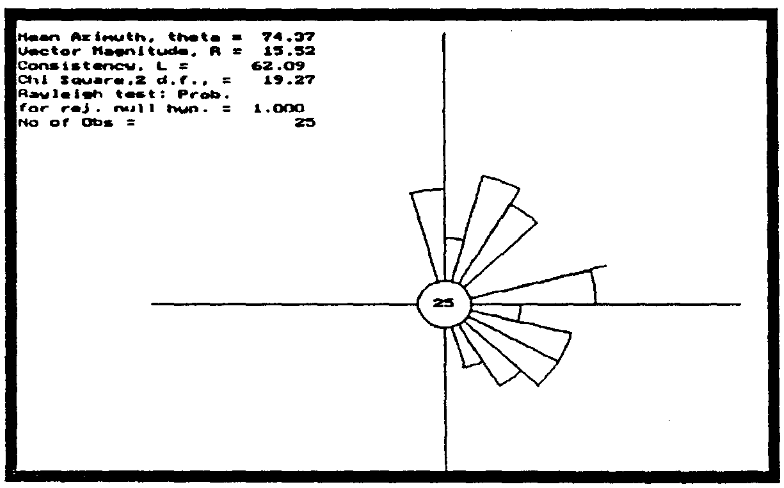
Fossil Hill Site 2



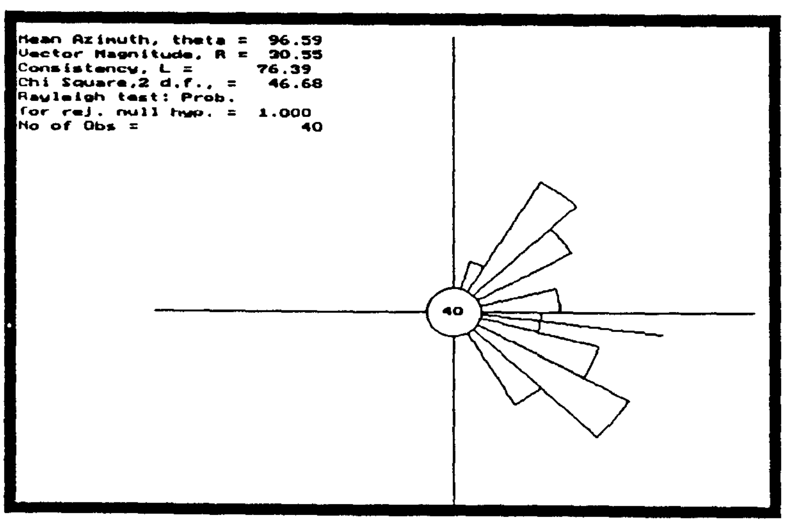
Fossil Hill Site 3



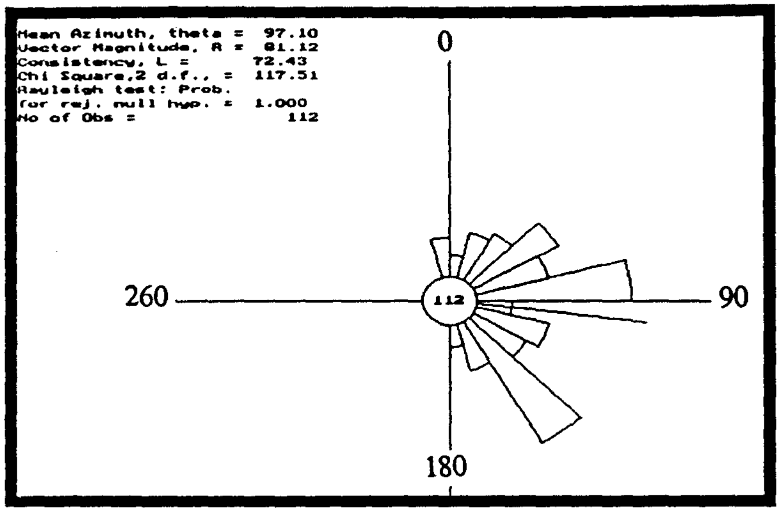
Fossil Hill Site 4



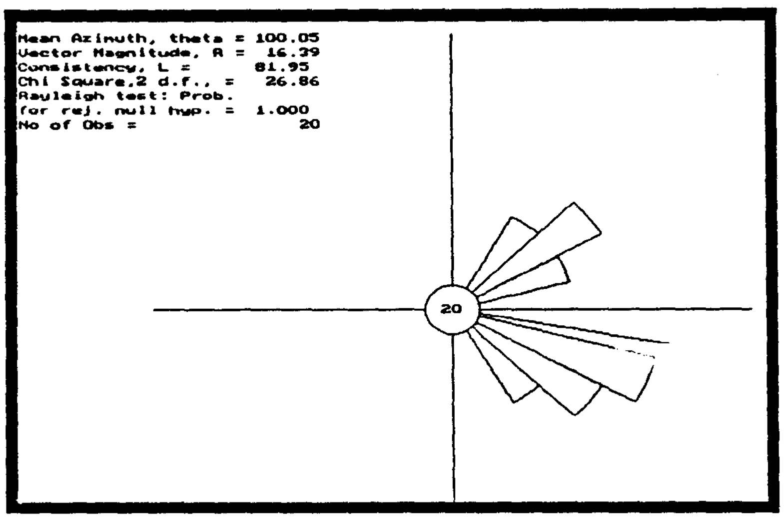
Fossil Hill Site 5



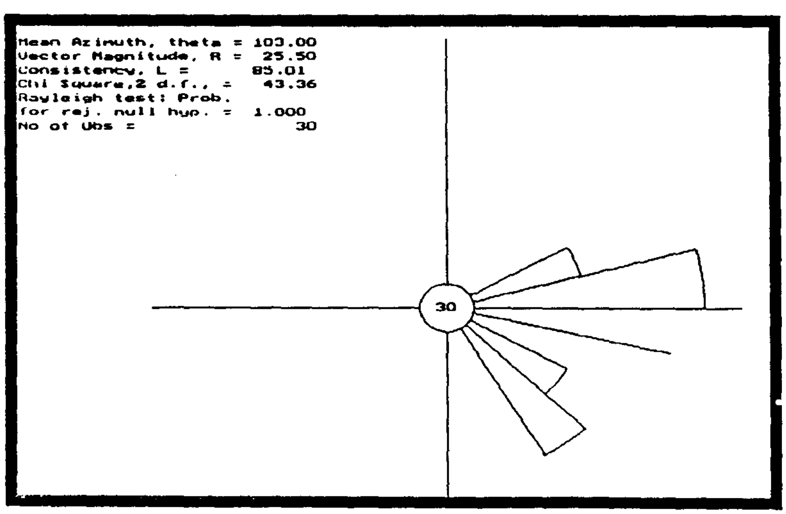
Manitoulin Formation: All Sites



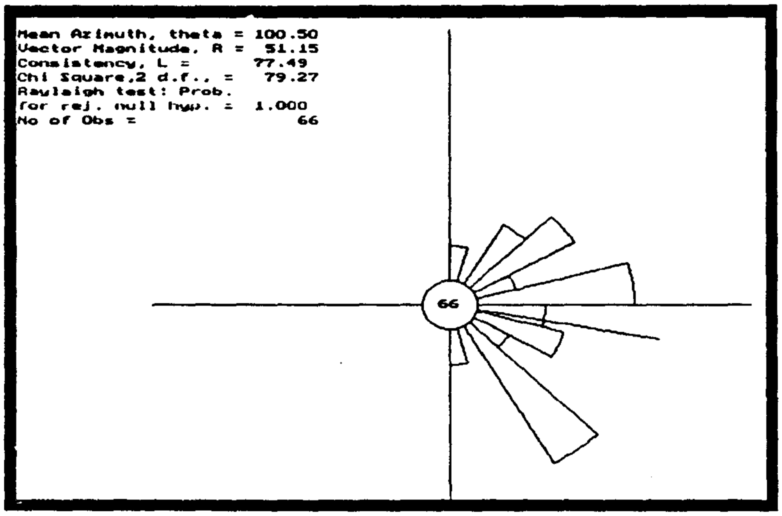
Manitoulin Formation Site 1



Manitoulin Formation Site 2



Manitoulin Formation Site 3



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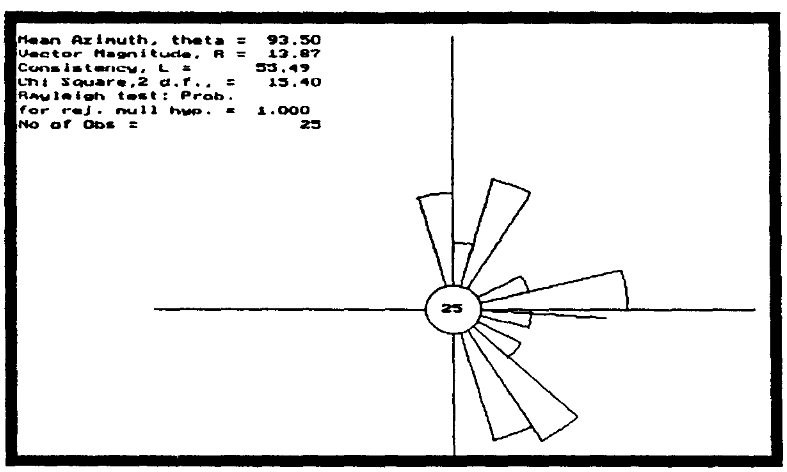
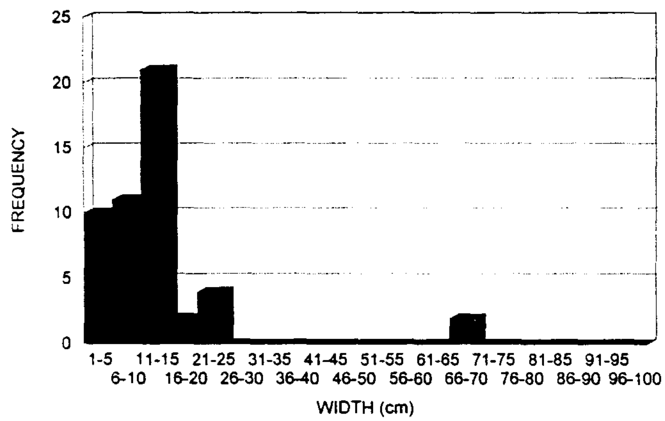


