SOLUTION PITS

By

JOHN ROBERT BELL

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ABSTRACT

Littoral solution pits were studied along 4 shorelines in the Guelph and Amabel Formations of the Bruce Peninsula. Pit depths, diameters, and densities were measured at several elevations above and below water, and various distances from the shorline. Differences in pit characteristics were related to differences in shoreline energies, lithologies, and fluctuating lake levels in the post glacial period.

Pit depths above water are shallower than pit depths below water. This conclusion supports previous hypotheses proposed by Cowell (1976) and Ford (in Goodchild, 1984) that the depth of solution pits increase with increasing water depth. The conclusions also indicate that pits are initiated above water, and that solutional deepening of pits can occur underwater.

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INTRODUCTION

Solution pits, a small scale karren feature, have been observed in the dolomitic shores of the mainland and islands located at the tip of the Bruce Peninsula. It is hypothesized that the characteristics of solution pits (depth, diameter, and density) change with changes in elevation. This hypothesis stems from an observation made by Ford in a previous study of the karst in the Bruce Peninsula. Ford noted that "viewed from a boat, it appeared that...the depth of the pits might increase with depth of water"(Goodchild, 1984, p 120). It is therefore the purpose of this study to look at the pit characteristics along these shores, and suggest possible causes for any differences observed.

Pit characteristics were studies on four shorelines; the south east and north west shores of the south west third of Bear's Rump Island, the east shore of Cove Island from the lighthouse to Cassel's Cove and Dunk's Bay on the mainland (Fig. 1). Subaerial pit characteristics were measured at various locations within these shorelines, however, only on Cove Island were both subaerial and subaqueous pit characteristics measured.

At each location the depths, diameters, and density of pits were measured. Depths and diameters of pits were measured using a vernier caliper. Pit densities were determined by couting the number of pits in a .5 m X .5 m sample

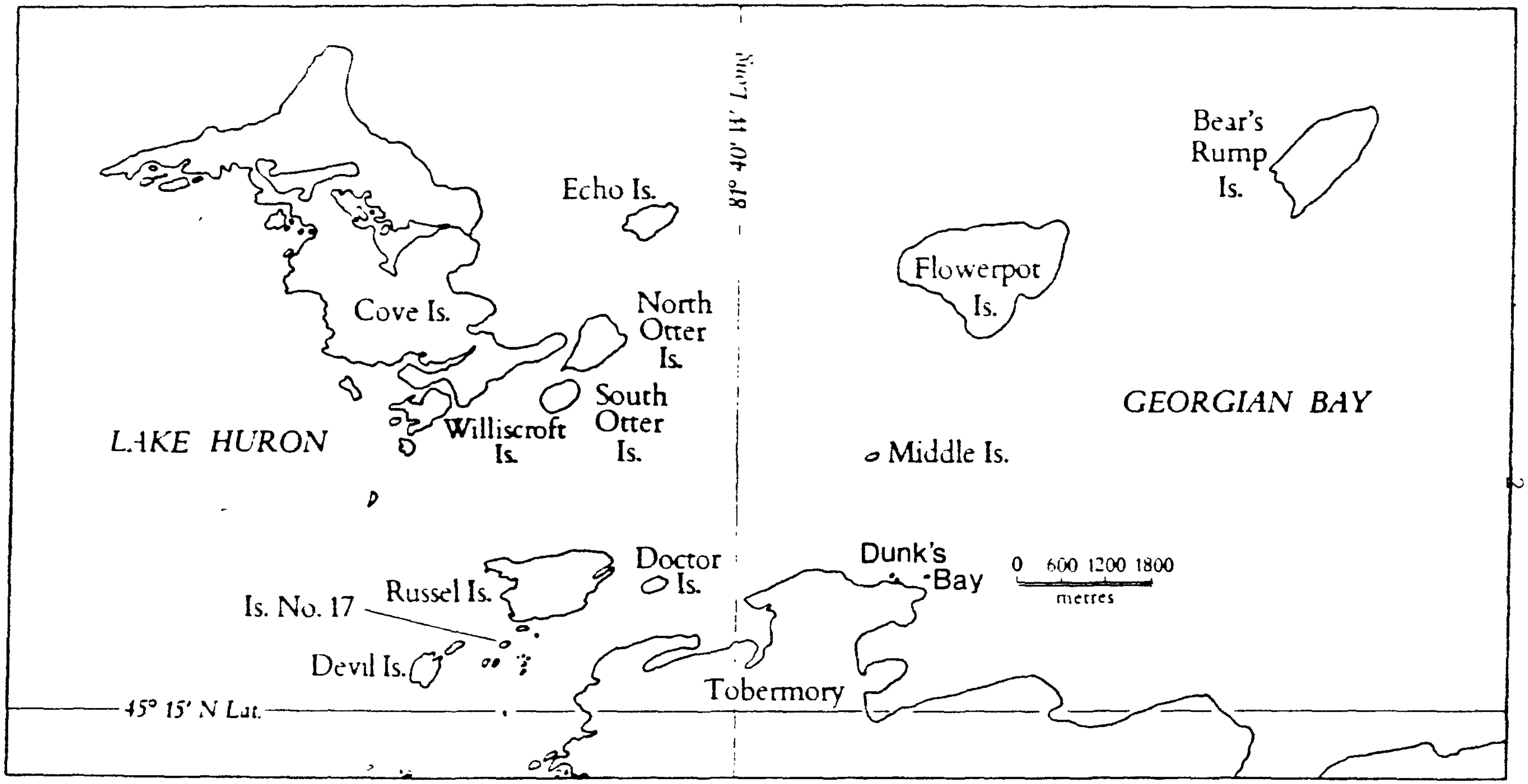


Figure 1. The Tobermory Islands
Source: Goodchild (1984).

grid, and classifying the pits in one of three categories (see section 3.1). The distance of the pitted surface, as well as its elevation were measured with respect to the waterline. All characteristics were measured from pits lying in flat surfaces

Solution pits have been observed in limestones in various locations around the world. These locations include tropical areas (Sweeting 1966), the coastal regions of Western Europe (Guilcher, 1958), and the shores of large lakes in Western Ireland (Williams, 1966).

Guilcher (1958) outlines the typical zonation of corrosion forms on coastal limestones in the British Isles. Guilcher finds that there is intensive pitting and honeycombing in the upper spray zone where the limestone is covered with small black lichen. These honeycombed corrugations are less than one inch in size.

Williams (1966) refers to small hemispherical pits that are commonly found along the shores of large freshwater lakes in Western Ireland. The process responsible for the formation of these micro depressions is attributed to chemical solution by water.

Sweeting (1966) makes reference to solution depressions which vary in size from a few mm to about 60 cm in diameter, and are normally less than 10 cm deep. These depressions are enlarged by solution from water, and their walls are smoothed by the action of algae and lichen. Sweeting also discusses the formation of step topography, and the scaling or exfoliating process of thinly bedded limestones.

Solution pits have been included in several studies of the karst on the Niagara Escarpment (Pluhar (1966), Pluhar and Ford (1970), Cowell (1976), and Goodchild (1984)).

Pluhar (1966) and Pluhar and Ford (1970) studied small-scale karren features at locations close to Hamilton on the Niagara Escarpment. Pluhar describes pits as being 'circular or semi-circular, frequently with widening bottoms' (p 48), and suggests that bedding-lapies initially begin with pitting along a fracture or micro joint. In some cases trench-lapies may develop instead of bedding-lapies by the amalgamation of pits along joints. Pluhar also notes the presence of small round pits which were not located on joints. She suggests that these pits might be the result of pore enlargement by solution in a highly porus zone within the lower porosity rock.

Cowell (1976) discusses the karst geomorphology of the Bruce Peninsula. He suggests that lithology and environment are two factors which control the karren morphology of the Bruce. The lithologic factor is observed by the different karren assemblages displayed by the two main carbonate rock units, the Guelph and Amabel. The environmental factor is indicated by the presence of only one karren feature, pitkarren, on both the Amabel and Guelph Formations in the narrow shore or littoral zone of Lake Huron.

Cowell provides average depth and diameter measurements from subaerial pits in the two formations. His results show that the pit dimensions measured in the Amabel are larger than the dimensions of the pits in the Guelph. Cowell also proposes that subaqueous pits attain even greater dimensions.

Goodchild's (1984) report is a resource management study of caves in the Georgian Bay Islands National Park for Parks Canada. Important information relevant to the interpretation of the area is provided in this report. Of particular interest is the section on solution by D. C. Ford. Ford notes that the islands are all holokarstic. That is, all water that falls on the islands is routed underground and is discharged at springs below the lake surface. Thus there are no fluvial landforms on the islands.

Ford also makes a distinction between pit karren and littoral karren found on the Georgian Bay island surfaces. Pit karren are "dense patterns of pits displaying a wide range of shapes and sizes, draining to irregularly placed and oriented solution clefts" (p 100). Pit karren are common on the reefal Guelph rocks. Littoral karren are "very dense patterns of smaller, more regular pits developing at the waterline in massive units of both the Amabel and the Guelph Formation" (p 100).

The type of karren being studied in this report is littoral karren. Thus all reference to pits (of any sort) refers to pits which are found in the littoral zone. Subaerial pits refers to pits which are located in the dolomites above the water surface, and subaqueous pits refers to pits located below the water surface.

