LAPIES AND RELATED SMALL KARST FEATURES

ON THE NIAGARA ESCARPMENT

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ON THE NIAGARA ESCARPMENT

By

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Chapter 1.

INTRODUCTION: THE PURPOSE OF THE INVESTIGATION: METHODS: REGIONAL GEOLOGY AND TOPOGRAPHY

Purpose

It was said, more than sixty years ago, that the lapies problem was solved. Nevertheless, much work still remains to be done, in order to clear up controversial aspects, and to find answers to questions that have since been raised. New observations, quantitative field and laboratory analyses and experiments are needed to justify or discard the statements and suggestions of others of the past and the present.

The principal aim of this thesis is to bring the problem a step nearer to resolution, by establishing a connection between the chemical and physical properties of the host rock and the features being developed in them, under various climatic and weathering conditions. A second aim is to describe and classify these forms where they occur in sample areas of the Niagara Escarpment, considering their appearance in relation to those factors which may localize, accelerate, or hinder growth. Thirdly, an attempt is made to clear up some of the still-existing controversies and misunderstandings in the terminology, the chemical and physical processes, and the control of structure. Finally, new problems are raised and hypotheses are presented.

The mode of study

The first part of the work consisted of field surveying, observations and sample collecting at four sites on the Niagara Escarpment close to Hamilton. The sites were:

1. Latitude 43°8'33", Longitude 79°27'15", above the eastern-most rock quarry, one and one-half miles southeast of the town of Beamsville, Ontario, reached via Quarry Road, east of the town, on highway #8. The elevation above sea level is 600 feet.

The fractures, that are being altered by solution processes, are well exposed at the surface on the top of the cuesta. An area of 32,940 sq. yards (approximately) has been mapped and a much greater area has been analysed.

2. Latitude 43°17'45", Longitude 79°59'30", is in the Dundas, Ontario vicinity. The land is the property of Canada Crushed Stone Ltd., about half mile north of highway #5, at 825 feet above sea level. It is about two miles from the steep escarpment face, to the northwest.

The fracture survey has been carried out here over 150 sq. feet of surface of the rock outcrop, which is being stripped bare from its soil cover, to make room for the rapid mining operation.

3. Latitude 43°20'45", Longitude 79°51'45", Burlington, Ontario, two miles north of the village of Waterdown, about three-quarters of a mile south of highway #15, directly above the vertical cliff face. One continuous trench of 420' has been mapped at this site, parallel to the face.

4. Latitude 43°25'15", Longitude 79°53'10", Mount Nemo and north of Waterdown, one and one-half miles northwest of Nelson, Ontario; on highway #25. No mapping was done in this area, only the bare small solutional features have been photographed and rock samples were collected for analytical purposes. Figure 1 (locality map).

The sites were chosen because all of the rocks at the four points are pure dolomites with little variations in the chemical components, all are covered with glacial till or suffered recent loss of the overburden, due to erosion or man's activities. They differ in internal rock-structure and texture and in their positions on the escarpment. The differences in the rate of chemical weathering from place to place, and the variations of the karst features are therefore considered to be in relation with rock structure and texture.

Using the field data, fracture pattern maps were drawn. These provided a base for strike-length frequency analyses, and for determination of the effects of regional and local factors in controlling lapies development (see Figures 2 a & b).

The laboratory work consisted of porosity and permeability measurements, chemical analyses, microscopic texture and structure studies (staining, comparative grain size and impurity distribution). Special consideration was given to primary, "pressure-solutional" features (see Appendix I) in relation to superimposed secondary lapies, which the writer named 'double lapies'.

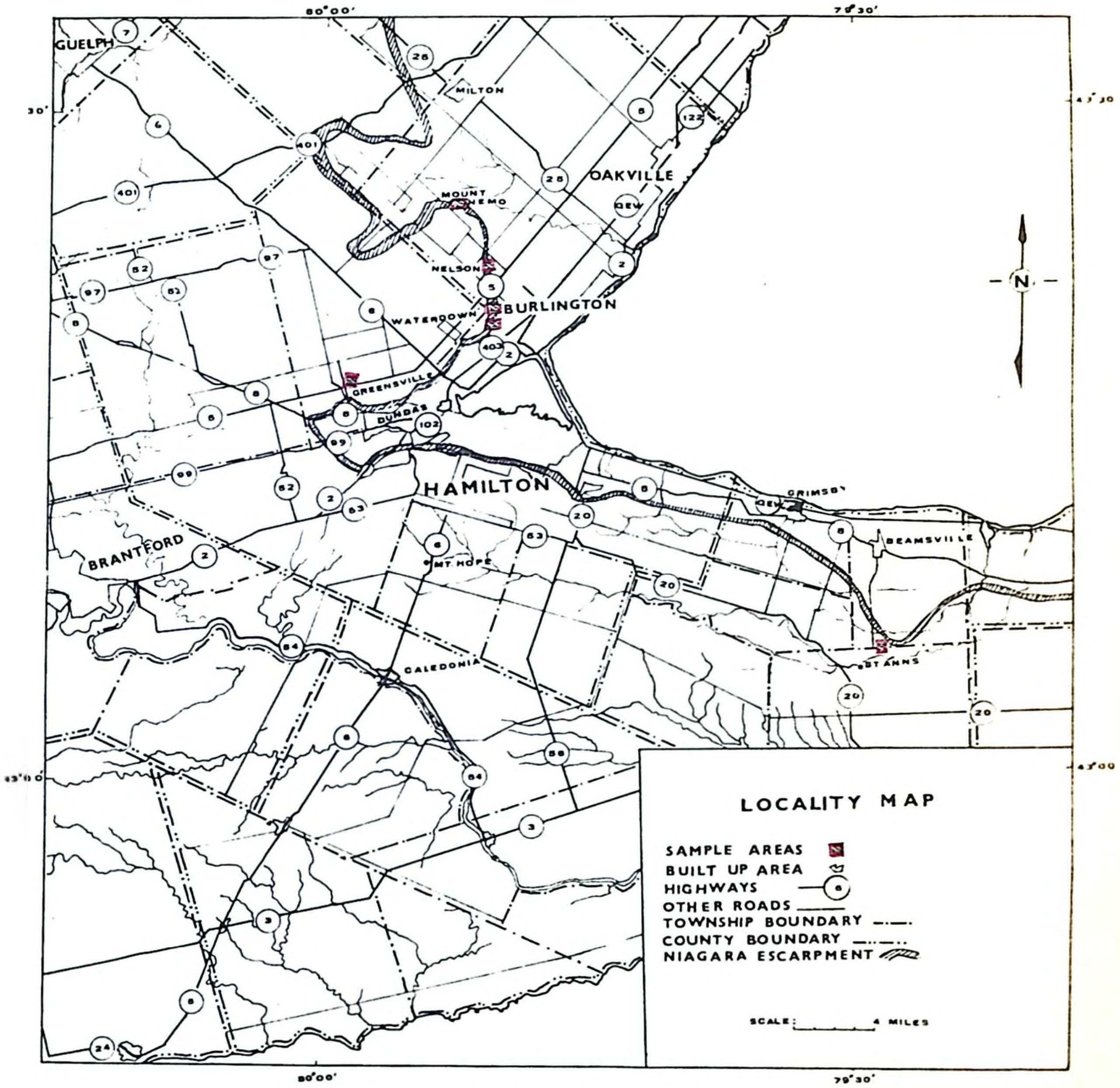

LOCALITY MAP
SAMPLE AREAS
BUILT UP AREA
HIGHWAYS
OTHER ROADS
TOWNSHIP BOUNDARY
COUNTY BOUNDARY
NIAGARA ESCARPMENT
SCALE: 4 MILES
N
80°00'
79°30'
43°30
43°00
GUELPH
MILTON
OAKVILLE
MOUNT NEMO
NELSON
BURLINGTON
WATERDOWN
GREENSVILLE
DUNDAS
HAMILTON
GRIMSBY
BEAMSVILLE
ST ANNS
BRANTFORD
MT HOPE
CALEDONIA
QEW