APPENDIX TWO

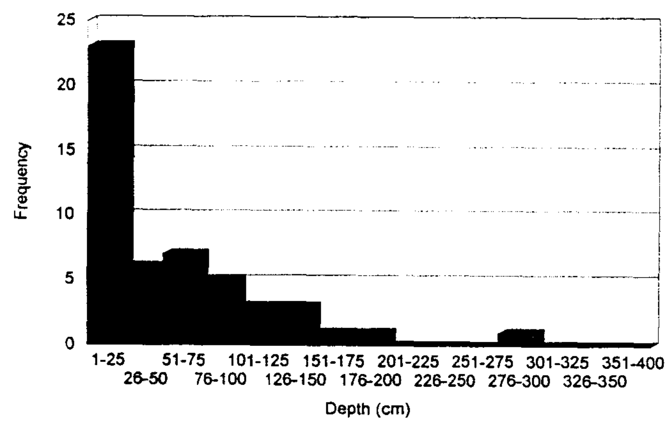
HISTOGRAMS FOR JOINT WIDTH, DEPTH AND LENGTH: INDIVIDUAL PAVEMENT SITES

AMABEL:SITE 1

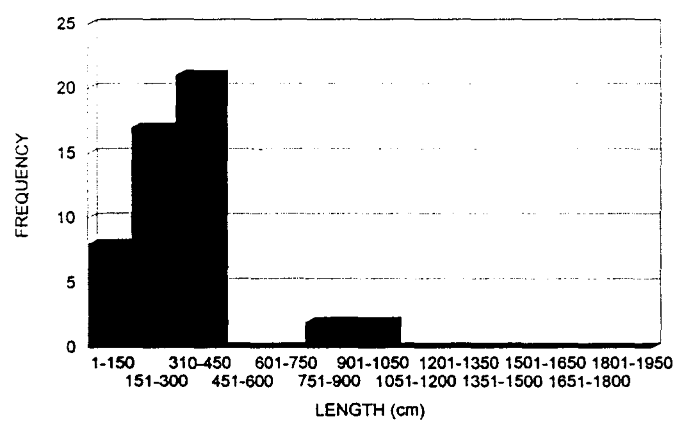
FREQUENCY OF JOINT WIDTH



FREQUENCY OF JOINT DEPTH

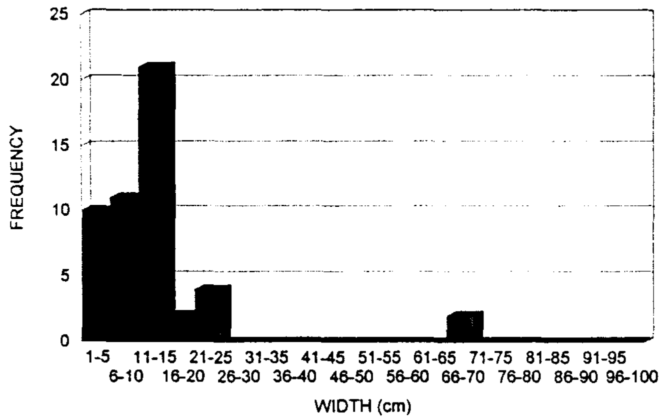


FREQUENCY OF JOINT LENGTH

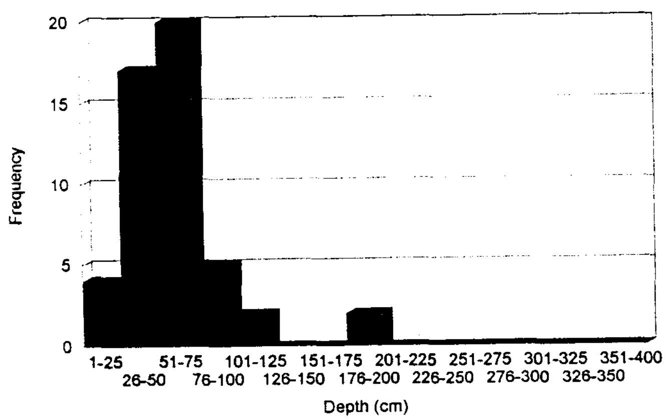


AMABEL:SITE 2

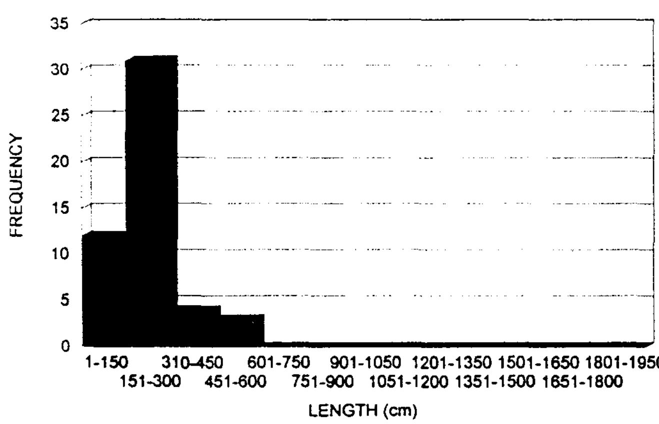
FREQUENCY OF JOINT WIDTH



FREQUENCY OF JOINT DEPTH



FREQUENCY OF JOINT LENGTH



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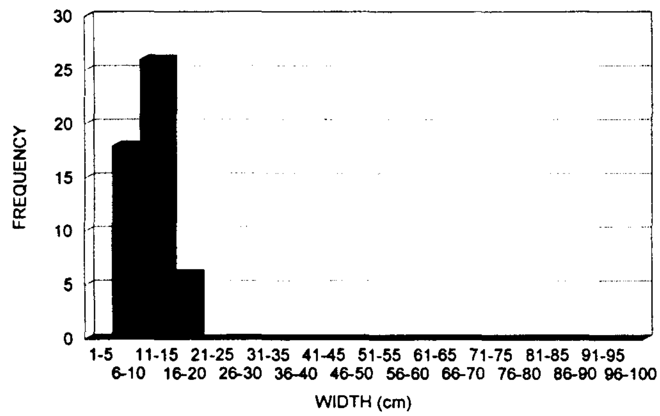

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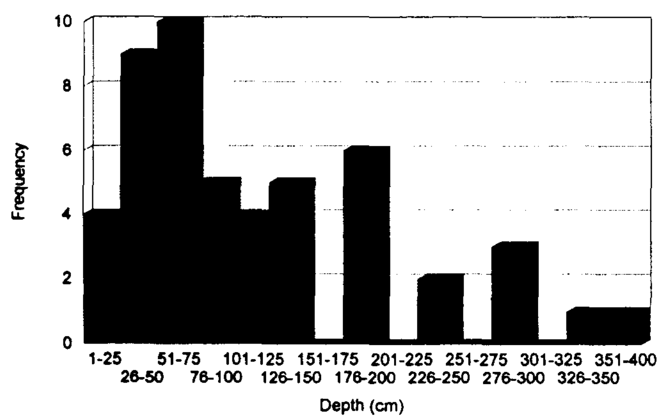

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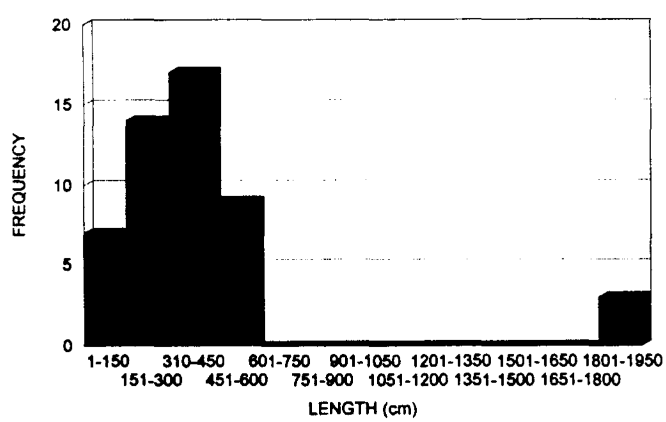

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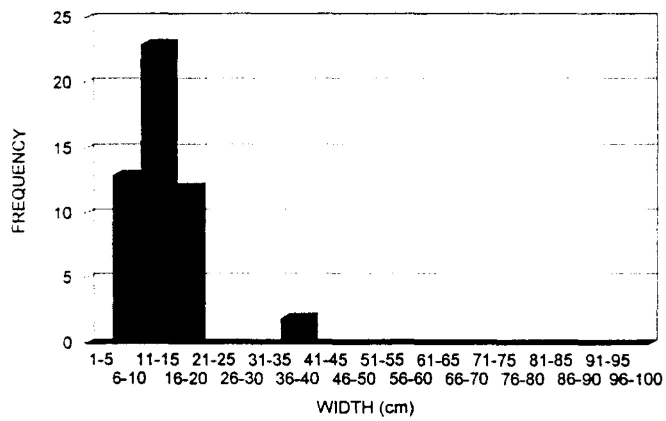