2. DESCRIPTION OF STUDY AREA

2.1 General

This chapter provides a description of the study area in terms of its physiography, climate, geology, glaciation, wave energy and solution. The descriptions closely follow the report by M.F. Goodchild (1984).

Bear's Rump and Cove Island are two of a group of 17 islands owned by Parks Canada in the Tobermory Islands Unit (TIU). The Unit is located at the tip of the Bruce Peninsula in the waters of Lake Huron. These islands represent a partially drowned continuation of the Niagara Escarpment.

Cove Island is the largest of the group. It is low and flat lying, nowhere more than 15 m above the waterline. The shoreline consists of a mixture of cliffs, cobble beaches and limestone pavements. There is a lighthouse at the northern tip of the island which is occupied during the shipping season. A boat dock and helicopter landing pad in this vicinity provide relatively safe access onto Cove Island. Other than this and a few unmaintained trails the island is undeveloped.

Bear's Rump Island, the most remote and isolated of the Islands in the TIU lies 10 km away from Tobermory to the northwest. The north and east shores of the island are exposed to Georgian Bay. Access to the island is restricted to all but the calmest of weather and water conditions due to the lack of good harbours and the tendency of the water surrounding the island to be rather choppy.

A major portion of Bear's Rump consists of a plateau 40 m above the waterline. The plateau abruptly ends in the northeast where steep cliffs descend to the water. Towards the southwest the plateau gradually grades into a limestone pavement. This pavement continues underwater for a considerable distance to the southwest, and is bounded to the southeast and northwest by raised cobble spits. Step topography is well developed and can be observed on both the southeast and northwest shores of the southwest third of the island.

Dunk's Bay, a small shallow bay situated on the mainland just east of Tobermory opens into Georgian Bay. It is protected from wave action by several small islands at the bay mouth. The land around Dunk's Bay is flat and a limestone pavement is exposed at the shoreline. Accessibility to Dunk's Bay is very good as there are roads which lead from Tobermory directly to it.

2.2 Vegetation

During the late 1800's and early 1900's the islands were logged, and probably burned over. Thus the present vegetation cover likely represents the growth that has occurred since early in the 20th century. The vegetation on the islands is supported by a thin, poorly developed layer of soil and consists of a dense woodland in which "birch and eastern white cedar predominate, with the species limited to where conditions are more suitable, and with poplar stands in poorly drained areas" (Goodchild, 1984, p 4).

2.3 Climate

Due to the time it takes to warm and cool the surrounding bodies of water the spring and fall seasons on the islands are later in arriving. The effects of the lakes are also felt in the summer which tend to be somewhat cooler on the islands than on the mainland.

During the winter months lake Huron freezes extensively, particularly along the shores. As a result in the early spring the effects of the ice pressure can be observed by ice push ridges which have developed parallel to the waterline. The mean annual temperature at Tobermory is 6.5° C and the total annual precipitation is 85 cms (Goodchild, 1984). Due to the combination of all these climatic effects the climate of the islands is classified as cool temperate according to the Koppen-Geiger climatic classification.

2.4 Niagara Escarpment

The islands at the tip of the Bruce are a part of a chain of islands stretching from Tobermory to Michilimackinac. These islands represent a dissected, partially drowned continuation of the Niagara Escarpment. "The line of the escarpment traces the northern rim of the Michigan Basin, a sedimentary basin centred in southern Michigan" (Goodchild, 1984, p 6).

The Niagara escarpment emerges from the Appalachians in upstate New York and extends northwards through the Niagara Peninsula, across southern Ontario and through the Bruce Peninsula and the islands to Manitoulin. The escarpment then continues around the northern tip of the Michigan Basin "through the chain of islands to Drummon Island, the Straits of Michilimackinac and the upper peninsula of Michigan to the Door Peninsula in Wisconsin, and is finally lost in the glacial deposits of southern Wisconsin" (Goodchild, 1984, p 6).

The escarpment consists of shales, sandstones and carbonates that were deposited and developed in the Michigan Basin. The erosion and weathering of the less resistant formations above and below more resistant Silurian reef formations has produced the form visible today.

2.5 Geology

In the stratigraphy of the region, it is the dolomites of the Amabel and Guelph Formations with which this study is concerned (Fig. 2). The Amabel Formation is the massive equivalent of the Lockport Formation which forms the caprock at Niagara Falls. In the TIU the Amabel is exposed above water on only two islands. On Flowerpot Island the Amabel is exposed where it forms the horizontally bedded layers on

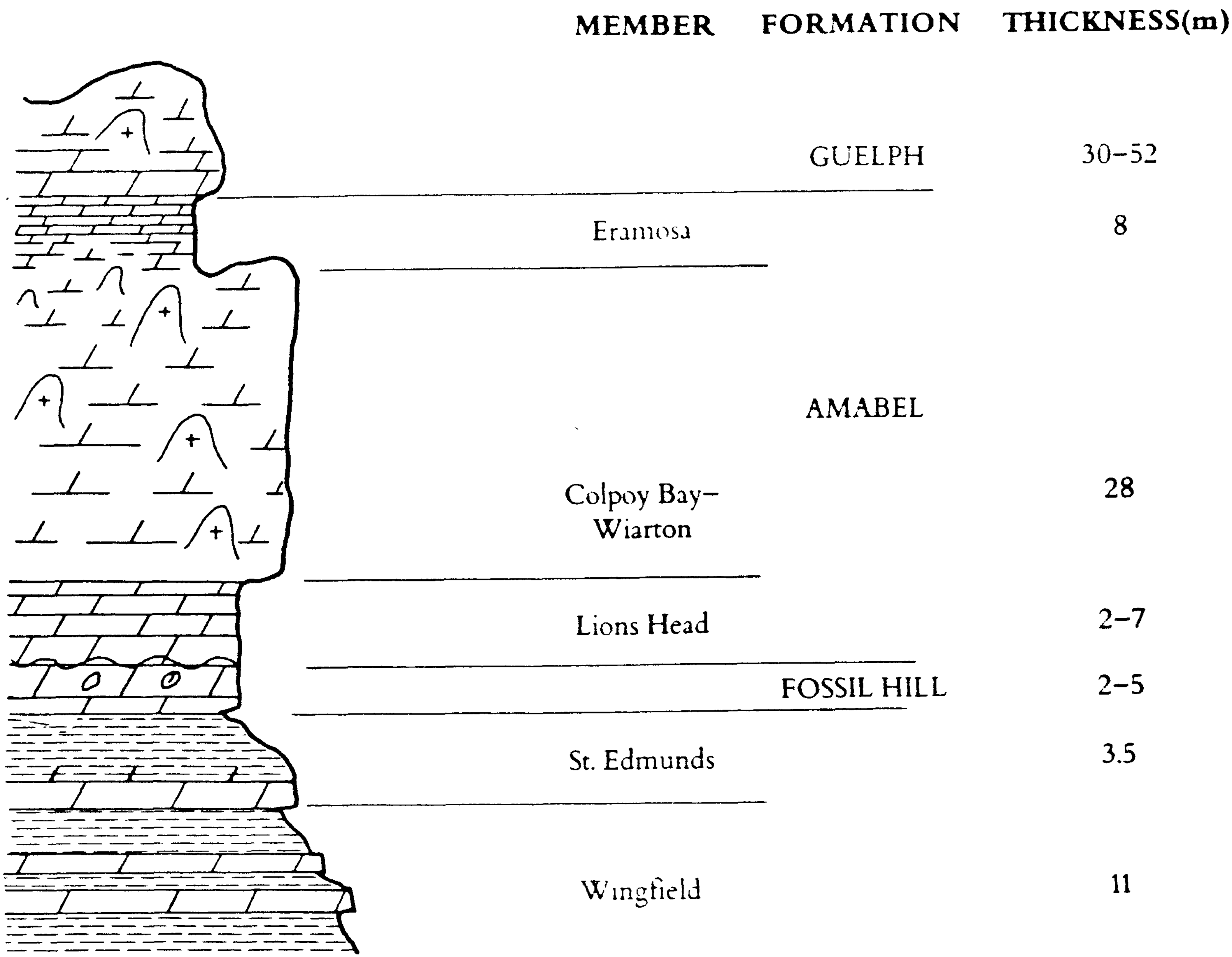


Figure 2. Stratigraphy of the Bruce Peninsula, after Liberty and Bolton (1971). Source: Cowell (1976).

which the Flowerpot stacks are developed, and on Bear's Rump the Amabel can be observed in the southwest third of the island where the limestone pavement is exposed. On the mainland the Amabel forms the escarpment from Cabot Head West to the vicinity of Cyprus Lake Provincial Park.

The Amabel Formation is divided into three members i) Lions Head, ii) Colpoy Bay-Wiarton, and iii) Eramosa. Cowell (1976) describes these members as follows:

Lions Head - a dense, thinly bedded, white dolomite that has a dark brown weathered surface. It is characteristically well-bedded and jointed and hence has a blocky nature.

Colpoy Bay - Wiarton - a fine to coarse grained, very pure, light grey dolomite with blue purple mottling. It is a massive biohermal member with locally thin bedded intereefal strata. This member is very resistant to mechanical erosion and often forms the top of the escarpment. The best solutional weathering features are found in this member of the Amabel.