Figure 1

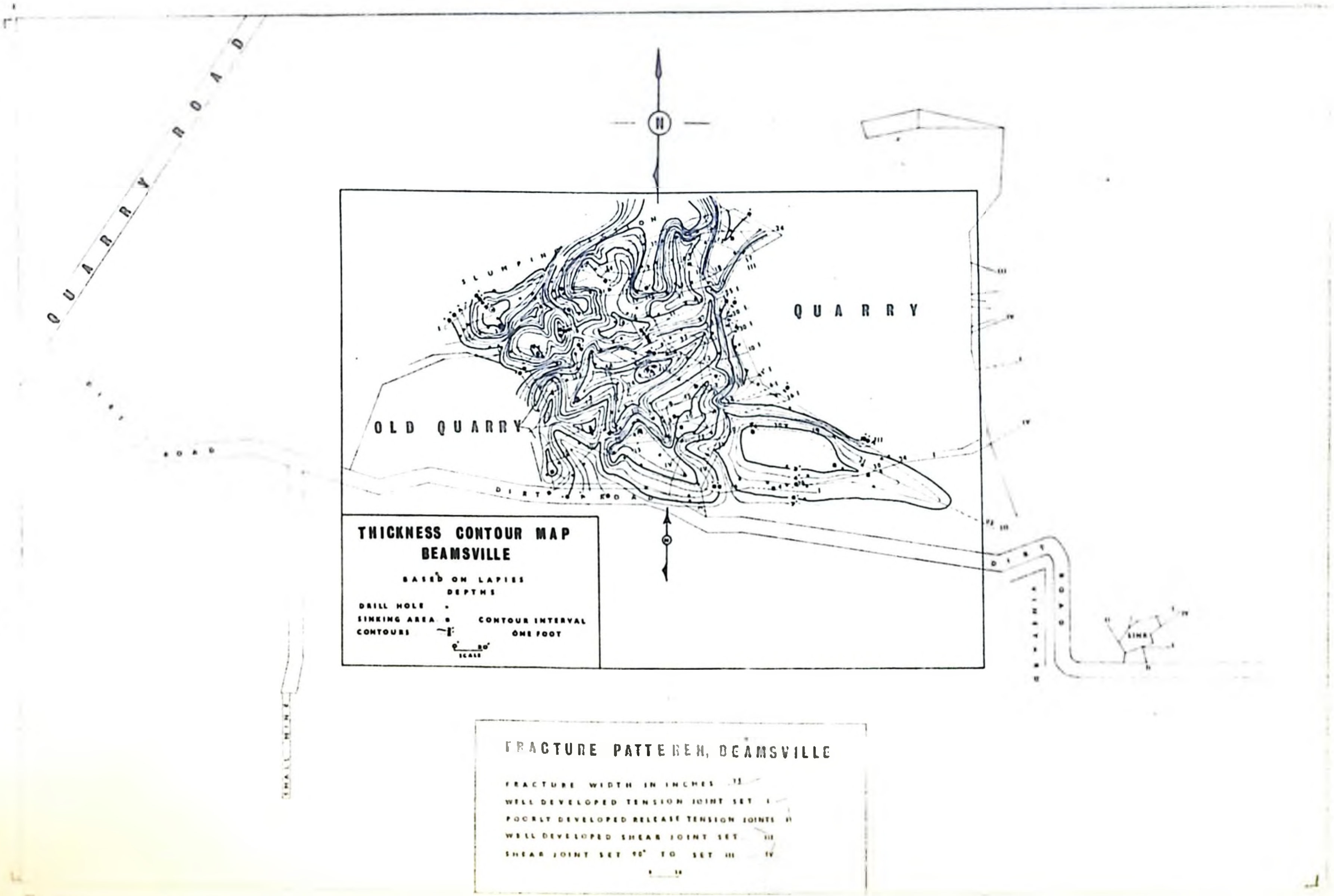

QUARRY ROAD
N
SLUMPING
QUARRY
OLD QUARRY
DIRT ROAD
DIRT ROAD
SHALE MINE
SINK
I
II
III
IV
THICKNESS CONTOUR MAP
BEAMSVILLE
BASED ON LAPIES
DEPTHS
DRILL HOLE
SINKING AREA
CONTOURS
CONTOUR INTERVAL
ONE FOOT
0'
20'
SCALE
FRACTURE PATTEREN, BEAMSVILLE
FRACTURE WIDTH IN INCHES
WELL DEVELOPED TENSION JOINT SET I
POORLY DEVELOPED RELEASE TENSION JOINTS II
WELL DEVELOPED SHEAR JOINT SET III
SHEAR JOINT SET 90° TO SET III IV