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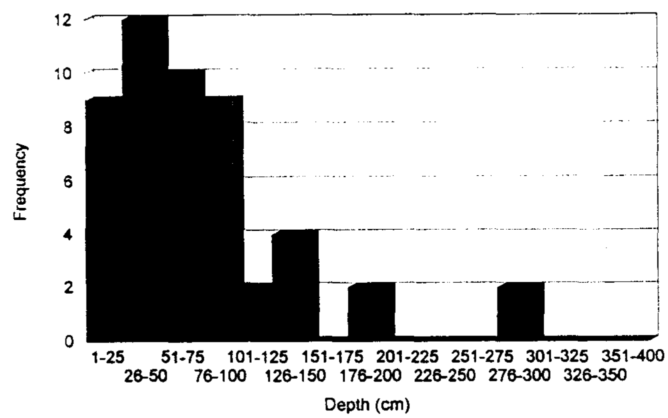

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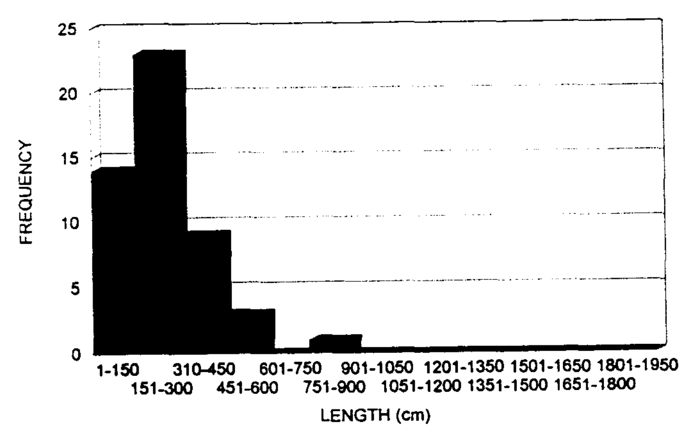

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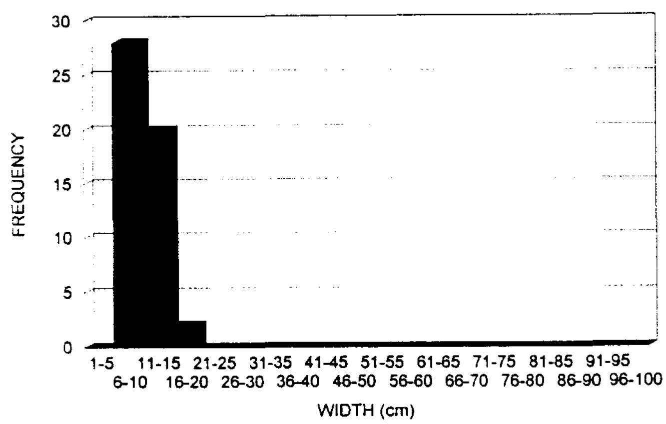

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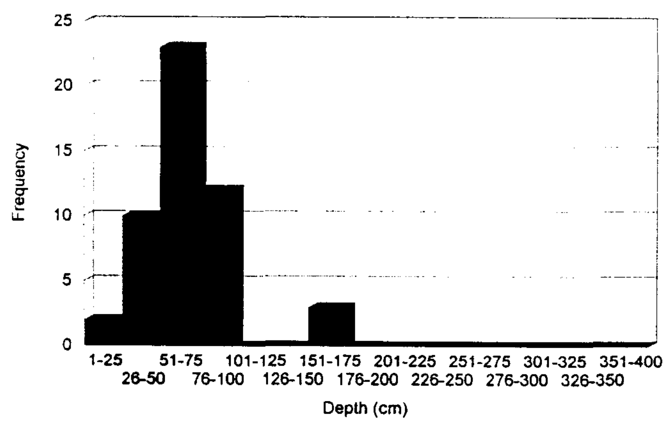

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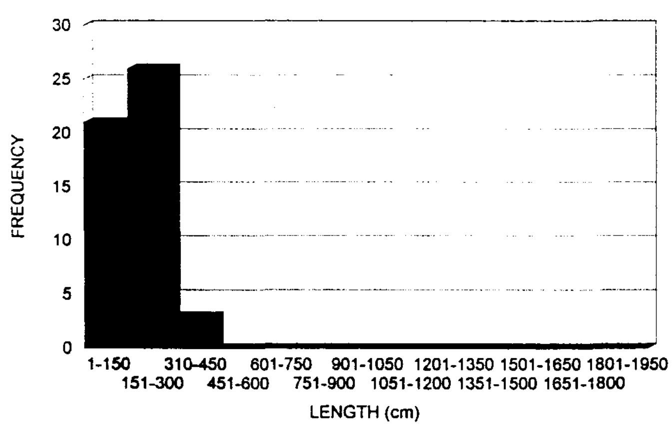

AMABEL:SITE 6

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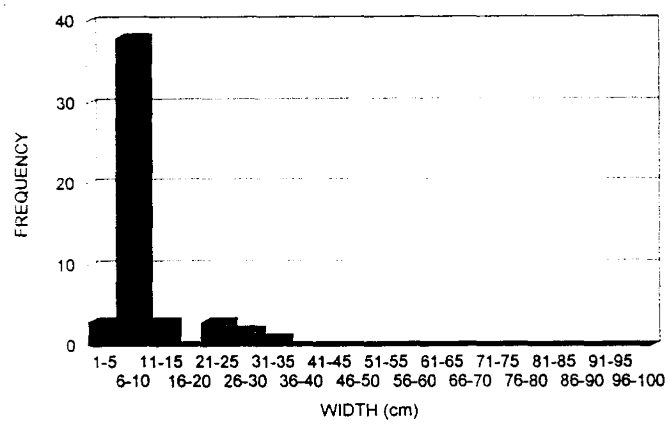

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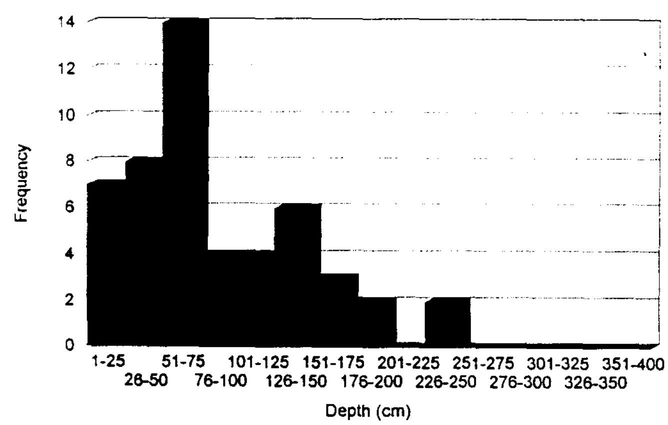

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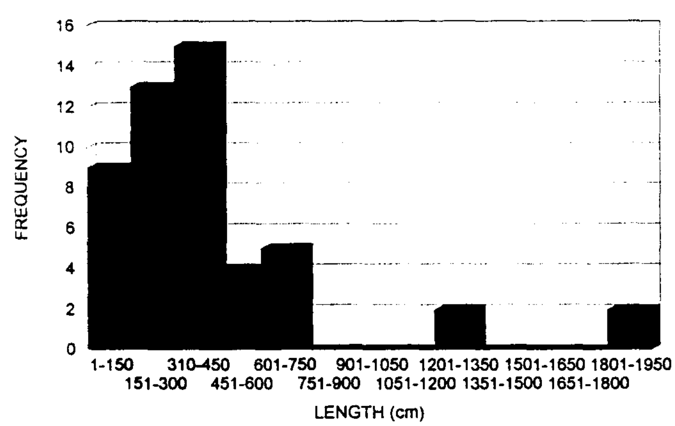
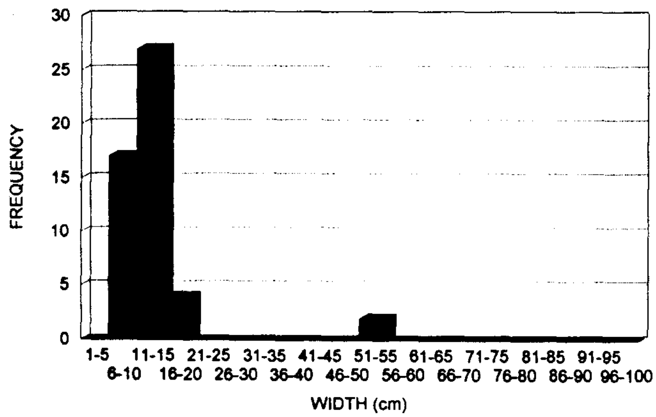


AMABEL:SITE 7

FREQUENCY OF JOINT WIDTH



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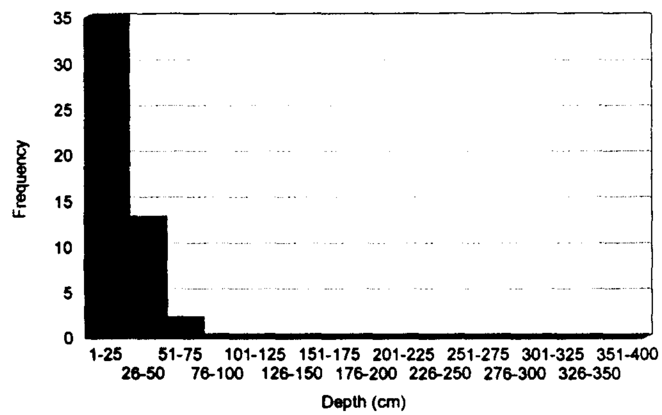