Eramosa - a thin bedded, grey to light brown dolomite which is usually bituminous often having a petroliferous odour. This member is believed to be time transgressive between the Colpoy Bay-Wiarton and Guelph biohermal facies.

In the TIU the Eramosa member is largely absent and no good above-water exposure has been found.

The bulk of the islands above waterline in the unit are formed from the Guelph Formation. This formation is described as "primarily a reefal complex of greyish, tan or dark brown, fine to medium granular or fine to coarse crytalline dolomite". It has a sugary texture when broken which is a result of dolomitization.

Both the Guelph and the Amabel Formations contain reefs (bioherms), as well as intereefal material. The bioherms are massive rocks of high primary porosity. In the Guelph, as a result of the high porosity, a distinctive rough and vuggy weathered surface is produced. Planes of weakness related to growth of the bioherm occur in an approximate magnetic direction of 270/90°. However the bioherms display very little jointing, and fractures are rare and random in orientation. Consequently, the bioherms are very strong and secondary porosity is low.

The interreefal material which overlies and underlies the bioherm is strongly bedded and highly jointed. Much of the interreefal material is poorly consolidated, as a result it is structurally weak and has been extensively eroded by glacial and wave action.

2.6 Glaciation and post glacial history

The major features of the landscape in the Michigan Basin are primarily forms which have occurred during the last million years. Features which existed before this time have since been obliterated by glacial activity.

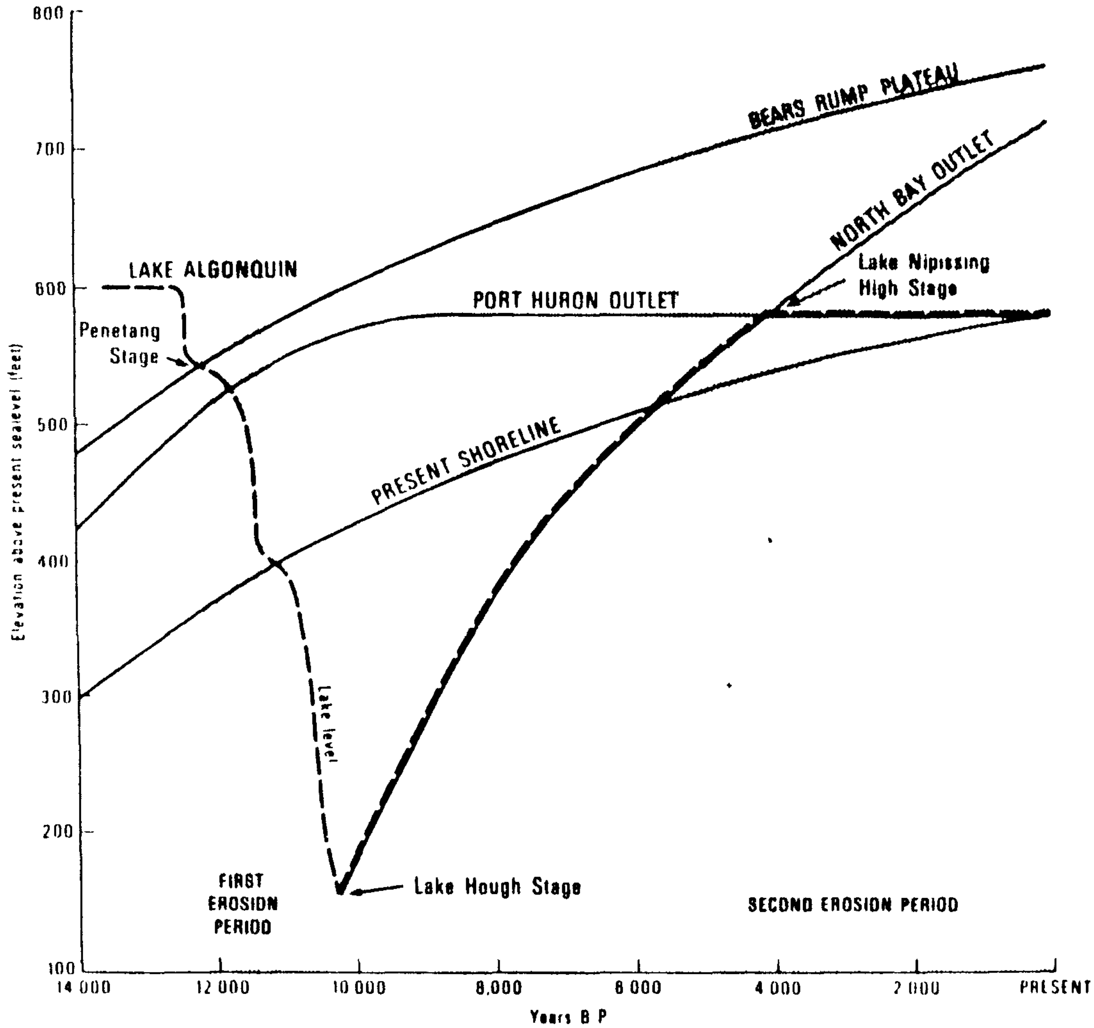
The last major glaciation affecting the basin was the Wisconsin ice sheet. Movement of the ice was strongly affected by the escarpment. To the south of Cabot Head the main ice movement was in a southerly direction parallel to the peninsula. However, west of Cabot Head the ice was forced to climb the escarpment. Erosion was especially heavy in this area, and the escarpment was eroded back to a much greater extent. Only extremely resistant outliers remain in the form of islands such as those in the TIU (Goodchild, 1984).

During the retreat of the ice a proglacial lake developed against the southern slope of the glacier. As the ice continued to retreat the land began to rebound from isostatic uplift. Throughout the time of ice retreat the size and water level of the proglacial lake fluctuated. A series of stages have been identified which correspond to different times and water levels at which the lake existed (Fig. 3).

STAGE 1 corresponds to the earliest and deepest of the proglacial lakes, Early Lake Algonquin. This lake had one outlet which drained south through the present day location of Chicago. The shores of this lake would have existed at a present day elevation of 265 m above sea level. At this contour level all of the islands and most of the Bruce Peninsula would have been submerged.

STAGE 2: as the ice continued to retreat new outlets for the lake formed. The sudden draining of water caused a rapid lowering of the lake level. This was the Penetang stage. The lake level continued

Figure 3. Lake Levels in the Post Glacial Period. Source: Goodchild (1984).



to drop and by 12000 bp the plateau on Bear's Rump Island was completely exposed and has remained emerged since. By 11000 bp the lake level had dropped to below 120 m thereby exposing the present shoreline to subaerial erosion.

STAGE 3: The lake level continued to drop while the glacier continued to retreat. At one point the lake level dropped to such a low stage that Georgian Bay was separated from Lake Huron. These two lakes are called Lake Stanley (Georgian Bay) and Lake Hough (Lake Huron). Thus stage 3 is the Lake Hough stage. At this time the lake level was 75 m below the present lake level. Hence the top of the islands would have been approximately 90 m above the surface of the lake. This stage reached its minimum around 10,400 bp.

STAGE 4: In this stage isostatic uplift had a significant effect on the lake level. After the Lake Hough stage the North Bay outlet for the lake was rising faster than the islands and the peninsula. As a result the water level began to rise. By 5500 bp the present shoreline was again submerged. The water level continued to rise until 4000 bp when the water level reached its maximum for this stage. This maximum occurred when the elevation of the rising outlet reached the elevation of the Port Huron outlet.

When this occurred drainage of the lake took place into Lake Erie. This is the Nipissing stage and at its maximum the water level at the islands would have been 30 m higher than at present.

STAGE 5: Over the past 4000 years bp isostatic uplift combined with drainage through the Port Huron outlet has resulted in a drop in the lake level from the Lake Nipissing high stage to its present level.

Except for a few small patches, the deep cover of till, outwash, and lacustrine deposits, which characterize most of the sedimentary rock terrain in southern Ontario, are absent on the Georgian Bay Islands and Bruce Peninsula. This is a result of the cover having been washed away during the long periods of submergence and short periods of emergence. Thus there are large portions of bare rock which have been exposed to wave and karst action for long periods of time.

2.7 Wave action

Wave action and solution are two processes which have been acting on the dolomite surfaces of the islands. Wave energy is influenced by wind strength and fetch length. The strongest winds in the Tobermory area come from the northwest and north. However it is the fetch length over which the wind blows uninterupted that determines the effect that the wind will have. The greatest fetches are in the north, northeast, and east for Bear's Rump Island, and in the south and southwest on the southwest shore of Cove Island. From the available fetches and dominant wind directions it can be said that the southeast shore of Bear's Rump has a greater wave energy than the northwest shore, and that the east shore of Cove Island has a greater wave energy than sheltered Dunk's Bay.

The greater the wave energy the stronger the erosive capabilities. Waves erode rock by creating enormous pressures of compression and expansion. The ability of material to withstand these pressures decreases if it is fractured or unconsolidated, and thus it erodes easier and more rapidly. Mechanical erosion may also occur in the zone of wave action by abrasion. Cobbles being rolled around by swash and backwash may abrade the dolomite surface.