FIGURE 2

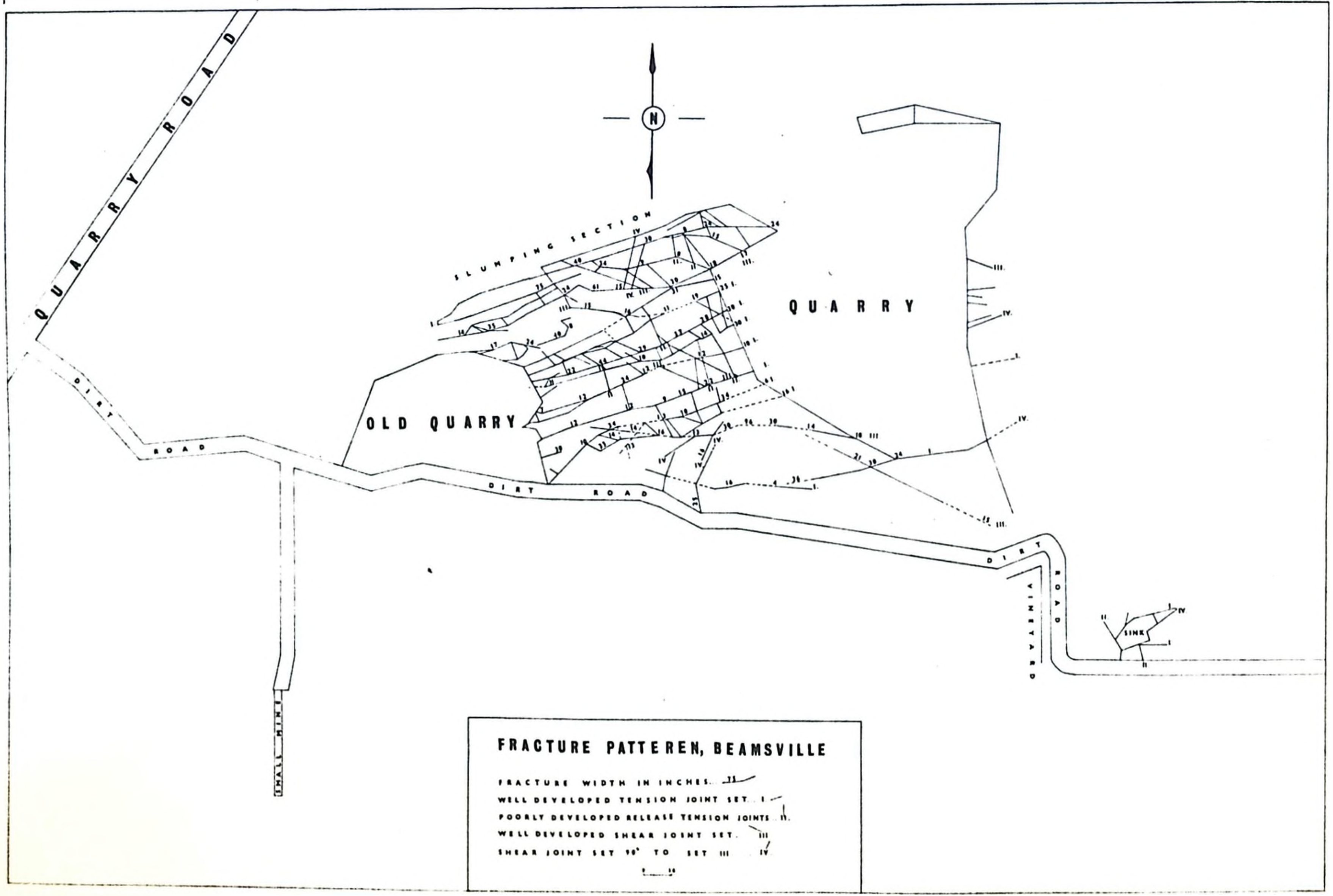

FRACTURE PATTEREN, BEAMSVILLE
FRACTURE WIDTH IN INCHES.. 75
WELL DEVELOPED TENSION JOINT SET .. I
POORLY DEVELOPED RELEASE TENSION JOINTS .. II.
WELL DEVELOPED SHEAR JOINT SET. III
SHEAR JOINT SET 90° TO SET III .. IV.
N
QUARRY ROAD
SLUMPING SECTION
QUARRY
OLD QUARRY
DIRT ROAD
DIRT ROAD
DIRT ROAD
VINEYARD ROAD
SHALE MINE
SINK

FIGURE 2 a

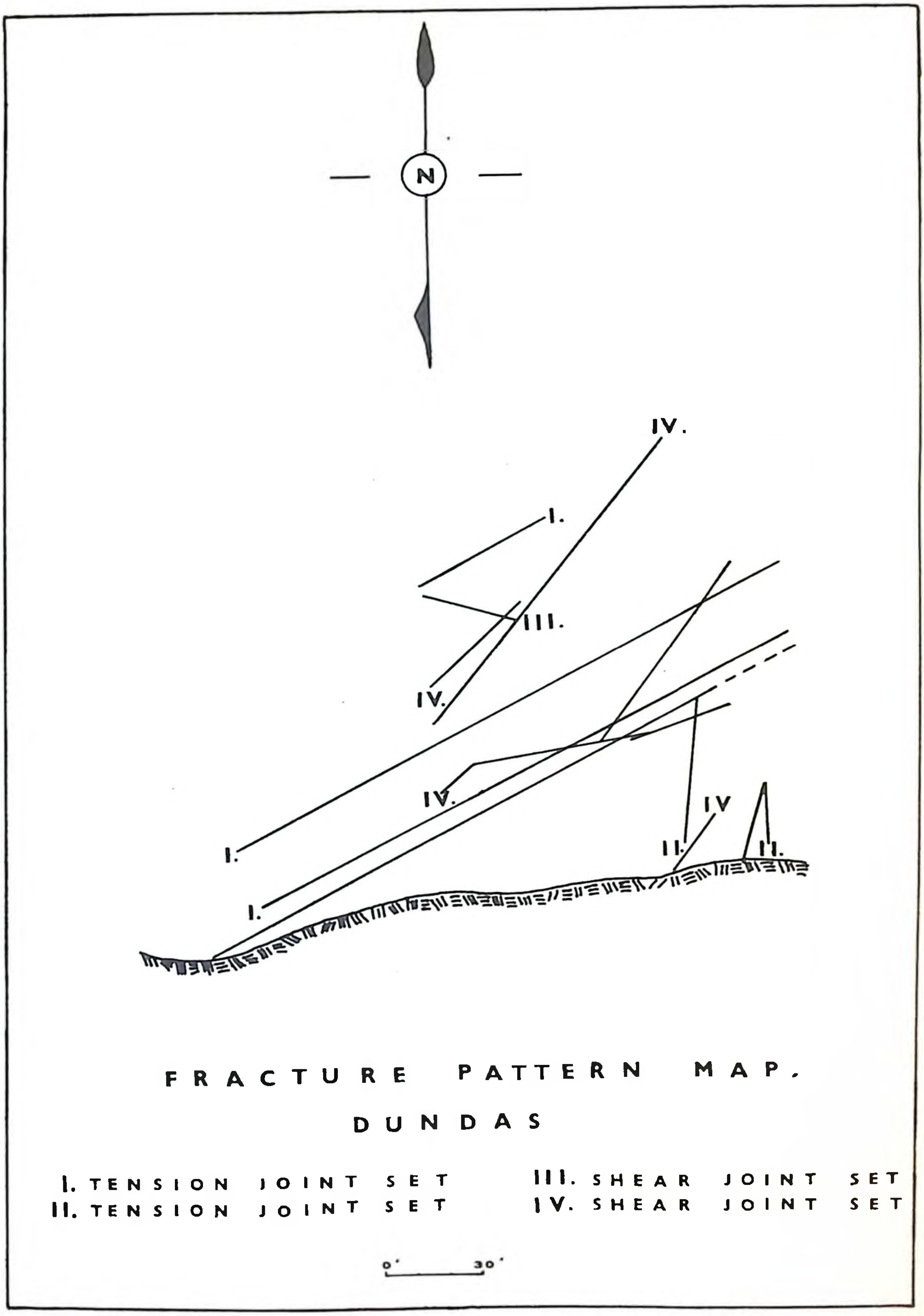

N
IV.
I.
III.
IV.
I.
IV.
I.
IV
II.
II.
FRACTURE PATTERN MAP.
DUNDAS
I. TENSION JOINT SET
II. TENSION JOINT SET
III. SHEAR JOINT SET
IV. SHEAR JOINT SET
0'
30'

Figure 2b

The writer is greatly indebted to Dr. D.C. Ford, who supervised this work, Dr. D.M. Shaw of the Department of Geology kindly provided necessary equipment, Mr. H.D. Falkiner made thin sections and cut hand specimens, Mr. J.R. Muysson gave advice on the use of rapid methods in chemical rock analyses. Last, but not least, I am grateful to Mr. A. Pluhar, who assisted with the field work.

The Silurian Geology

The bed rocks considered are carbonates of Middle Silurian age. They form a resistant cap over brittle, softer sedimentary layers, and are responsible for the cuesta-vale topography development in Southern Ontario.

A good stratigraphic summary is given by Bolton (1957). While stratigraphy will not be discussed here, the section at Niagara Falls is presented (Fig. 3) to show the relative positions of the rock beds examined at the four locations. The section shows that the Beamsville outcrop, along with the Nelson and Burlington surface rocks, are of the Lockport formation. The Dundas area and, possibly, the Mount Nemo site, are in the Guelph formation.