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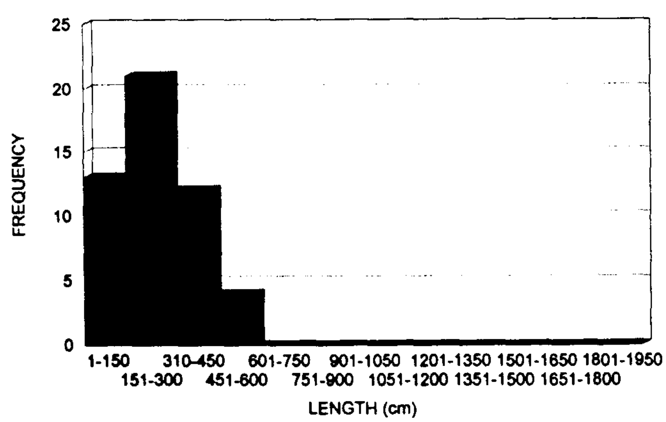
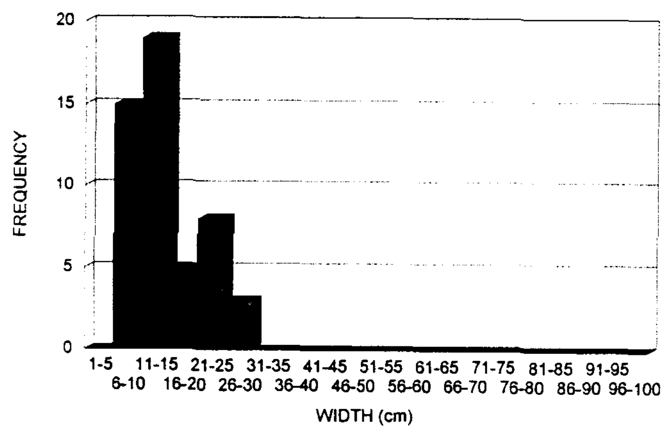


AMABEL:SITE 8

FREQUENCY OF JOINT WIDTH



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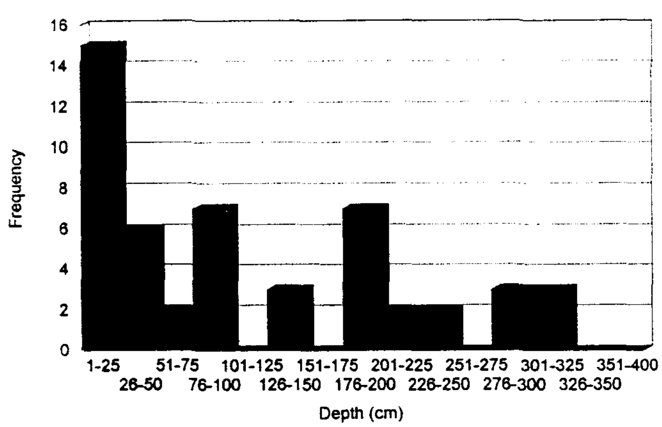

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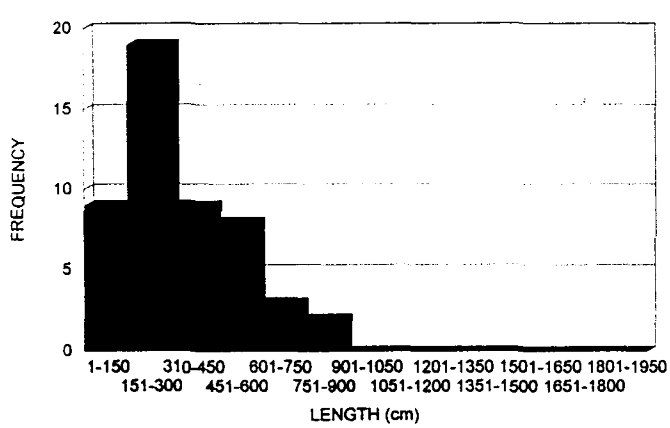

AMABEL:SITE 9

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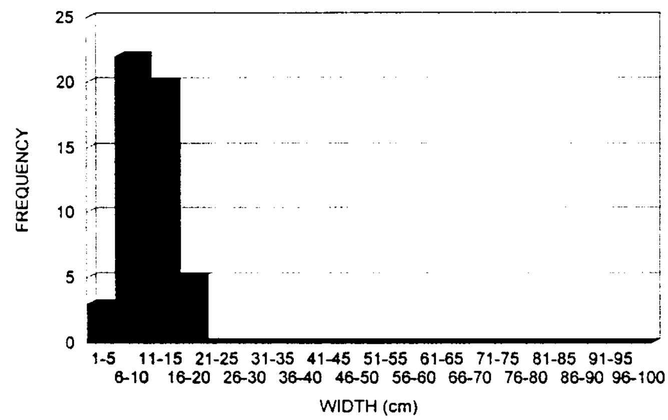

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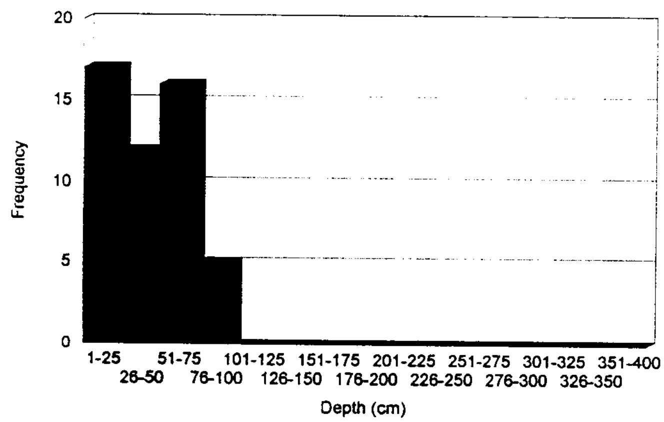

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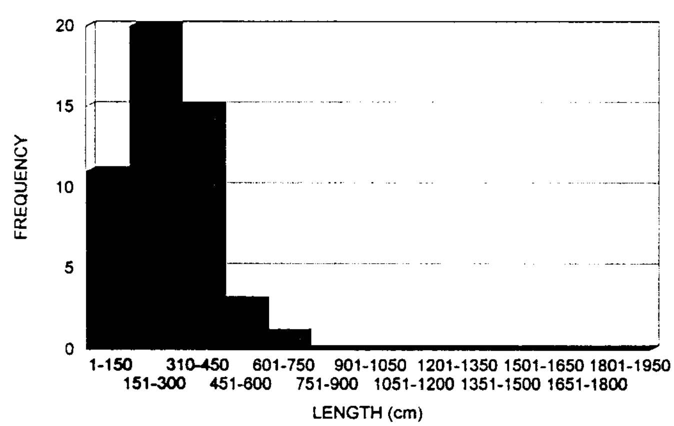
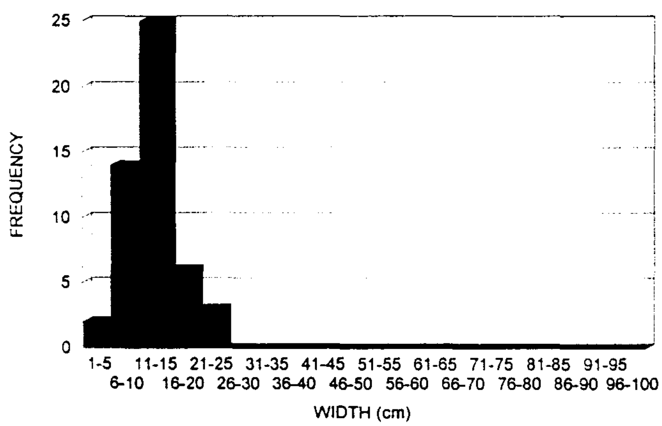


AMABEL:SITE 10

FREQUENCY OF JOINT WIDTH



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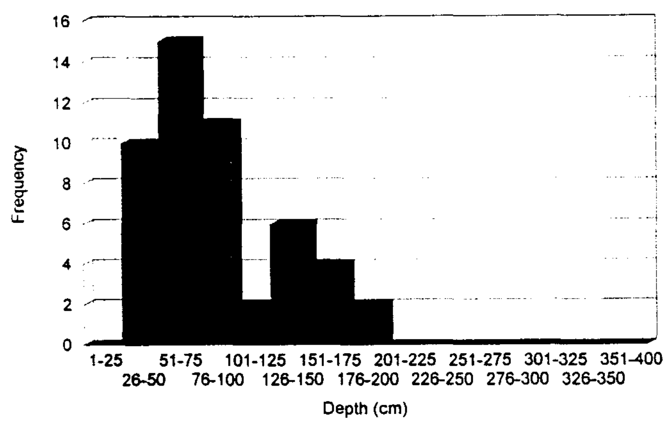

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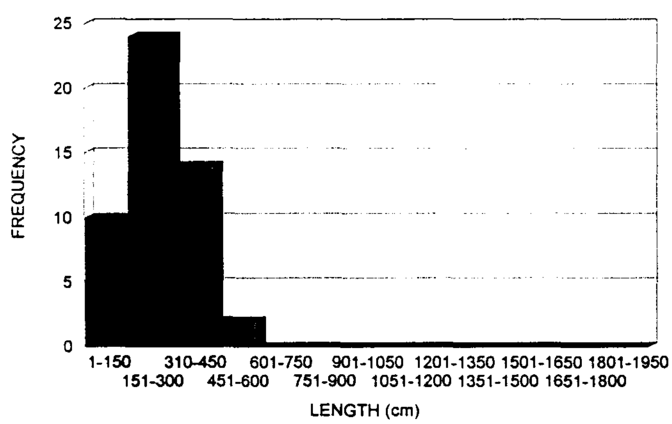