2.8 Solution

Further erosion in the wave zone may occur by solution. Solution occurs through a series of steps in which the carbon dioxide-water-calcium carbonate system interacts to produce bicarbonate ions. The complete process can be expressed in the following way: (Jennings, 1971)

$$CaCO_3 + H_2O + CO_2 \text{ (dissolved)} \rightleftharpoons Ca^{2+} + 2\ HCO_3^-$$

$$\upharpoonleft\downharpoonright$$

$$CO_2 \text{ (air)}$$

If the water is saturated with carbonate the reaction will continue only as long as more CO_2 diffuses into the water.

Although Lake Huron is essentially saturated with carbonate, two factors may allow solution in the zone of wave action. First the saturated protective boundary layer will be easily and rapidly penetrated in the wave zone, and second a mixing of saturated groundwater with saturated lake water may produce an undersaturated water capable of further solution. This second factor is known as Mischungskorrosion.

Fairbridge (1968) suggests that there may also be diurnal fluctuations in solution capability in small ponds of water. At night, with atmospheric cooling and CO_2 production (from respiration and bacterial activity) the water becomes solutionaly stronger. During daylight warming, algal photosynthesis, and evaporation reduce the solution strength of the water. Thus, diurnal oscillations are from etching during the night to induration during the day.

Solution above the zone of wave action may be influenced by factors such as precipitation, snowmelt, biogenic activity, and water percolating through soils rich in CO_2, all of which will contain or contribute CO_2 to produce carbonate unsaturated water. Solution may also occur below the zone of wave action. The processes of subaerial and subaqueous solution will be discussed further in chapter 4.

3. SOLUTION PITS

3.1 General Characteristics

Solution pits, a small scale solutional weathering feature, are a form of littoral karren observed in both the Amabel and Guelph Formations. They are found on the sub-aerial pavements in the littoral zone of the islands and mainland in Lake Huron, and continue underwater. The pitting is not usually widespread across the pavement surfaces, but where it does occur the pitting tends to be in high densities.

The shape and size of pits vary, but generally the pits are round in plan view with diameters averaging approximately 20 mm. Pits with diameters of less than 10 mm tend to be very shallow with depths appearing to be less than 5 mm. Pits of this size are referred to as micro-pits.

This study is concerned with the larger (normal) pits in which the diameters range from 10 mm to 40 mm. Pits of this size are classified in one of three categories: i) single, ii) multiple, or iii) linear. Multiple and linear pits refer to a form of pitting that occurs when a number of single pits coalesce. If the pits coalesce in clusters they are referred to as multiple, and if they coalesce along a straight line they are referred to as linear.

There were two locations in the Amabel and two in the Guelph at which pit characteristics were studied. In each formation one of the locations was a relatively high energy shorline, and the other a lower energy shorline. This allowed for a comparison of solution pit characteristics between two lithologies and two types of shore line energies.

3.2 Differences between two lithologies: Guelph vs Amabel

There are important differences in pit characteristics between the two lithologies. These differences can not be attributed to chemical composition because both the Guelph and Amabel have the identical composition of $(Ca_{1.2}Mg_{0.8}CO_3)_2$ (Cowell, 1976). Therefore differences in pitting must be the result of other factors.

3.2.1 Pit dimensions:

Dimensional differences exist between subaerial pitting in the Guelph Formation and subaerial pitting in the Amabel Formation. In the Guelph Formation pit diameters averaged 19 mm with depths averaging 17 mm. Whereas in the Amabel Formation pit dimensions were bimodal, having an average diameter and depth of 29 mm and 16 mm respectively, or 16 mm and 10 mm respectively. The two sizes of pits in the Amabel may be due to the smaller pits being weathered products of the larger pits. This possibility is discussed in section 3.4.

A regression analysis was done to determine if there

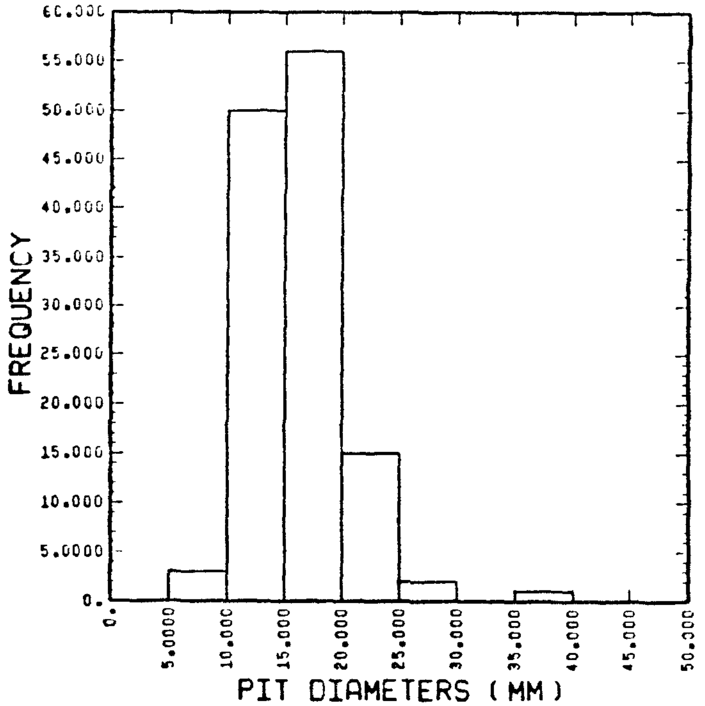


FIG 4a: HISTOGRAM OF PIT DIAMETERS MEASURED IN THE GUELPH FORMATION ON COVE ISLAND. (NOTE THE UNIMODAL DISTRIBUTION)

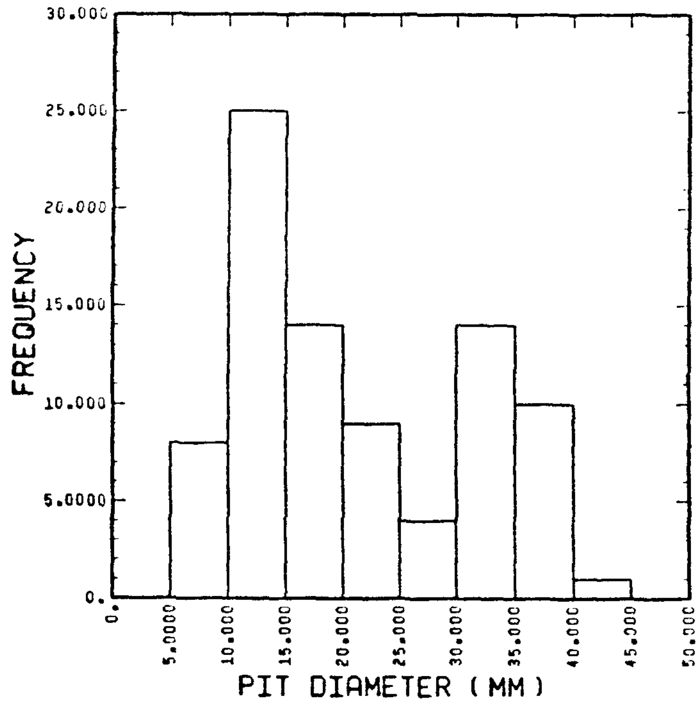


FIG 4b: HISTOGRAM OF PIT DIAMETERS MEASURED IN THE AMABEL FORMATION ON BEAR'S RUMP ISLAND. (NOTE THE BIMODAL DISTRIBUTION)

was any relationship between pit depth and diameter. The results showed no linear correlation between these two characteristics for pits in the Guelph Formation. However a correlation of 61% existed for the pits in the Amabel. An explanation for the differences in pit dimensions between the two lithologies may be related to differences in porosity.

3.2.2 Porosity:

Porosity may be an important factor determining pit characteristics. With this in mind a simple porosity analysis was performed on samples taken from the two formations. The results show the dolomites of the Guelph Formation to be more porus than those of the Amabel (Table 1). From this result, if one considers the pits to be initiated at a pore space, one might predict that the higher the porosity, the greater the number of pits. Indeed this is what is observed. Density counts from samples in the Guelph and Amabel show a much higher density of pitting, with a greater proportion of pit amalgamation, in the Guelph, whereas in the Amabel, pitting commonly occurs singularly. Furthermore, it appears that because of the larger porosity, density, and greater amount of pit amalgamation, the diameters of pits in the Guelph can not achieve the size of the diameters obtained by pits in the Amabel.

TABLE 1 Porosity values of samples taken from the Guelph and Amabel Formations

A) Guelph Formation (Cove Island)

Sample	Dry Weight(a) (g)	Wet Weight(b) (g)	% Porosity(c)
1	42.201	43.201	2.315
2	60.380	61.734	2.193
3	60.210	61.000	1.327

B) Amabel Formation (Bear's Rump Island)

Sample	Dry Weight (g)	Wet Weight (g)	% Porosity
1 NW shore	54.620	54.970	0.633
2 SE shore	32.157	32.303	0.774
3 Interior	78.891	79.302	0.517

a) Dry weights were measured after baking samples in an oven for a period of 2 weeks.

b) Wet weights were measured after soaking samples in water for a period of 2 weeks.

c) $\% \text{ Porosity} = \frac{\text{Wet Weight} - \text{Dry Weight}}{\text{Wet Weight}} \times 100$

3.3 High energy shorline vs lower energy shoreline

In chapter 2 it was noted that Dunk's Bay has a less dynamic shore than the east coast of Cover Island, and that the south east shore of Bear's Rump Island has a more energetic shoreline than the north west shore. Thus, one might expect to see a difference in pit characteristics between the higher and lower energy shorelines in both formations.