At Beamsville, the upper strata consist of light gray to buff, medium-fine grained, highly porous and permeable dolomite, 9' to 17' in thickness. They are sparsely fossiliferous with crinoidal stems and moulds. This is the Gasport member of Lockport formation, underlain by the DeCew formation, which overlies the gray, brittle, Rochester shales.

COLUMNAR SECTION OF MIDDLE SILURIAN EXPOSED AT NIAGARA FALLS

AFTER T.E. BOLTON

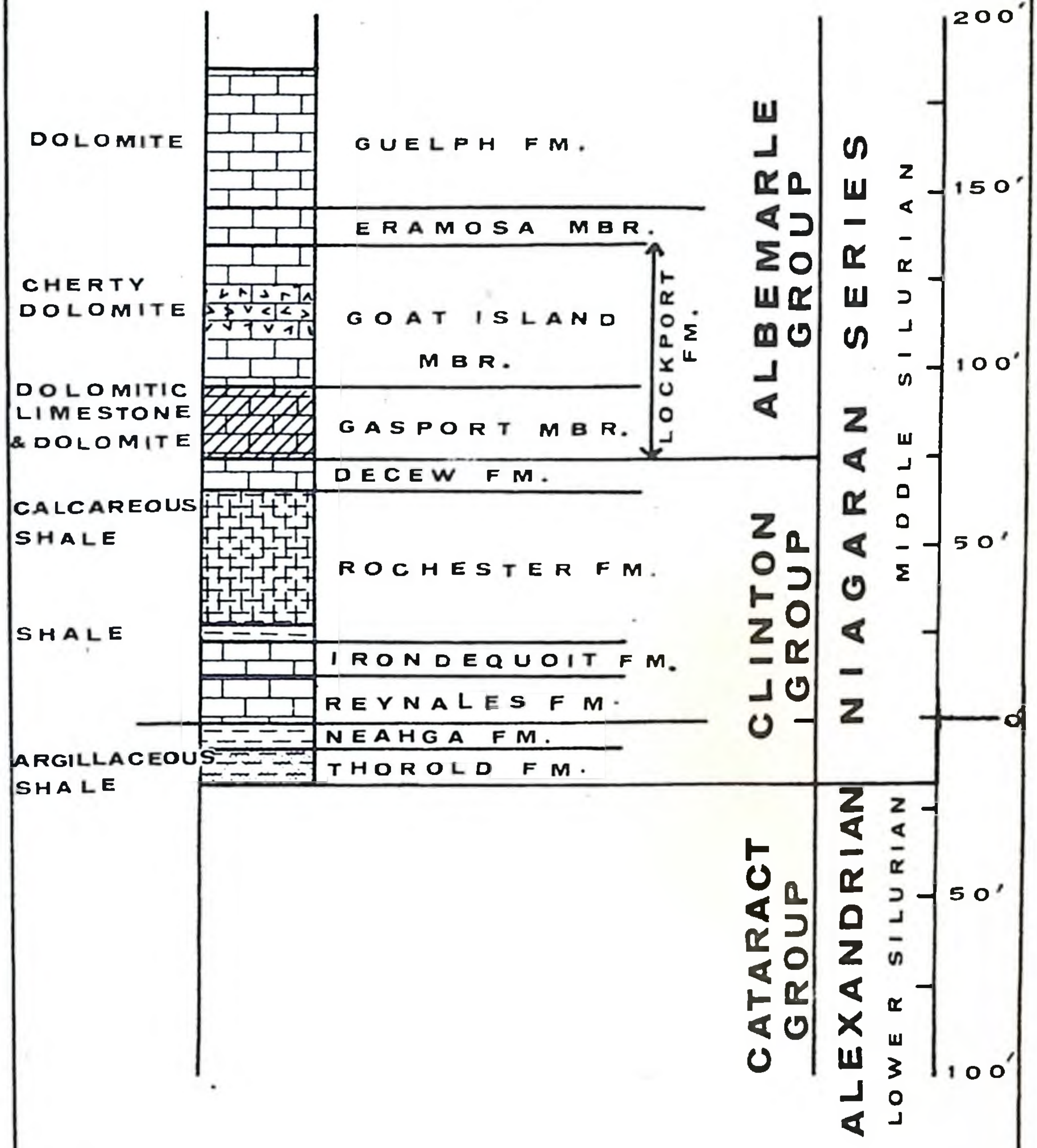


Figure 3

Solution widened joints extend down through the full thickness of the Gasport formation. Small pits and sub-parallel groovings are present in all carbonate rocks in the walls of the quarry, and in the naturally slumping cliff-face. However, the types and the general appearance of these pits and grooves vary with the lithology; this may be used to correlate rocks of a given zone.

At Burlington, the rocks at the surface are of later Lockport age, because rocks similar to those found at Beamsville underly them. This dolomite is darker and finer grained than the Gasport rocks, and contains more impurities and fossils. Its porosity and permeability are lower. The solutional forms are more extensive horizontally. Holes along bedding planes, developing into small blind cavities, are frequently seen, especially in vertical walls. Chemical weathering at the base of these rocks tends to create overhanging faces and slumping, aiding the retreat of the escarpment.

At Nelson Lookout similar features are developed in the Lockport. Lithologically these rocks differ from those of Burlington, being dark bluish-gray and ultrafine-grained. Some specimens seem quite porous, but have a very low permeability. The rocks are highly fossiliferous, with crinoid stems of snow-white recrystallized carbonate. These dolomites show little solution, where exposed.

Mount Nemo provides the same, or nearly the same situation, the rocks are being fossiliferous and almost impermeable. Glacial grooving and polishing is found.

At Dundas the Guelph dolomites are fine-grained and almost completely dolomitized. Dark brownish-gray and full of stylolites, their upper surface has been glacially polished, with young solutional pits and trenches being found under glacial till.

The topography

The Niagara Escarpment, stretching between the Niagara River and the tip of Bruce Peninsula is a geomorphic region in itself. Chapman and Putnam, (page 133) say that it is a simple escarpment with many small embayments and a few larger breaches. The relief ranges from 50 to over 1775 feet.

Its appearance suggests fluvial development, without glaciation. Strangely enough, little modification of the rock surfaces and some deposition of drift were left by the melting ice. In the Interglacial times however, deep valleys were cut through the Paleozoic rocks of the Niagara Escarpment. During the glacial stages, several depositional and denudational features were created, along many sections, the escarpment is largely or wholly buried by Wisconsin or earlier drift but elsewhere the drift has been elevated from the rock face and upper edge. It is here that karstic development has occurred or is best seen.

Chapter 2.

AN OUTLINE OF THE LITERATURE

Terminology

Lapies are structure-controlled, selective solutional or solution-erosional pits, groovings and trenches, developed in carbonate rocks which are deteriorating into rectangular blocks and ridges, with or without regolith cover. They may start at the surface, immediately below, or at a depth, developing upward or downward or both ways. There is a definite link between the formation of closed depressions, caves and lapies, the principal variables being the angles of joints and bedding planes, which are being widened by solution, and the depth at which the process is in progress.

The terms "lapies", "cutters" and "karren" have the same meaning, and are all structure-oriented, at different depths, whether or not they are influenced by slope inclination or bedding plane inclination.