AMABEL:SITE 11

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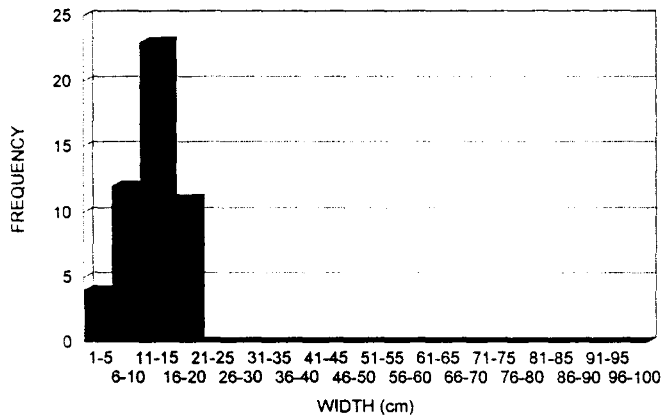

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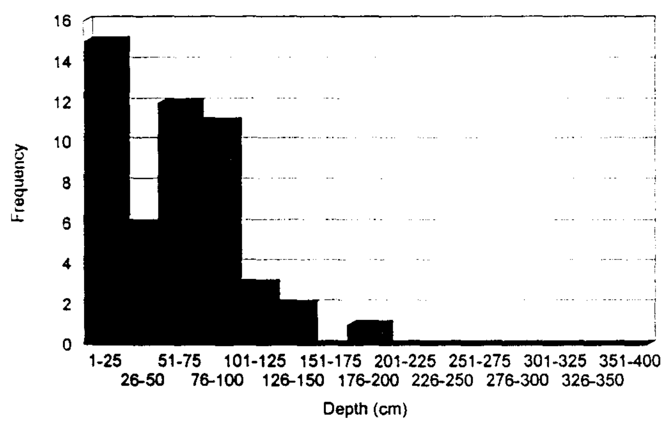

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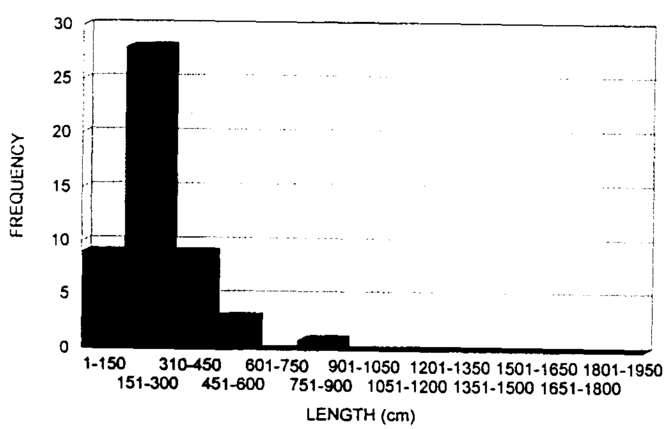
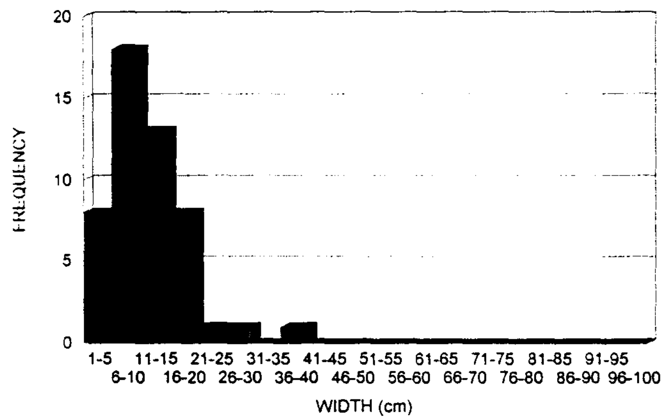


AMABEL:Other Sites

FREQUENCY OF JOINT WIDTH



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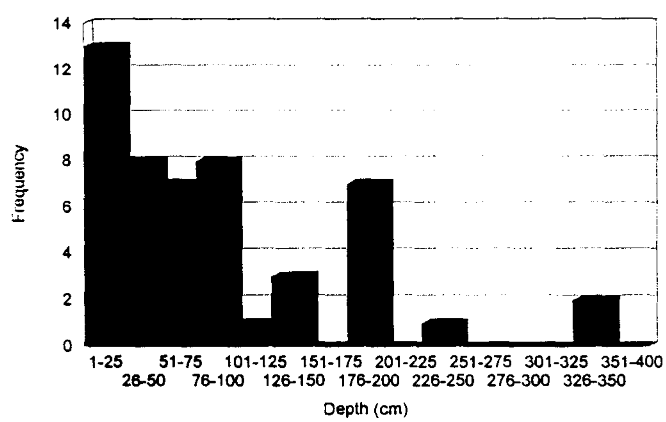

FOSSIL HILL:SITE 1

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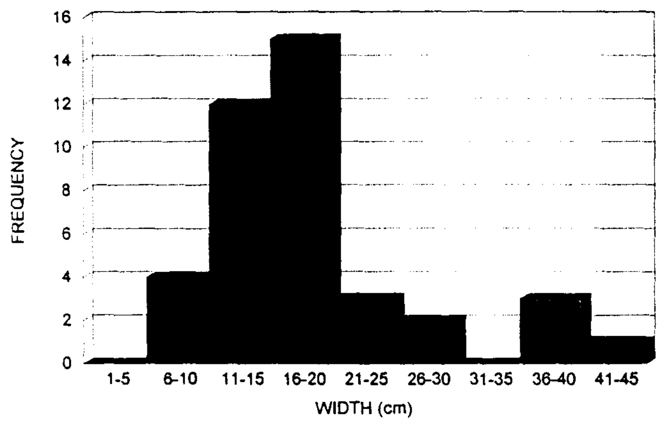

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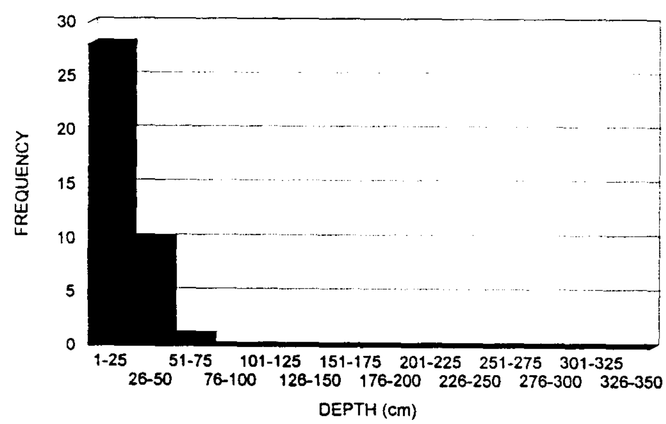

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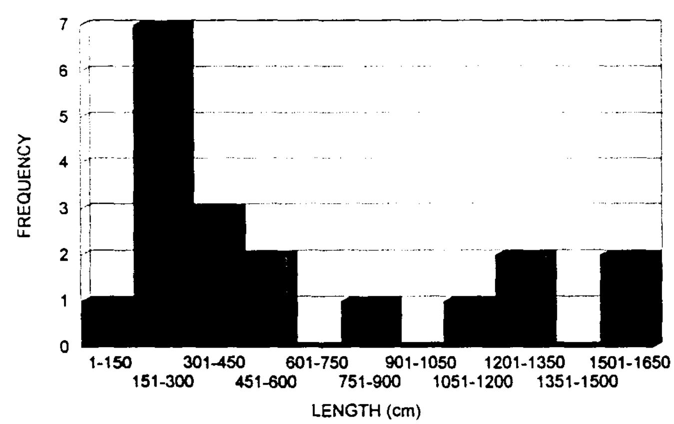

FOSSIL HILL:SITE 2

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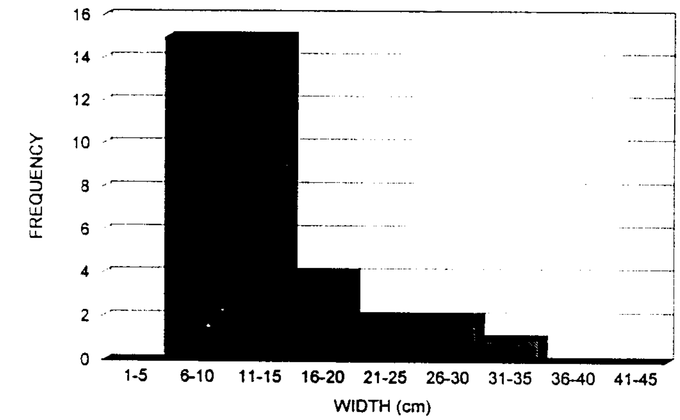

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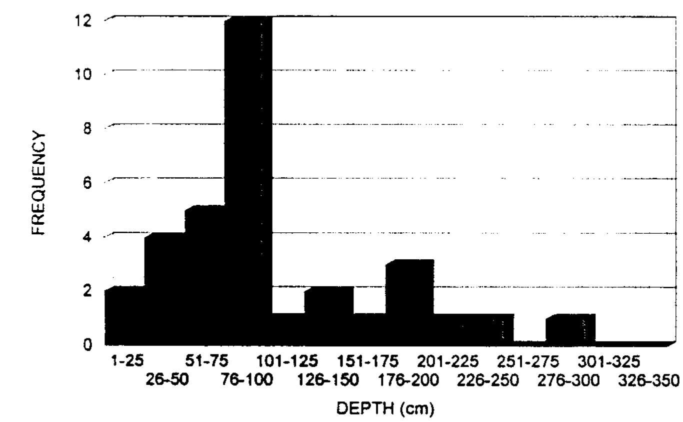