3.3.1 Density distribution:

One difference observed was that of pit distribution. In both lithologies solution pitting in the higher energy shoreline was less abundant than in the lower energy shoreline. At Dunk's Bay pitting was widespread covering the entire pavement surface, whereas on Cove Island the pitting occurred in patches. However in the Amabel, on Bear's Rump Island, although the pitting occurred in patches on both shorelines, the number and size of the pitted patches was greater on the lower energy shoreline.

The differences in density distribution may be partially a result of wave erosion. Evidence of the erosive capabilities of waves was clearly visible on the south east coast of Bear's Rump Island. Surface flaking had occurred as far back as 30 m from the waterline. On these freshly exposed surfaces no sign of pitting of any kind was present. The remainder of the pavement was essentially devoid of pitting with the exception of scattered micropitting and a few isolated densely pitted patches.

In contrast, at Dunk's Bay the pavement was covered primarily by one bedding plane in which pitting was continuous across the entire exposed surface. This may be due to the bay being sheltered from intense wave action, thereby preventing the erosion and flaking of the bed in which the pitting occurs. Thus, the lack of pitting on the higher energy shoreline with respect to the lower energy shoreline, and the fact that pitting occurs in patches, is possibly explained by intense wave action having: 1) removed the bedding surface in which the pitting may once have been present, and 2) prevented further development of new pits.

3.3.2 Trends:

a) Bear's Rump Island

On each of the south-east and north-west shores of Bear's Rump Island, two density counts were made. Although this is not enough data to warrant a confirmed trend, the data does suggest that a possible trend may exist. Considering each shore individually, what is observed is that the density of pitting decreases as the elevation and distance from the waterline are increased. Furthermore, the pit density is greater on the lower energy shoreline than on the high energy shoreline.

Similar observations were made with respect to the average depths and diameters of the pits. Both of these pit characteristics were observed to increase in size as elevation above and distance from the shoreline was increased. Even the standard deviations of the average pit dimensions showed an increase inland with increasing elevation, thereby indicating a greater variety of pits inland. Once again the shoreline energies appeared to have an influence, as the pits on the lower energy shore were larger than the pits on the higher energy shore (Table 2).

b) Cove Island

At Cassel's Cove, on Cove Island, density counts were attempted at various distances inland. The surface was relatively flat lying and the elevation fluctuated between approximately 0.3 m to 0.4 m above the waterline. No trend existed at this location. The distribution and density of the pits appeared to be influenced by the bedding planes in which they had formed. That is, the density counts were obtained from different bedding planes, each at slightly different elevations. The different elevations resulted from a small scale form of step topography in which the bedding planes stepped up or down several cm's as one moved inland. The 'stepped' influence of bedding planes on the density distribution of the pits is discussed in section 3.4 (Table 3).

TABLE 2 Pit Characteristics in the Amabel Formation

Which Shore of BRI	Distance From Shoreline (m)	Elevation Above Waterline (m)	Number of Pits in .25 m^2 Sample Grid	Average Pit Diameter (mm)	Average Pit Depth (mm)
NW	8.6	.2	276	21.3±8.3	15.9±9.1
NW	18.3	.6	185	31.1±10.9	23.2±13.8
SE	2.7	.15	208	15.8±4.4	10.7±4.0
SE	8.8	.70	120	27.3±10.0	15.4±6.9

TABLE 2 Pit Density Counts in the Guelph Formation (Cove Island)

Distance From Shoreline (m)	Number of Pits in .25m^2 Sample Grid
5.0	349
7.1	372
10.8	331
23.4	327
36.7	407

3.4 Bedding influences

The influence of beds and bedding planes on pitting was observed in two characteristics i) pit dimensions, and ii) pit density. On Bear's Rump Island the beds of the Amabel are very thin, and it was not uncommon to observe that the bed underlying the pitted surface had also been solutionaly affected. In some cases one could observe large bowl-shaped pits that had completely dissolved through the upper bed and continued into the lower bed. The diameter of the pits as they entered the lower bed were similar to the diameters of smaller bowl-shaped pits found in the same bed exposed nearby. This suggests that the smaller pits were originally the bottoms of larger pits. (Pluhar, 1966, came to the same conclusion from her observations of pit karren in the Hamilton-Dundas area). Therefore, the bedding influence on pit dimensions as in the above situation would have the effect of exposing pits exhibiting smaller secondary dimensions instead of the primary characteristics (Fig. 5).

The second bedding influence, on pit density, is more a function of time than anything else. In both the Amabel and Guelph Formations stepped topography was observed, and where pits had developed on a step the pitting had a distinct distribution; pit density was much greater in the front of the step than in the back. This density distribution can be attributed to time of exposure of the lower bedding surface. In other words, a step is created and the

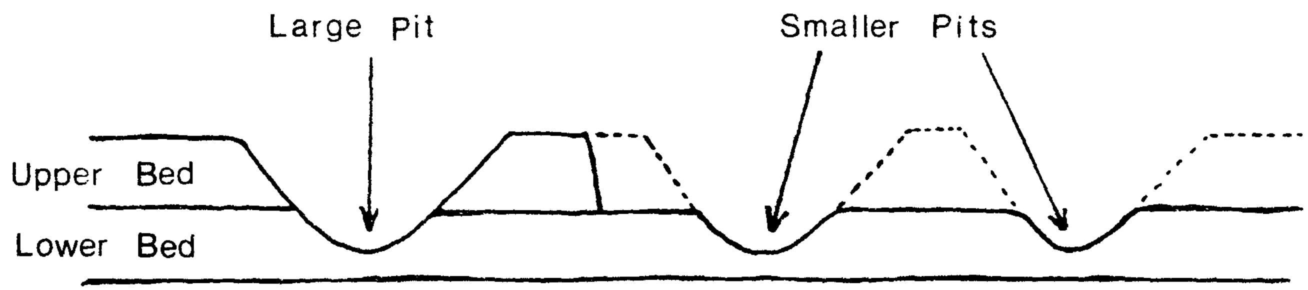


FIGURE 5: <u>Bedding Influences on Pit Size</u>

Dimensions of large pit as it enters lower bed is similar to dimensions of smaller pit in same bed exposed nearby.

lower bedding plane exposed, as the upper bed is peeled back. Thus the front of the step will be exposed before the back of the step, and therefore, there will be more time for pits to develop in the front of the step than in the back (Fig. 6).

3.5 Subaerial vs subaqueous pitting

Subaerial and subaqueous pit characteristics were examined in the Guelph Formation. Definite differences in pit characteristics were found to exist. The most obvious difference is that of size, with differences in pit depth being most evident. That is, subaqueous pits had much greater depths than subaerial pits. Another difference observed between subaerial and subaqueous pits is that subaerial pits have average pit depths less than the average pit diameter, whereas subaqueous pits have average pit depths greater than the average pit diameter. Associated with these differences in pit dimensions is differences in pit shape.

3.5.1 Pit dimensions:

The greatest pit depths recorded were from subaqueous pits. Pit depths greater than 30 mm were not uncommon underwater, and the maximum pit depth recorded of 60 mm, was taken from a pit at a depth of 6 m underwater. In subaerial pits however, pit depths greater than 30 mm were very rare. Depths usually averaged approximately 17 mm