Historically speaking the various alternatively positive and negative features, their origin and relation to larger features (dolines and caverns) have long been a challenge to geologists and geographers. Many still-helpful suggestions were made by scholars a hundred or more years ago, although the methods they used would be considered rather primitive in our days.

During the past century, the problem of karstification has been seen to be of great complexity, and the tendency toward detailed field and laboratory work has greatly increased.

Rose (1835) pointed to the relation between carbonate solubility and carbonic acid. He experimented with the calcite-aragonite system and tested the effects of temperature and impurities in solution on the amount of $CaCO_3$ and CO_2 precipitation. He also tried to establish the influence of trace elements (strontium, barium and lead) in solution.

Mojsisovich (1880) stressed structural control of karren and dolines, particularly the importance of regional faulting.

Kraus (1887) worked in the same manner as Mojsisovich, stating that very small joints may localise solutional enlargements, and that the deepening is greater or steeper slopes. He also recognised the modifying action of lithology, vegetation cover, and rate of surface erosion.

Heim (1877) recognized that different types of lapies may be formed side-by-side, and concluded that this is due variations of lithology, structure and plant life.

Eckert (1895) pointed to the importance of grain size and mineral components of rocks involved, and of the biological factors and thin surfaces of impurities previously present in the strata. He also accepted the idea of structural control of the karst processes. Eckert was able to show lapies formation under an overburden. He also tried to prove the post-glacial origin of these features. His descriptive classification of lapies types was probably the basis of the later classification of Bögli (1951), who is presently working in the same area (Bisistal-Glattalp).

Sawicki (1909) thought that lithology, rock-structure, elevation above sea level, climate and the position of the watertable were determining factors in the presence of karstic erosion. His classification reflects the cyclic concept. In Youth, the grooves are shallow rills, which later will expose the structural clefts, or 'rinnen'; as soon as a part of the surface is reduced to the level of water table the stage of maturity is obtained. When most of the land is levelled, old age begins. With the return of drainage to the surface, more and more water was able to escape in the form of evaporation and the rate of erosion decreased.

In pure limestones the features are well developed, while increasing amounts of impurities result in premature deposition, clogging and watertable changes.

Tucan (1911) emphasized the influence of grain size and shape on solubility changes. He discovered that the water moves faster in the wider channels than in the narrow fractures, because of lower friction in the former case. A lesser amount of water causes lapies development, and faster flows caused caverns; these may, however, be interconnected.

Cvijic (1924) also accepted lapies as fluvial forms, and summarised their development in a geomorphic cycle.

1. In the youthful stage, the limestone surface is undulating. Flat-bottomed grooves with sharp divides develop sinuous courses along the topographic lows.

2. In the mature stage, the lapies are fully developed. The channels are three to four meters deep, with hollows and ridges.

3. In the final stage, the lapies are declining and the surface is greatly reduced. Insoluble residuals and clastic debris are accumulating; the features become covered by soil, with only a few low outcrops.

The channels and grooves interfluves were well described and appear to be similar to Bögli's Kleft karren, rinnen karren, and rillen karren in many respects.

Palmer (1927) applied the term to parallel, widely spaced grooves in other than carbonate rocks; these grooves are similar to rillen karren and are now called 'pseudo-lapies'.

Lindner (1930) studied lapies development in relation to the perennial snowline and to rock chemistry. He found maximum occurrence of lapies in the zone immediately below the snowline. The paucity of vegetation here was considered to give optimum conditions for their initiation. But he also showed lapies development decreasing with increasing dolomitization.

Lindner's contribution to geomorphology lies in the recognition of the importance of scientific detailed analysis, in addition to observations and descriptions.

Laudermilk & Woodford (1932). This work is a further classification and description of rillen-type lapies, found on boulders and pebbles in California, in areas of four to seven inches of rain-fall annually. The authors recognize: 1. Parallel sinuous grooves, 2. a deeper dendritic pattern, with sharp crests, 3. unorganized features without major orientation, 4. a composite type of the other three. They experimented with acid solutions and with air blowing, the latter representing the influence of the wind. They obtained nearly classical samples for the different types of solution, with the air movement tending to smooth out the crests. Pure, dense limestone was considered the material for best formation, the amount of rainfall being an influencing agent.

Duggely (1934) and Baier (1937) have found a link between solubility of limestone and the bacterial count in the crushed stone. They concluded that the higher the number of micro-organisms the greater the solubility of the carbonates, even when many of the bacteria did not use calcium in their metabolism. The amount of free carbon dioxide also showed a tendency to increase with the number of bacteria. This kind of study may have a place in the present day research, as the results are promising. Other factors should also be taken into account in the same time.

Adams & Swinnerton (1937) pointed to the importance of the partial pressure of CO_2 present in the atmosphere and in the soil air. The amount of .0003 (millibar) in the air presents a solubility of 63 ppm for $CaCO_3$, but as much as 400 ppm may be dissolved in waters of karst terraines. This would require .065 atmospheres partial pressure, which is provided from the soil air, and released by the vegetation. Different soils contain different amounts of carbonic acid, and the solubility of the rock below changes accordingly.

J.F. Smith Jr. & Albritton C.C. (1941) described solutional pits and furrows found on slopes of different inclinations, and established limiting angles.

Shallow circular to semi-circular pits (tinajitas) are located in greater number on 3° slopes than on any other inclination, but found up to 20° slope, in arid and semi-arid regions. Solutional facets, with etched walls and ponding tendency, had the same distribution, increasing in number with flatness of topography. Solution furrows, as described by Laudermilk and Woodford, required at least 20° inclination. These furrows, however, had a 'V'-shaped cross-section.

Zotov (1941) gave a short summary of field observations in New Zealand. Pits found along joints or isolated from them were greatly deepened where Rhizoids were growing and increasing the CO_2 in the soil fill. The enlargement of the pits was a linear function of the Rhizoid population. The process started only a few hundred years ago, when forests were destroyed. He estimated that complete decomposition of large boulders by this process would require only a few thousand years.

Bögli (1951). This author's ideas about karren morphology and the origin of the described types are perhaps the best accepted today. The major type of karren field is a flat terrain, found in areas of low dips, and termed flach-karren. It consists of older kluft karren and younger rinnen karren side by side, together with still younger grooves, pits and surface undulations.

The deep kluft karren superimposed on structural joints divide the outcrop into large blocks, which will disintegrate further by channels of rinnen karren of different ages. The latter often act as tributaries to the former, as they are shallower and commonly start developing at the steep faces of the solutional widened fractures.

The initial undulating rock surfaces, in which the channelling starts may develop under a soil or snow cover, but the prerequisite of true channels is rain-water action upon water-soluble rock.

Kluft karren and rinnen karren had been described earlier by several authors (using different terminology), but none had classified them to the same extent, in relation to the same processes, and in the light of so many influencing factors. Kluft karren and rinnen karren are fluvial forms, erosional and solutional in origin, with flat bottoms and rounded crests. Kluft karren are simple joint enlargements, while rinnen karren are developed from pits on inclined surfaces. The pits tend to join by enlargement, becoming trench-like channels of great sinuosity. The presence of humic soil is an important deepening agent, but rain-water is the most important corrosive element in karren formation, and the flat-bottomed features are attributed directly to rain-water concentration. Melt waters are faster agents, so that where both rain and snow melts are available, V-shaped incision is present in the middle of the flat floor. Full scale development of this type is present in some areas located in the shadow of cliffs. The grooves are deeper where the snow has the chance to stay almost throughout the year, and the channels smooth out and disappear as they run out to sunny places. Rinnen karren may sometimes form by oversteepening of the cliff face, creating bench- or bank-karren, which later become rinnen karren. There are several peculiar types also listed here, which are also essentially rinnen karren, but are named otherwise by Bögli.