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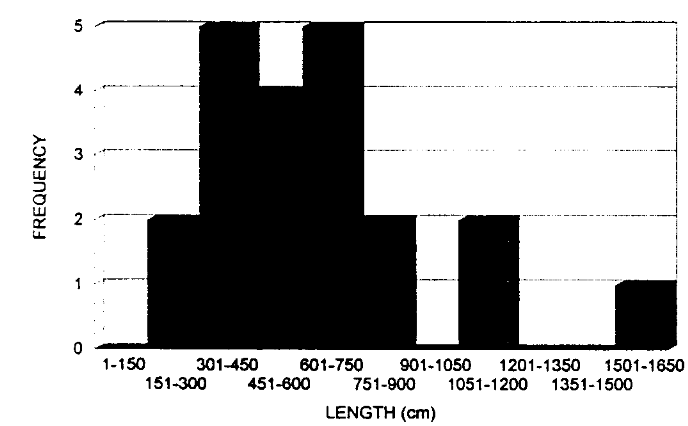

FOSSIL HILL:SITE 3

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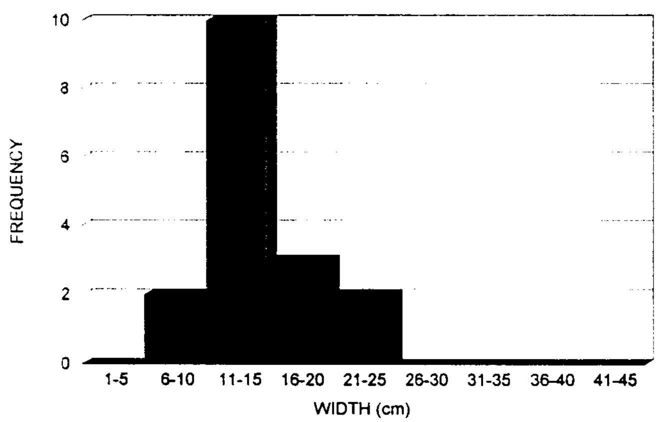

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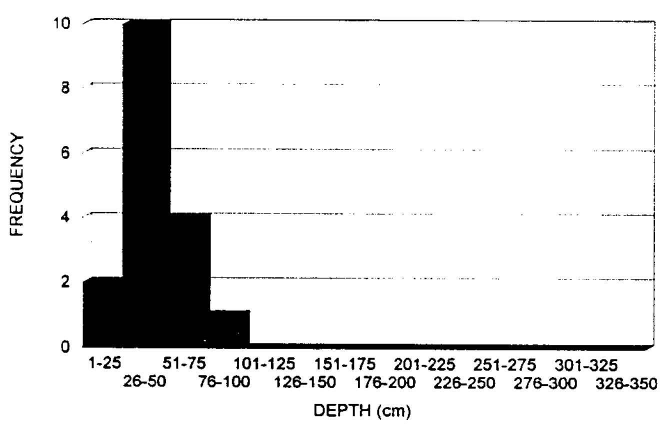

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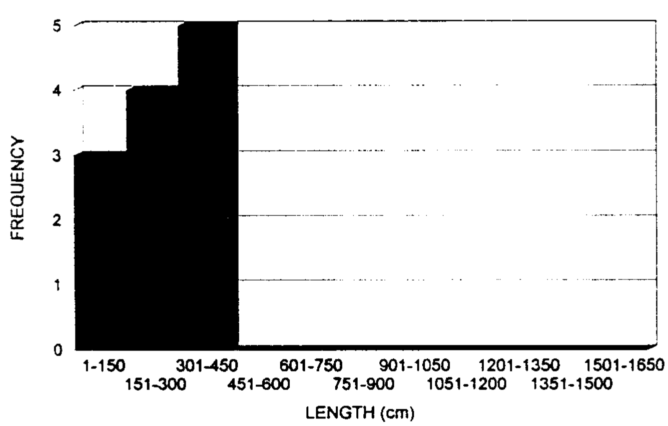

FOSSIL HILL:SITE 4

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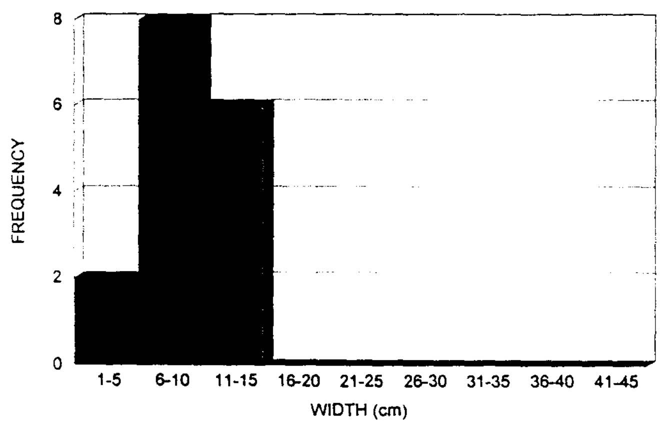

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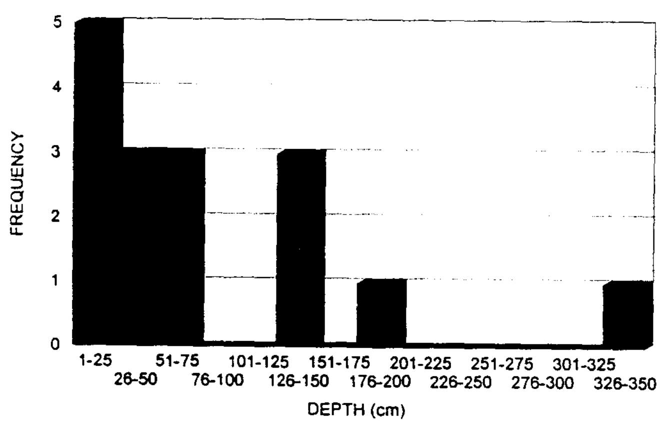

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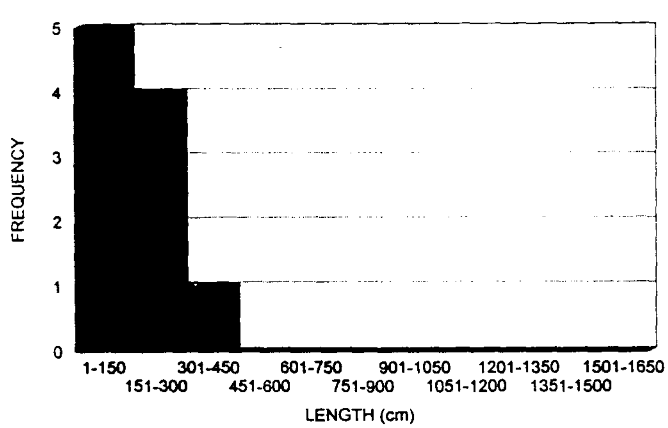
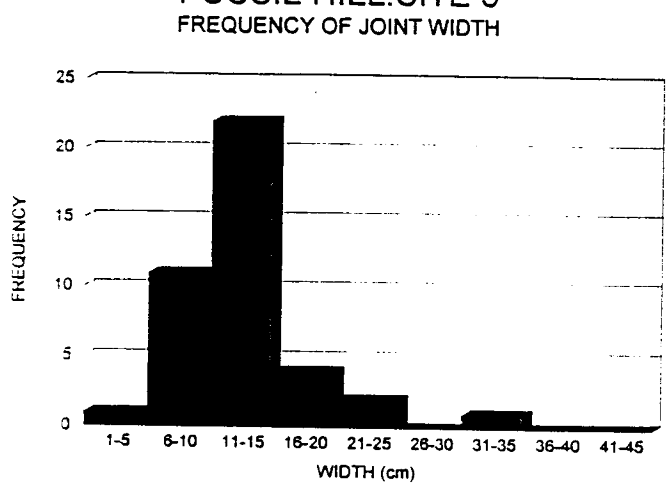
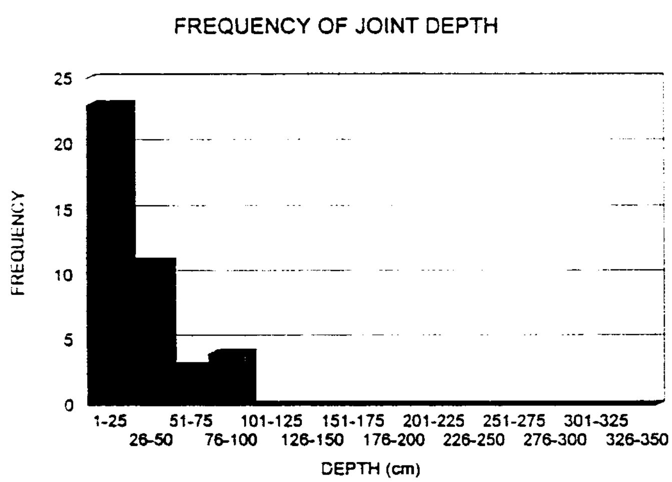
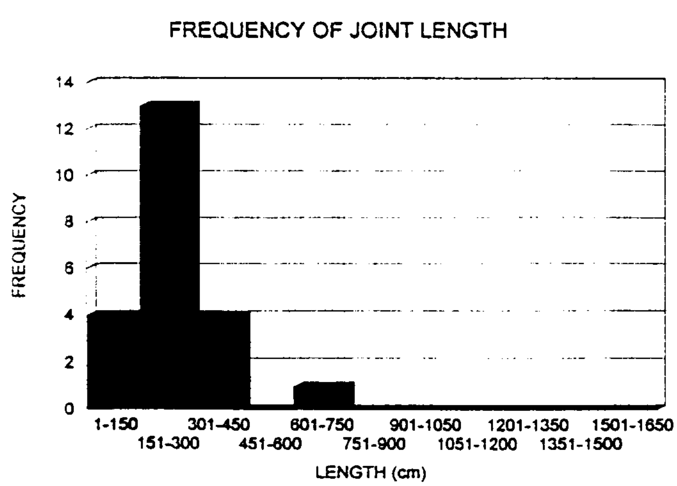