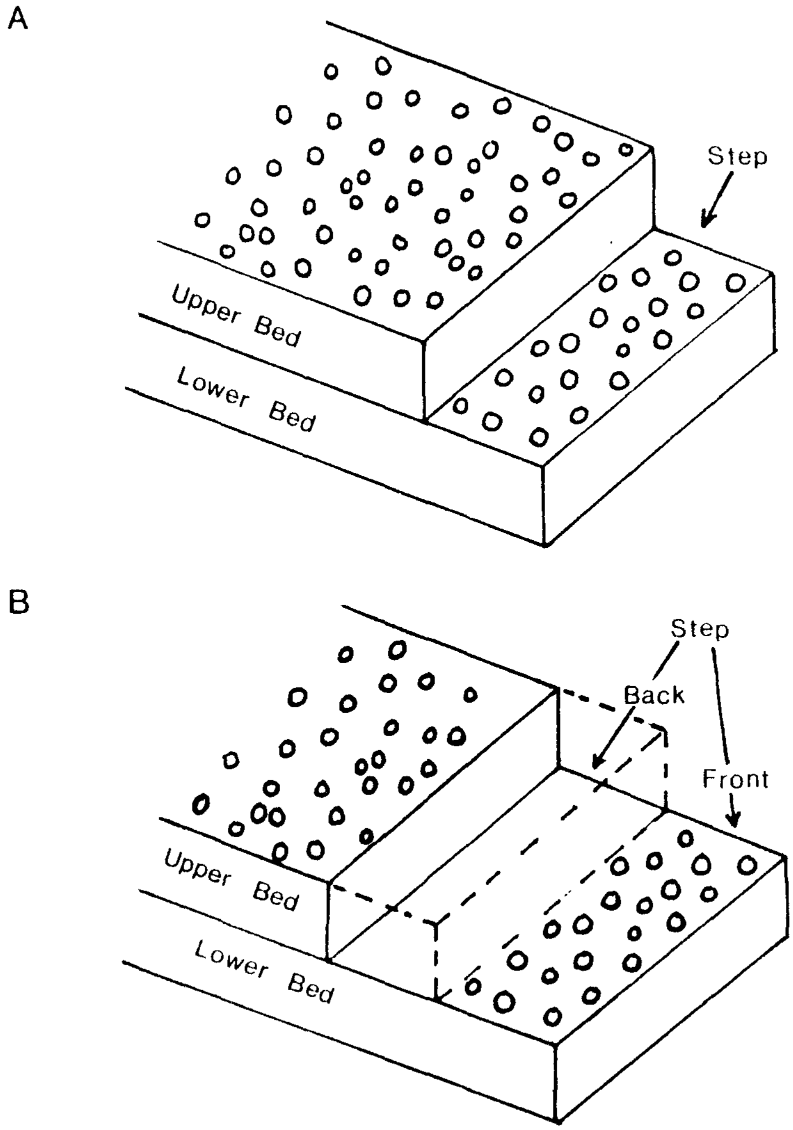


FIGURE 6: Bedding Influences on Pit Density

A) the step is exposed and pits develop in the lower bed.

B) The upper bed has been peeled back exposing more of the lower bed. There are NO pits at the back of the step because the surface has not been exposed to solutional processes for as great a length of time as the front of the step.

and the maximum depth recorded from a subaerial pit was an unusual 46 mm.

The depth of 46 mm belonged to a pit that was part of a linear chain that appeared to have developed in a micro fracture. Thus, there was a zone of weakness along which the pits were developing. Linear pits within this zone of weakness had greater depths than single and multiple pits that had not developed in the micro fracture. Thus, solution must be more active in the micro fracture.

The diameters of subaerial pits measured from 11 different grid sites in the Guelph Formation averaged 19 mm. The diameters of subaqueous pits measured from 5 different grid sites at depths of 5-6 m underwater averaged 15 mm. Thus, the depth and diameter results measured from subaerial and subaqueous pits in the Guelph, show an increase in the depth/width ratios in pits below the modern waterline.

3.5.2 Pit shapes:

Pits above water had bowl or parabolic profiles in which the inner walls of the pits were frequently lined with very small intense micropitting. These shapes were also observed underwater. However, a bulb-like shape was a more common profile observed in the subaqueous pits found at deeper water depths. Furthermore, the inner micropitting observed in the subaerial pits was virtually absent in the pits of a sample taken from a pitted surface 6 m underwater.

Perhaps the different shapes and sizes of the pits might be used to suggest an evolutionary pattern in the growth of pits. This possibility will be discussed in the next chapter. (Fig. 7)

4. HOW DO PITS FORM?

There is no explanation as yet which fully describes the initiation and growth of solution pits. Goodchild's (1984) statement that rainwater is an important factor in the development of solution pits is probably true. However, the development of solution pits is probably much more complex than simple solution by rainwater. Surf spray, snowmelt, mixing corrosion, lichen, and time are possibly additional factors contributing to the initiation and growth of solution pits. Cowell (1976) suggests that "the most likely explanation of the development of littoral pits on the Bruce Peninsula concerns biologic solution in a fresh water environment" (p 84). The biologic activity comes from lichen, algae or mosses which are visible on all the subaerial rock surfaces.

4.1 Inferences

From the various characteristics of pitting that have been described, certain inferences can be made with respect to pit development:

A) Pits may develop at pore spaces in the rock. All that would be required is water containing carbon dioxide to penetrate into the pore space and react with the carbonate walls, thereby enlarging the pore space. The growing pore space would amalgamate with other pore spaces and eventually it would become visible as a small micropit.

B) The presence of lichen on the subaerial pavement suggests that biogenic activity may be a significant contributing factor to pit development. Lichen patches near pits were observed to have similar diameters to those pits. In some cases the lichen were actually living in the pits. Furthermore, a pattern could be followed from a freshly exposed surface containing no pits, through a moderately lichen-covered surface still containing no pits, to a heavily lichen-covered surface containing small micro pits (Appendix, plates 2ab). This pattern suggests that pits develop under lichen.

C) Many normal sized subaerial pits contained inner micro-pitting and lichen growth. It is therefore possible that micro-pits are initiated by pore space enlargement under lichen and develop into normal sized pits by either a) micro-pit amalgamation, or b) micro-pit enlargement. However, if normal sized pits are formed by amalgamation one would expect to see iregularly shaped pits instead of circular pits (Fig. 8). Perhaps the circular shape is due to the growth pattern of the lichen, or perhaps the shape is irregular if looked at in finer detail. This would require further study to produce a conclusive answer.

Figure 7 : Pit shape evolution

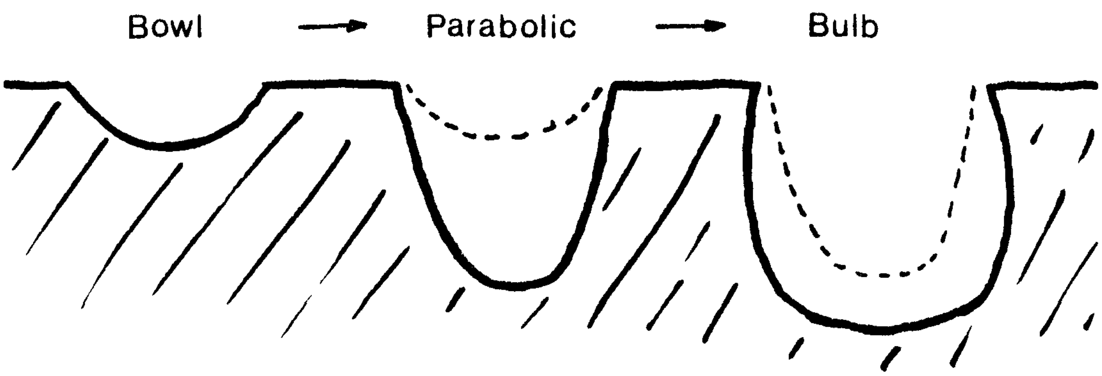
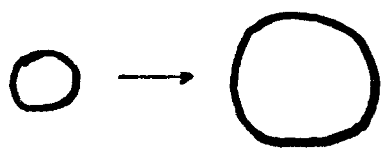
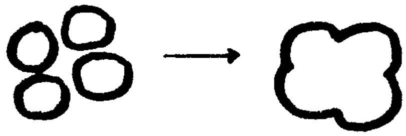


Figure 8

A) Micro-pit enlargement (circular shape)



B) Micro-pit amalgamation (irregular shape)



D) If pits initially begin as micro-pits, then the intense micropitting observed in the subaerial surfaces as opposed to the relative lack of it in the subaqueous surfaces suggests that

1) pitting is initiated above water

and therefore,

2) the subaqueous pits were initiated when the lake level was at a lower stage.

E) Because the dimensions of the pits show shallower pit depths and larger pit diameters above water than below water, then

1) solution must occur underwater
2) solution in subaqueous pits is greater in a vertical direction than in a horizontal direction
3) solution in subaerial pits is greater in a horizontal direction than in a vertical direction.

4.2 Subaqueous solution

Many problems are encountered when trying to explain the mechanism by which pits will deepen underwater. In Ireland downward facing pits have developed in a rock overhang in fresh water. These subaqueous pits deepen by ionic activity. That is, light hydrogen ions rise into the pits and react with the carbonate rock to produce bicarbonate ions. The denser bicarbonate ions then sink out of the pit allowing more hydrogen ions to rise and react. In Lake Huron the pits are upward facing, thus the light hydrogen ions would rise away from the pit instead of into it. Therefore, the solution process deepening the subaqueous pits in Lake Huron must differ from the process operating in Ireland (Fig. 9ab).

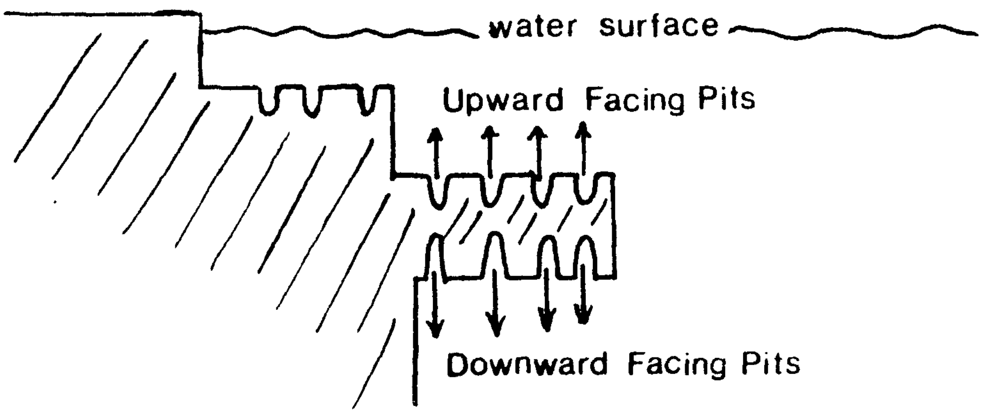
The waters of Lake Huron are divided into two layers based on density differences that occur as a result of temperature differences. The maximum density of fresh water occurs at a temperature of 4°C, this is the temperature of the bottom layer. Water warmer or colder than 4°C will be less dense and lay above the bottom layer. The surface layer and bottom layer are separated by a zone where a rapid change in temperature with depth occurs. This zone is the thermocline (Hough, 1958).