All types are related to water movement in origin, although the author accepts that structure, vegetation, bacterial content, climate, porosity etc. are also important factors. He does not mention any measurements or analysis he has made. It must therefore be assumed that

Bögli either used the available data of others or simply codified the reasoning of previous workers.

Bögli finds definite proof of the microclimatic effects of lapies development at 2300 m elevations, where snow and melt water are available throughout the summer season. The rinnen karren here are fully developed, having the deepest portions in the areas of constant shadow, gradually shallowing toward the sunny sections and disappearing in the full sunlight. This related to greater evaporation in areas where the outcrop surfaces are subjected to constant exposure to sunlight.

The writer made an attempt to calculate the amount of limestone that has been carried away in solution, and estimated the ages of different karren types. He concluded that development took place during the last interglacial of the Pleistocene period.

During the course of the present research, Bögli's definitions were applied to features of the rocks of the Niagara Escarpment, and were found to be largely applicable.

Weyl (1958) calculated the penetration distance of water in pores of ideal geometry, in relation to saturation of the water with $CaCO_3$. Assuming laminar flow (pore diameter under 1 mm), 90% saturation requires a distance of $.572\ \bar{v}a^2/D$, where $\bar{v}$ is the average flow velocity of the solution, a is the capillary radius (circular) and D is the diffusion constant of the solute in solution, and is of the order of $2 \times 10^{-5}\ cm^2\ sec^{-1}$. The chemical decomposition of the pore walls may be a few times greater than the penetration distance, if free downward gravity movement is assumed. The rate of solution is limited by diffusion rather than by dissociation; therefore, the removal of rock will depend on the rate of transport only, in the case of calcite. It is fastest when solid-liquid-gas interfaces are in contemporaneous association. In the case of dolomite, the dissociation is probably most important.

Parry (1960) describes lapies developed in massive pure limestone in Yorkshire, England. The lapies are assumed to be post-Pleistocene in age. The joint system here is parallel to faulting and widened by solution. The area has disintegrated into flat-topped blocks, which he calls "clints", separated by widened fissures, "grikes". Lapies developed on the interfluves have dendritic pattern on slopes of 12°-15°. He assumes the necessity of snow for development, and places the process in a cold periglacial climate.

Howard (1963) states that joint enlargements or 'cutters' should not be termed lapies. "Cutters" develop only under a soil cover, whilst lapies develop on bare rock surfaces, often on the "pinnacles" remaining between cutters. Cutters prefer pure limestone and may have such extent that they constitute the major karst-forms in some areas. They may cut into rocks of 45° dip and yet remain vertical, not being influenced by bedding or oblique joints.

Cutters are equilibrium features, according to Howard. He does not accept the applicability of the cyclic concept to their development, although he admits that sometimes they appear to be of cyclic origin.

Monroe (1964) describes parallel karst trenches in Puerto Rico. They are distinguished from cutters and called "Zanjones". They develop in thin bedded limestone, being terminated by underlying massive beds. The trenches run up valley sides, over ridges and across valley floors - being unrelated to slopes. The blocks between Zanjones are unjointed, while the trenches themselves are open joints.

Fellows (1965) described dendritic-patterned cutters, draining into major widened joints, as being dominant in the area, and caused by lateral movement of water toward the deeper channels. They are possibly joint controlled. They may result in the formation of sinks, if water transport is faster than the accumulation of residues.

Chapter 3.

STRUCTURAL AND TOPOGRAPHICAL CONTROL OF LAPIES

Joint fractures present in water-soluble rocks play a very important role in karstification, serving as localizers and as routes of penetrating and flowing waters. The nature of joint development should be clearly understood when karst study is undertaken.

The Origin of Fractures has long been under investigation. It is now proven that faulting and folding produce stress which may find release in fractures. The number, size and orientation of joints in a given area of equal stress conditions is greatly influenced by the lithology and the local topography (e.g. slope inclination). Dealing with competent limestone in a syncline there is a local compression with the direction perpendicular to the fold axis. In an anticline, the direction of the smallest stress would be that of the local tensional stress in the outer arch, which is perpendicular to the fold axis. The median stress is located in the highest folded layers. The result in either case is a set of shear joints at an acute angle, which is bisected by the largest stress direction. The orientation will differ with the fold axis direction. The angle between two components of shear fractures is very small (20°) and is intersected by the main stress direction. Tension joints may develop perpendicular to the main stress direction as an elastic compressional release or may be parallel to the compressional stress. The intervening angle between two sets of tension joints is from 15° - 80° (Parker, 1942). Therefore, shear and tension sets cannot always be differentiated by intersept angles alone. Where folding or other deformation is very slight, (as it is along the local Niagara Escarpment), the interpretation of joint systems may be difficult and controversial. Data other than bearing and frequency are an aid.

In the sample areas, the following types may be recognized:

<u>either</u> 1. Three sets of tension joints, one of them parallel with the regional dip.

<u>or</u> 1. Tension joints parallel with the regional dip.

2. Two sets of shear joints forming an acute angle with the deduced principal stress direction and further differentiated from 1 above by the greater straightness of sidewall and greater depth of kluft karren developed on them.

<u>plus</u> 3. release tension joints at right angles to main tensional set; 4. gravitational joints due to lateral pressure release at the vertical face of the escarpment.

Interesting and very valuable studies have been carried out by Harris, Taylor and Walper, on the relationships of fracture frequency to lithology and topography. The fracture density was found to be inversely proportional to the thickness of a given rock unit with constant lithology. When dealing with different rocks the number of fractures per unit area of rock of constant thickness, gives the lithological datum. Once this is established, isofracture maps may be constructed, which may be very valuable in karst geomorphology for relating fracture frequency with types of solutional forms.

In the Beamsville area, three well-developed, and one poorly-developed fracture sets have been recognized and mapped (Figure 2). This fracture-pattern map clearly shows the orientation of the representatives. The main set, indicated by I on the map is parallel to the general direction of dip of the bedding, i.e. toward the south-west, where the centre of the syncline lies (Michigan Basin). Ragged and sinuous, grading or breaching into other sets, it is limited to one stratigraphic or lithologic unit. These are tension joints, parallel to the greatest stress direction. Complicating the picture is the shearing superimposed on these tension joints, which is due to the present topography and related to gravitational slumping along the vertical cliff face which coincides with the tension joints. The right-angled components of these movements are also present but are not always readily recognized in the field. The slumping at this locality may be related to a small structure or depositional break which causes reversed dips, i.e. toward the north-east. The underlying soft, fragile, shales also aid in the process of fracturing by providing a plastic base (Caley, 1940).

A strike-length-frequency diagram (Figure 4) constructed from field data (Table 1-g) shows relationships between strike bearings and the longitudinal extension of fractures. The main direction, with a length of 892', is S 70°W, but those fractures trending from S 60°W to S 87°W may be parts of the same set.