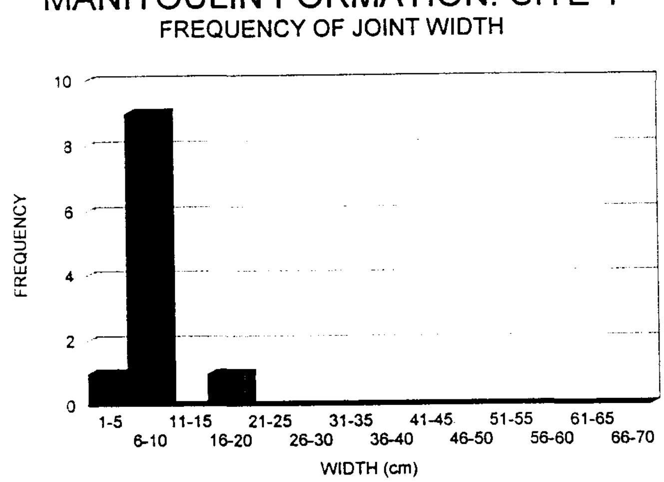
FOSSIL HILL:SITE 5

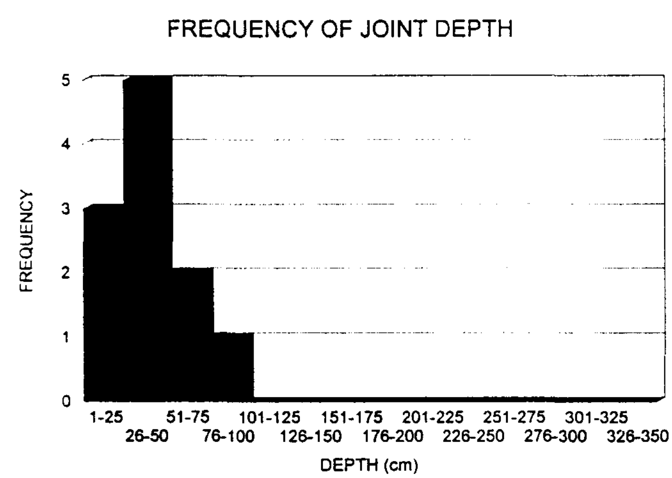






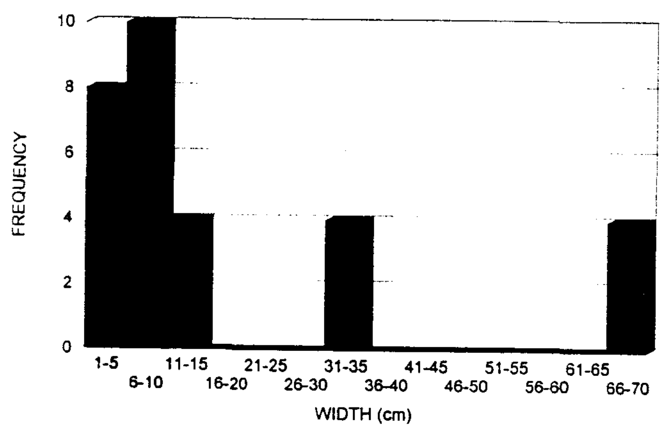
MANITOULIN FORMATION: SITE 1



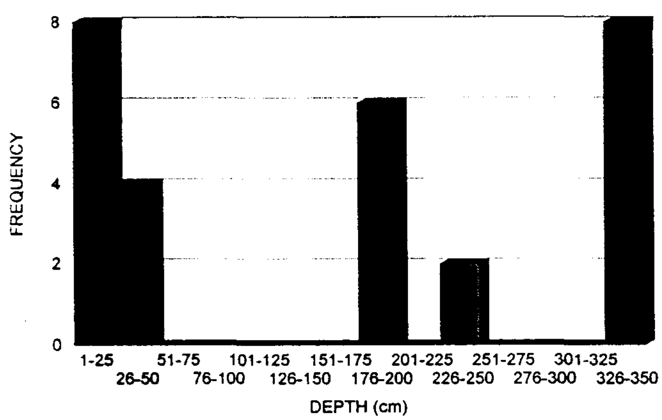


MANITOULIN FORMATION:SITE 2

FREQUENCY OF JOINT WIDTH

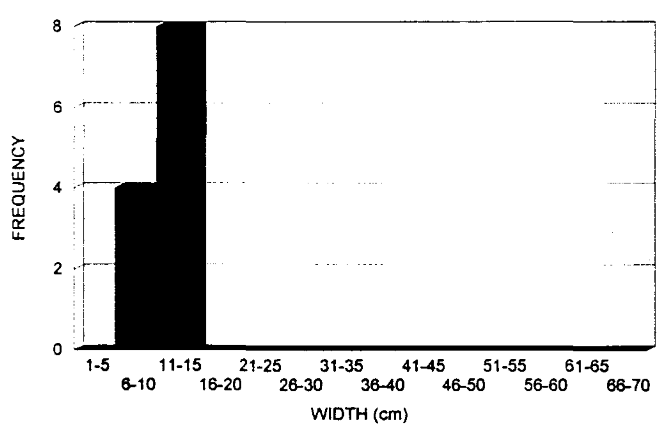


FREQUENCY OF JOINT DEPTH



MANITOULIN FORMATION:SITE 4

FREQUENCY OF JOINT WIDTH



APPENDIX THREE

TECHNIQUES FOR INSOLUBLE RESIDUE ANALYSIS

TECHNIQUE FOR INSOLUBLE RESIDUE ANALYSIS

1. Weigh initial rock sample (broken into chips).

2. Weigh filter paper.

3. Place rock chips in beaker and pour 9 N HCl over them.

4. When reaction (fizzing) completely ceases, decant samples through filter paper. If any rock chips remain, add fresh acid until dissolving is complete.

5. Dry filter paper with residue for 24 hours in oven.

6. Weigh filter paper with residue, and subtract weight of filter paper to obtain weight of residue alone.

APPENDIX FOUR

SIGNIFICANCE VALUES FOR TABLE 3.18

Values for Table 3.18
Significant Differences between Insoluble Residue Samples
based on K-S two sample test

Test 1 = Amabel vs. Fossil Hill
Test 2 = Amabel + Fossil Hill vs. Manitoulin + Kagawong
Test 3 = Amabel vs. Kagawong
Test 4 = Manitoulin vs. Kagawong
Test 5 = Amabel vs. Manitoulin
Test 6 = Fossil Hill vs. Manitoulin
Test 7 = Fossil Hill vs. Kagawong

Test No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
	0.34	0.91	1.00	0.75	0.25	0.34	0.66

NOTE:

*** = < 0.01 significance
** = < 0.1 significance
* = < 0.2 significance
(indicates that the samples being compared are significantly different at the above level)

APPENDIX FIVE

METHODS FOR HYDRAULIC GRADIENT CALCULATION

Location of Points used to calculate Maximum Hydraulic Gradient Zone

All points are along the central scarp, which has greatest karst potential. Each location was the northernmost point on the scarp top, where the height difference for the calculation was taken. The calculation yielded a distance which gives the extent of the hydraulic gradient zone away from the scarp edge. Locations 1 to 22 are on the North Channel shore and the remainder are in the central island (some bordering lakes).

Point locations (from west to east):

1. Meldrum Point
2. Brittomart Point
3. Macrae Cove
4. Muriel Point
5. Newberry Cove
6. Chamberlain Point
7. south of West Point (on Vidal Island)
8. Vidal Bay
9. north of Shakey Lake
10. south of Lapthron Island
11. South of Morrisville
12. Cooks Dock (Gauthier Point)
13. south of Sackville Island
14. Elizabeth Bay
15. north of Elizabeth Bay town
16. northwest of Helen Bay
17. Helen Bay
18. northwest of Campbell Bay
19. Campbell Bay
20. north of Obigewong Reserve
21. north of Portage Lake
22. east of Lake Wolsey
23. west of Nameless Lake (southern scarp)
24. west of Nameless Lake (northern scarp)
25. south of Ice Lake
26. east of Ice Lake
27. east of Long Bay
28. west of Kakawaie Island
29. west of Perivale
30. east of Perivale
31. Jerusalem Hill
32. Cup and Saucer (southern scarp)
33. Cup and Saucer (northern scarp)
34. south of Otter Lake
35. Spring Bay
36. Big Lake
37. northwest of Martin Lake

38. northeast of Martin Lake
39. northwest of Windfall Lake
40. northeast of Windfall Lake
41. south of Windfall Lake
42. southeast of Windfall Lake
43. fish hatchery (south of Lake Manitou)
44. east of Sandfield
45. Sucker Lake
46. north of The Slash
47. west of Benson Point
48. Roberts Bay
49. west of Burnt Summit
50. Burnt Summit

Calculation:

$\cos \theta$ = adjacent side/hypotenuse

where:
θ = angle of regional dip ($1°$)
adj = vertical distance between scarptop and shales
hyp = distance of high hydraulic gradient zone back from scarp edge