All water circulation usually occurs in the surface layer while the bottom layer remains stagnant. However, during the spring the ice cold surface waters warm, and eventually the lake water is isothermal at 4°C. When isothermal conditions are reached water will circulate from the surface layer to the bottom layer. This is the spring overturn. The lake overturns again in the fall when isothermal conditions are reached by cooling of the surface waters (See Fig. 10).

As stated earlier, Lake Huron is essentially saturated with carbonate. This statement is based on measurements by

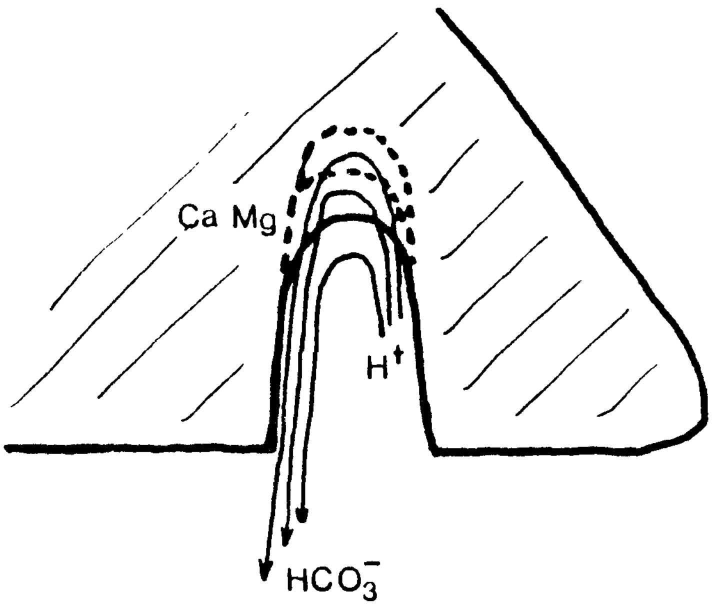
FIGURE 9a

A



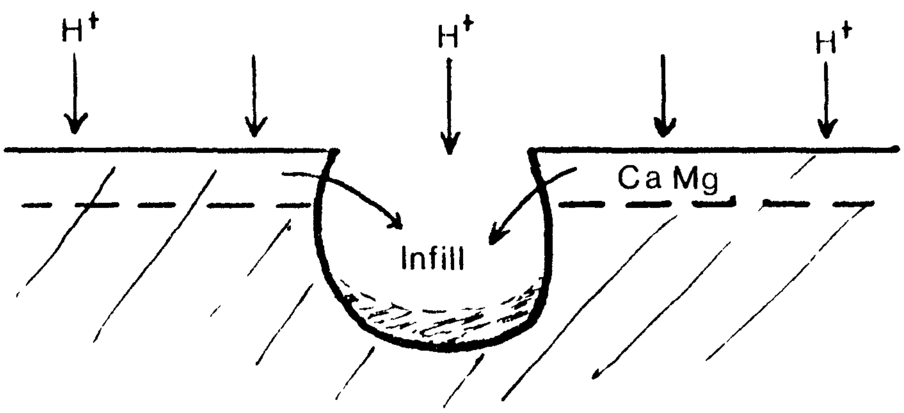
B

FIGURE 9b



C

FIGURE 9c



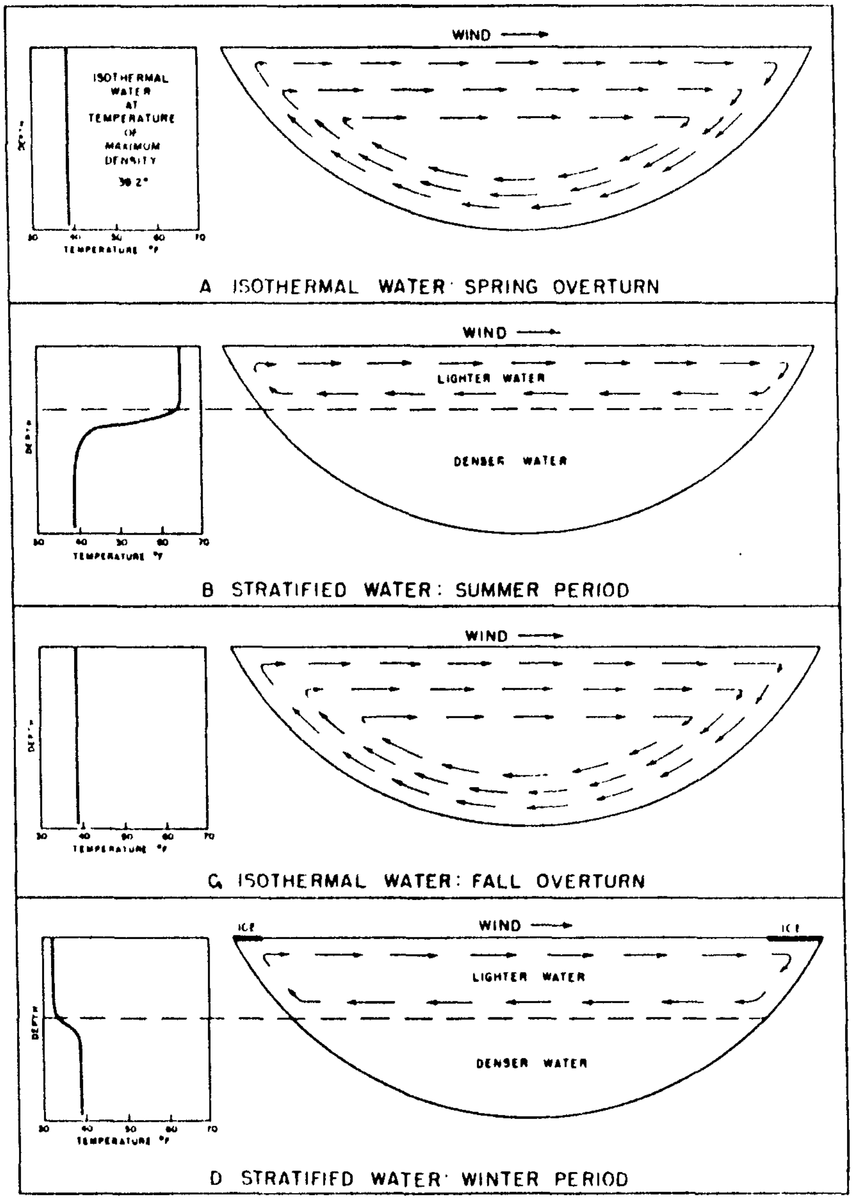


Fig 10: The annual temperature cycle in typical deep lakes of the temperate zone. In the deep part of a lake basin the water temperature remains close to 39° F throughout the year

Source: Hough (1958)

Cowell (1976) and concerns only the surface waters of Lake Huron. It is therefore possible that the deeper, colder waters of Lake Huron may be aggressive.

The acidity of the surface layer increases during the winter because the colder water temperature allows for increased CO_2 absorption, and the dissolved carbonate concentration is diluted by direct precititation. It has been reported (Ford pers. comm.) that the solvent capabilities of the spring surface water is 60-80 mg/l dolomite. Thus the deep waters can remain aggressive by being replenished with surface water carried downwards during spring overturn.

If the bottom layer is aggressive then it would seem likely that the entire lake floor would be solutionaly weathered and lowered, not just pits (Fig. 9c). Thus the question arises, how do pits deepen with respect to the lake floor. Further study is required, as an answer to this question is presently not available.

4.3 Suggested pit history

The fluctuating stages of Lake Huron (discussed in section 2.6) and inferences A-E can be tied together to produce a pit history.

A) i) During stage 3, when the lake level was dropping to the Lake Hough minimum stage, micropits would have developed in the subaerial surfaces.

ii) Solution would have occurred by subaerial processes, and thus the pits would have developed bowl-shaped profiles.

iii) The time available for pit development would have been greater at higher elevations than lower elevations. Therefore, the micropits at higher elevations would have larger dimensions and densities than pits at lower elevations.

B) i) During stage 4, when the lake level was rising from the Lake Hough minimum stage to the Lake Nipissing maximum stage, the pits became submerged. Pit enlargement then became greatest in a vertical direction as suggested in inference E. As a result of the increased rate in vertical solution the micropits would develop into normal sized pits at lower elevations faster than at higher elevations.

ii) Pit shape would also be affected by subaqueous solution. Vertical solution would change the bowl-shaped pits into parabolic-shaped pits, and eddying acidic waters within the bottom of parabolic-shaped pits could create bulb-shaped pits. Bulb-shaped pits may also be created by silt which has settled in the bottom of a parabolic shaped pit. In this case vertical solution would be inhibited by the silt armour and thus solution would occur in other directions. Thus an evolutionary pattern can be observed from a bowl-shaped pit formed under dominantly subaerial conditions, through a parabolic-shaped pit to a bulb-shaped pit formed under dominantly subaqueous solution processes (Fig. 7).