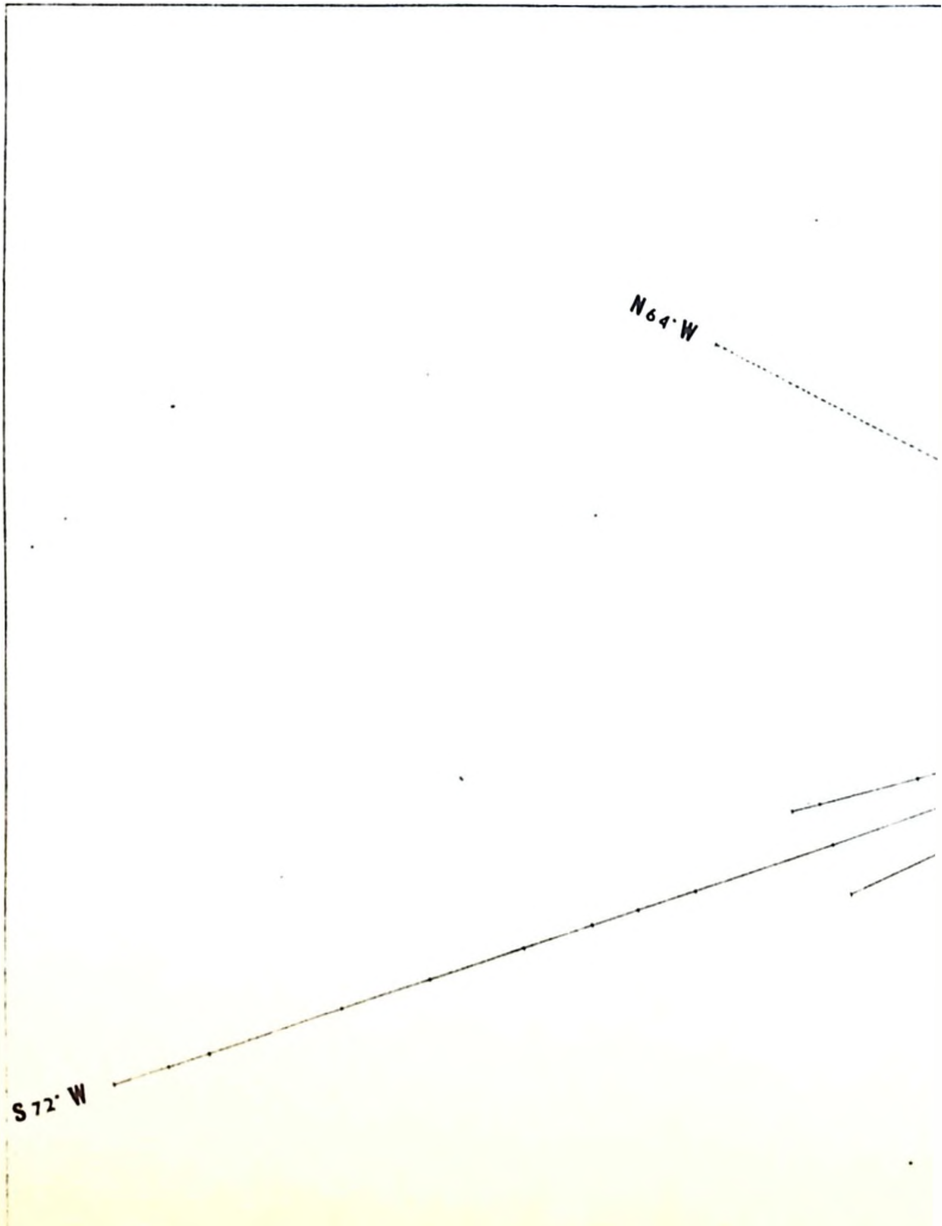
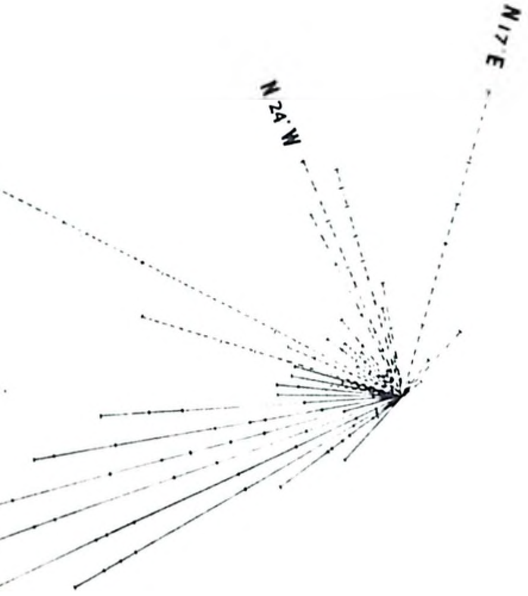


FIGURE 4



JOINT STRIKE-LENGTH FREQUENCY DIAGRAM

BEAMSVILLE ONTARIO

SET I
SET II
SET III
SET IV

Set II makes a right angle with set I and is probably due to tension release after the stress ceased. This is the most poorly developed set of the four.

Sets III and Iv are shear joints of type described above, the former being the better developed set with little deviation in the strike direction. There are only a few short fractures having intermediate bearings between set I and set II. The main direction of set III lies between N 73° W to N 64° W, with a sum of lengths of 479'. Members of this system are different in appearence from those of set I or II, having very straight and much deeper courses.

Set IV is perpendicular to set III and less developed, but both are continuous between parallel pairs of the main set (I), which thay display a pattern of repetitional geometry. For instance: as the srike direction changes in set I, from one trench to the next parallel trench, the bearings of set IV vary accordingly. This situation is apparent when the fracture pattern map and strike-length-frequency diagram are compeared. The fracture density and thickness ratios have not been calculated, but it was noted that fracture frequency greatly increases at the junctions of intermediate members of any one set. A narly radial pattern is formed, bearings of the fractures varying widely. (See Figure 5). This variability seems to be a result of rock decomposition, which has produced residual, inward-falling blocks.