HYDRAULIC GRADIENT CALCULATION dh/dl = 0.0175

H1= height of Cabot Head Shales or lake level (a.s.l.)
H2 = height of scarp top (a.s.l.)
D = distance of high hydraulic gradient zone back from scarp edge

SITE #	H1(ft)	H2(ft)	H2-H1(ft)	H2-H1(m	D(m)	D(km)
1	650	750	100	30.49	1746.95	1.75
2	625	750	125	38.11	2183.69	2.18
3	600	650	50	15.24	873.48	0.87
4	600	725	125	38.11	2183.69	2.18
5	600	625	25	7.62	436.74	0.44
6	650	700	50	15.24	873.48	0.87
7	650	775	125	38.11	2183.69	2.18
8	650	750	100	30.49	1746.95	1.75
9	650	775	125	38.11	2183.69	2.18
10	675	850	175	53.35	3057.17	3.06
11	700	825	125	38.11	2183.69	2.18
12	580	800	220	67.07	3843.29	3.84
13	580	750	170	51.83	2969.82	2.97
14	580	650	70	21.34	1222.87	1.22
15	600	675	75	22.87	1310.21	1.31
16	600	800	200	60.98	3493.90	3.49
17	580	675	95	28.96	1659.60	1.66
18	580	850	270	82.32	4716.77	4.72
19	580	700	120	36.59	2096.34	2.10
20	580	675	95	28.96	1659.60	1.66
21	580	675	95	28.96	1659.60	1.66
22	600	800	200	60.98	3493.90	3.49
23	750	850	100	30.49	1746.95	1.75
24	750	850	100	30.49	1746.95	1.75
25	800	900	100	30.49	1746.95	1.75
26	825	900	75	22.87	1310.21	1.31
27	700	750	50	15.24	873.48	0.87
28	725	825	100	30.49	1746.95	1.75
29	700	750	50	15.24	873.48	0.87
30	725	874	149	45.43	2602.96	2.60
31	825	900	75	22.87	1310.21	1.31
32	800	1100	300	91.46	5240.86	5.24
33	800	1050	250	76.22	4367.38	4.37
34	750	850	100	30.49	1746.95	1.75
35	650	725	75	22.87	1310.21	1.31
36	739	850	111	33.84	1939.12	1.94
37	650	800	150	45.73	2620.43	2.62
38	650	800	150	45.73	2620.43	2.62
39	650	800	150	45.73	2620.43	2.62

40	650	850	200	60.98	3493.90	3.49
41	650	800	150	45.73	2620.43	2.62
42	650	850	200	60.98	3493.90	3.49
43	650	800	150	45.73	2620.43	2.62
44	750	900	150	45.73	2620.43	2.62
45	825	975	150	45.73	2620.43	2.62
46	739	800	61	18.60	1065.64	1.07
47	580	700	120	36.59	2096.34	2.10
48	580	675	95	28.96	1659.60	1.66
49	700	850	150	45.73	2620.43	2.62
50	700	900	200	60.98	3493.90	3.49
MEAN	669.06	797.98	128.92	39.30	2252.17	2.25

APPENDIX SIX

STREAM DISCHARGE DATA FOR BLUE JAY CREEK

Blue Jay Creek at Tekhummah
Stream Discharge Data

Year	Mean Annual Q (m^3/s)	Total Annual Q (dm^3)
1985*	0.511	6,900
1986	0.537	16,900
1987	0.507	16,000
1988	0.611	19,300
1989	0.515	16,200
1990	0.604	19,000

* established June 28, 1985

Source: Canada Surface Water Data.

APPENDIX SEVEN

SEMI-DIURNAL AIR TEMPERATURES DURING FIELD SEASON

AND

VALUES FOR SET 1 REGRESSION

CLIMATE DATA FOR JUNE, 1993						
RAINFALL (mm)*				TEMPERATURE (C)*		
DATE	S.BAY	GORE BAY	AVG	MAX	MIN	AVG
1	2.3	0.4	1.4	12.0	4.0	8.00
2				15.0	2.5	8.75
3				15.0	3.5	9.25
4				14.5	4.0	9.25
5	0.1		0.1	16.5	6.0	11.25
6		0.6	0.6	4.5	17.0	10.75
7	1.8	0.8	1.3	16.5	9.0	12.75
8	4.3	6.4	5.4	16.5	10.5	13.50
9	5.5	10.0	7.8	17.0	10.0	13.50
10	13.0		13.0	20.0	9.5	14.75
11				20.0	9.5	14.75
12				22.0	7.0	14.50
13				21.5	3.0	12.25
14	1.8	12.8	7.3	22.5	11.0	16.75
15	4.0		4.0	15.5	11.0	13.25
16				17.0	5.5	11.25
17		11.8	11.8	16.0	12.0	14.00
18	17.8	14.6	16.2	17.0	14.0	15.50
19	0.1	0.4	0.3	18.5	13.0	15.75
20	24.8	27.8	26.3	18.0	13.0	15.50
21		2.0	2.0	21.5	11.0	16.25
22				22.5	18.0	20.25
23				19.5	8.0	13.75
24				22.5	7.5	15.00
25		5.8	5.8	22.5	15.0	18.75
26	2.2		2.2	19.5	11.5	15.50
27		0.1	0.1	21.5	3.5	12.50
28				21.5	11.0	16.25
29				19.0	10.5	14.75

*PRECIPITATION VALUES ARE FROM SOUTH BAYMOUTH FISH HATCHERY & GORE BAY WEATHER STATION. TEMPERATURE WAS RECORDED AT GORE BAY WEATHER STATION, ONTARIO, 1993.

#	SP COND	(mg/L) TOTAL HARDNESS	CaCO3 HARDNESS
1	270	165	97
2	390	226	117
3	360	202	119
4	350	222	127
5	490	292	197
6	300	196	110
7	270	162	102
8	310	202	137
9	250	145	99
10	450	286	175
11	350	217	137
12	390	249	144
13	360	226	121
14	570	360	222
15	340	201	110
16	340	236	131
17	330	213	123
18	570	323	208
19	360	231	129
20	750	422	240
21	665	345	224
22	530	307	185
23	390	286	157
24	340	251	140
25	350	271	155
26	380	285	152
27	240	165	120
28	320	249	177
29	380	297	156
30	250	159	108
31	100	61	38
32	395	287	160
33	210	135	96
34	410	321	175
35	420	314	183
36	300	215	122
37	290	215	119
38	260	192	113
39	260	191	107
40	860	548	335
41	500	391	210
42	250	215	119
51	420	314	160
52	380	280	151
53	440	328	184
54	620	422	254
55	530	403	231
56	390	316	171
57	400	328	198
58	545	447	245
59	460	346	195
60	260	193	111

61	190	124	87
62	340	299	160
63	280	217	141
64	330	272	190
65	410	331	197
66	380	307	172
67	380	305	170
68	390	266	148
69	310	220	139
70	300	214	127
71	350	205	133
72	500	366	215
73	370	239	148
74	500	354	228
75	590	374	272
76	450	357	196
77	430	318	181
78	400	298	175
79	450	344	199
80	390	276	153
81	450	324	243
82	430	309	181
83	440	337	189
84	320	253	137
85	340	245	124
86	475	345	196
87	370	263	154
88	335	240	142
89	720	475	273
90	480	356	199
91	430	336	203
92	660	498	289
93	360	260	149
94	390	294	159
95	410	317	163
96	410	310	166
97	340	244	158
98	350	277	183

TOTAL H. Regression Output:		
Constant		29.691348
Std Err of Y Est		31.858344
R Squared		0.8571644
No. of Observations		98
Degrees of Freedom		96
X Coefficient(s)	0.632807	
Std Err of Coef.	0.026365	

CACO3 H. Regression Output:		
Constant		13.981792
Std Err of Y Est		20.269474
R Squared		0.8438032
No. of Observations		98
Degrees of Freedom		96
X Coefficient(s)	0.381998	
Std Err of Coef.	0.016774	

APPENDIX EIGHT

TITRATION TECHNIQUES
FOR TOTAL AND CALCIUM HARDNESS

TOTAL HARDNESS TITRATION PROCESS

1. Place 100 ml of sample in 250 ml erlenmeyer flask.
2. Add 1 ml of buffer solution (hardness 1).
3. Add contents of 1 hardness indicator pillow or 1 crushed indicator tablet and swirl to mix.
4. Titrate with EDTA (M = 0.8) until the colour becomes pure blue.
5. Hardness (ml or ppm) = ml of EDTA acid used.

CALCIUM HARDNESS TITRATION PROCEDURE

1. Place 100 ml of sample in 250 ml erlenmeyer flask.
2. Add 2 ml of potassium hydroxide buffer.
3. Add contents of 1 calcium indicator pillow or 1 crushed calcium indicator tablet and swirl to mix.
4. Titrate with EDTA (M = 0.8) until the colour turns from pink to blue.
5. Calcium hardness (ml or ppm) = ml of EDTA acid used.

APPENDIX NINE

SIGNIFICANCE VALUES FOR TABLE 6.8

VALUES FOR TABLE 6.8

Significant Differences between comparable Alvar sites based on K-S two sample test

Test 1 = Amabel vs. Fossil Hill (sample size = 11)
Test 2 = Amabel Type 1 vs. Type 2B (sample size = 3)
Test 3 = Amabel west vs. Amabel south (sample size = 4)

MAXIMUM SIGNIFICANT DIFFERENCE

Grouping	T	C	S	P	J	B	M	O
Test 1	.619	.146	.618	.182	.346	.4	.509	.091
Test	.66	1	.67	.5	.34	.34	.5	0
Test 3	.5	1	.5	.25	25	.5	.5	.25

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