C) i) During stage 5, from the Lake Nipissing maximum to the present, the lake level has been dropping. Thus, pits which were submerged last during stage 4 were exposed first during stage 5. Therefore with reference to pits above the present waterline, pits at higher elevations will have been exposed to subaerial processes for a larger amount of time, and subaqueous processes for a shorter amount of time than pits at lower elevations. Hence, as one might expect, the pits at higher elevations will have greater diameters than pits at lower elevations. This trend did occur in the subaerial pits and was observed to continue in the pit diameters underwater.

ii) One would also expect to see the influence of the subaqueous processes more prevalent in the subaerial pits exposed in the lower elevations. This was observed in the pit densities where, because this study considered only the normal sized pits during density counts, the densities were greater at the lower elevations than at the higher elevations. However, the expectation one might have that pit depth would be greater at lower elevations was not observed. This may be due to the relatively small difference in elevation of the subaerial sample sites, and the rates at which the elevations were submerged and emerged.

5. CONCLUSIONS

Differences in pit characteristics occur with changes in elevation, lithology, shoreline energies, and time. These differences are:

A) Elevation

1) Pit density increases with decreasing elevation.
2) Subaqueous pit depth/diameter ratios are larger than subaerial pit depth/diameter ratios.

These differences in pit characteristics with elevation are probably related to the fluctuating post glacial lake levels, and the time of exposure of the surfaces to solution processes.

B) Time

Time appears to affect pitting in the following way:

1) The greater the length of time of exposure of a bedding plane to solution pocesses, the greater the amount of pit development.

C) Lithology

1) The Guelph Formation has greater pit densities than the Amabel Formation.
2) The Amabel Formation has larger pit dimensions than the Guelph Formation.

These differences in pit characteristics between the two formations are probably due to the Guelph Formation being more porus than the Amabel Formation.

D) Shoreline energies

1) Pit densities and dimensions are greater on lower energy shorelines than higher energy shorelines.

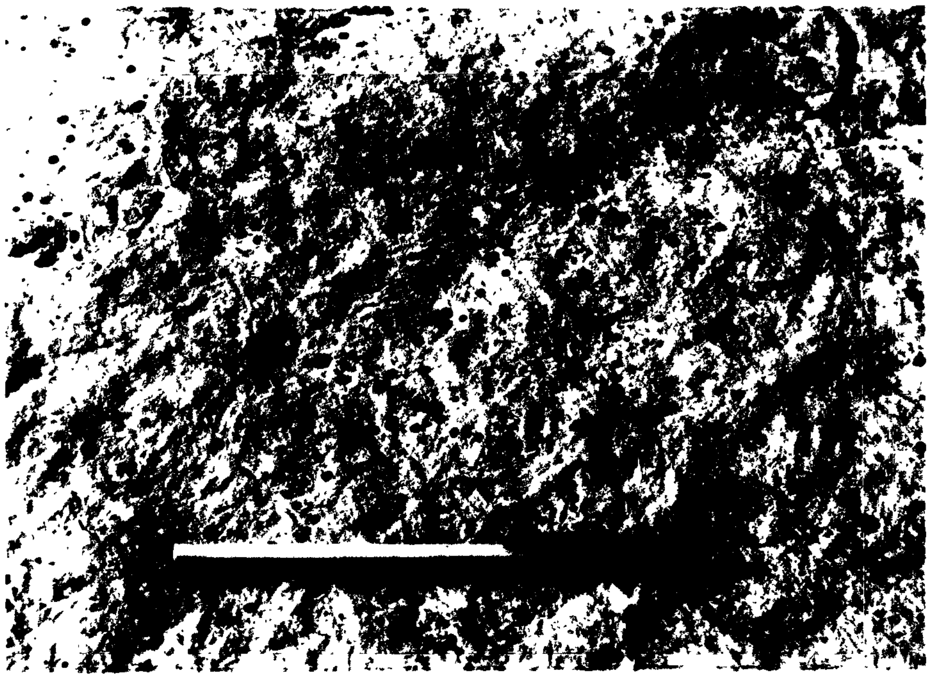
Differences in pit characteristics between shorelines with different energies exist probably because of an inhibiting effect on pit development created by larger erosive forces on the higher energy shorelines.

A P P E N D I X

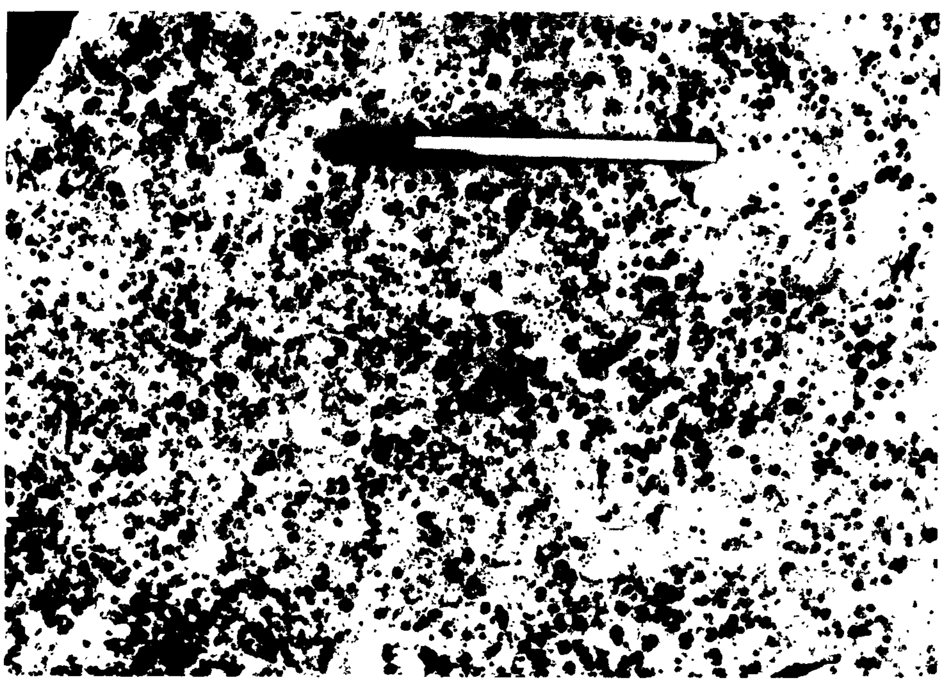
Plate 1

Surface flaking in the Amabel Formation on Bear's Rump Island. (pen is 30 m from shoreline)

Plate 2 LICHEN/PIT EVOLUTION



A Surface with little lichen growth and no pits (BRI)



B Surface with heavy lichen growth and micro pits present. (Note pits below each end of pen cap)

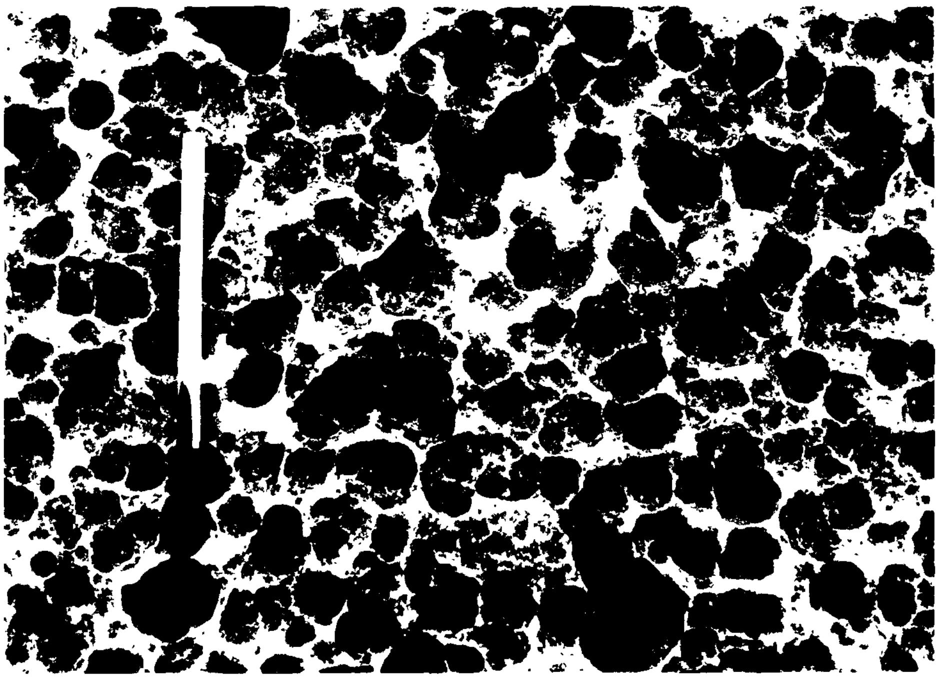


Plate 3 Pitting in the Guelph Formation, Dunk's Bay

Note the inner micro-pitting and lichen growth in some of the pits.

Plate 4 Bedding Influence on Pit Density

Amabel Formation, BRI

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