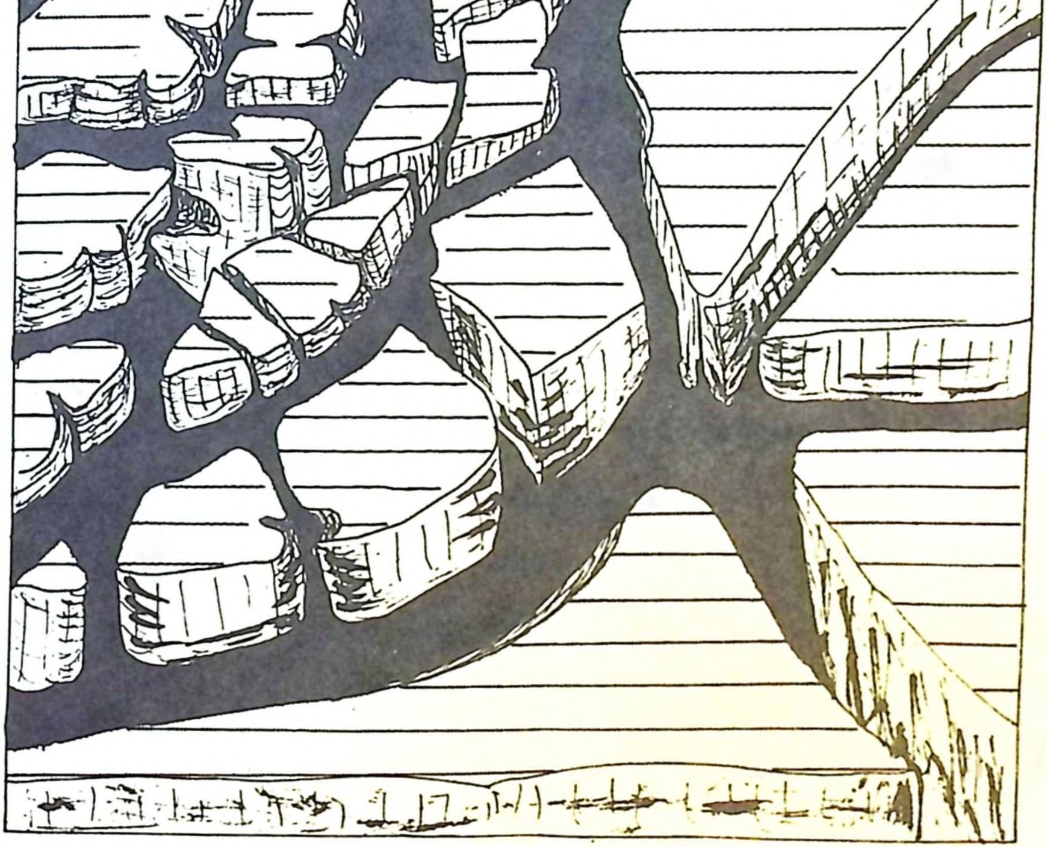
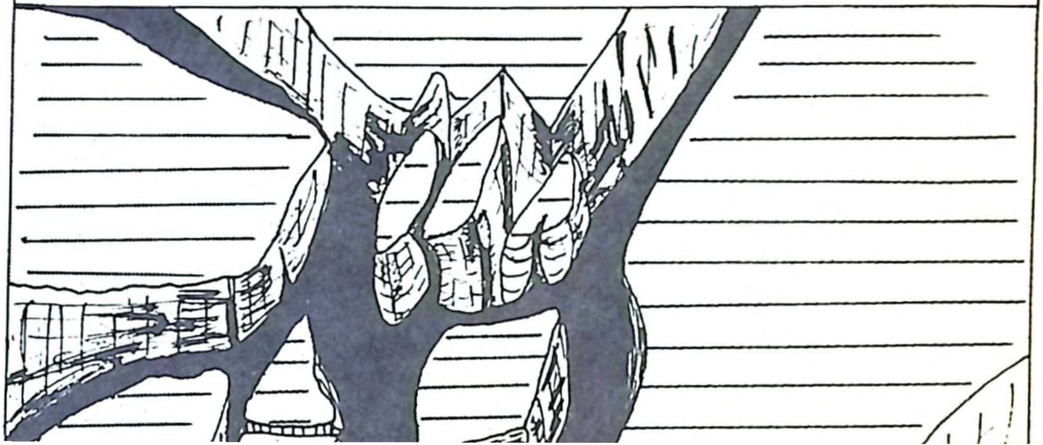


FIG. 5

DEPRESSION FORMATION
AT
INTERSECTION OF JOINTS



Such develop necessarily under a regolith cover according to many karst geomorphologists. But a situation like this might be at least partially due to the decrease of the thickness of a bed as solutional undermining proceeds. The new fractures may therefore be secondary in origin, and may be caused by the presence of pressure solutional planes (stylolites). The presence of soil may, of course, speed the process, but soil is not essential, as acid-producing bacteria might do the job at least as well.

At the site of Canada Crushed Stone Limited, Dundas, Ontario, joint-patterns of the same orientations as those described above, occur in the Guelph dolomites. The surveyed rock surface of about 2000 square yards contained all four of the fracture sets described and mapped at Beamsville, with about equal strike frequency and density for the same extent of surface. However, the Dundas joints have a different main strike direction. If bearings are projected to form a strike-length-frequency diagram and are superimposed on the similar diagram of the Beamsville location, it is easy to see that while the strikes of the different sets fall within the same range, the directions of the largest septa do not coincide for the two locations. The range of deviation for Beamsville is from S 61°W to S 80°W for set I, with S 72°W as the main strike direction. At Dundas the range is from N 61°E to N 80°E, with a major direction N 61°E. Since the strikes are reversed, the members of this latter set are merely extensions of the same system. The deviation of the main bearings is simply due to the local changes within the syncline or anticline in question. Sets II, III and IV, also showing the same relations between the two areas. Sets I and II are tension joints (with some doubt regarding set II), while sets III and IV are ~~shear-joints~~ similar to those found at Beamsville. The Dundas rocks are different in age and are of different lithology, being finer-grained, almost completely recrystallized, dolomites with many stylolites of varying orientations and sizes. They have low porosities and permeabilities. The vertical cliff face is also missing here, so that no considerable gravitational movement is present. The solutional alteration can therefore be more easily measured. Although not as striking to the eye as on the top of the escarpment, there is a large amount of rock missing, if both primary (pressure solution) and secondary processes are considered (Figure 7d).

At <u>Burlington</u>, only one trench-like open fracture was surveyed running parallel with the cliff face, just above the town dump. This is a very long and continuous, tension-type joint and is greatly influenced by the topography, expressed in gravitational slumping. It can be followed for a distance of 420'. The orientation of the greatest length is S 55°W (255'), but it ranges between S 20°W and S 55°W. The deviation between this and the main set at Beamsville is 17 degrees to the south, but the main strike direction at Burlington coincides with an intermediate fracture of set I of the Beamsville location. Traces of the other three sets are also present at Burlington, but cannot be followed for a good distance because of soil cover (see Photo 1,2 and 3). The effect of solution is evident in the trench-like tension joint and in the vertical wall of the escarpment, being more accentuated and richer in forms where the overburden is little or missing entirely. (See Table 9.)

Photo. 1/ Trench-lapies at Burlington

Photo. 2/ Joint enlargement by gravity movements, (Burlington).

To summarise, it seems evident that local tectonic and possibly regional orogenic movements have created the initial fracture patterns which are probably arranged according to synclinal fracturing processes. Local changes in topography, bed thickness and lithological factors have influenced the joint frequency. The karstic features superimposed on the fractures are not only localized by them but their shape and size are also dependent upon the structure.

Photo. 3/ Dolomite beds with clay (shale) interbeds (Burlington).

1965

Chapter 4.

LITHOLOGY AND LAPIES

The effects and importance of lithological factors in the processes of karstification are perhaps the most difficult to establish, since they have to be dealt with in great complexity. Lithological factors are: mineral components and their chemical relations, texture and micro-structure, initial and secondary porosity, permeability, dolomitization, etc.

Because lapies are superimposed on structural features which are dependent upon the rock's chemical and physical properties, a satisfactory investigation of lapies formation may not rely on field observations and on simple testing only. A large amount of often-tedious sampling, analyses and experiment is also necessary, in order to establish the complicated relations between lithology, rock structure, climate, biological factors, weathering and erosion.

Solubility of limestones

Chemical weathering of limestones and dolomites is for the greater part by solution in carbonic acid. Meteoric waters, when in contact with carbonate rocks, dissolve $CaCO_3$ soon after contact, but the amounts of $CaCO_3$ present in the waters of karst terrains is too large to be due to the atmospheric CO_2 alone. It must be assumed that waters passing through acid-rich soils or bacteria-filled pore-spaces becomes more active by picking up additional CO_2 and organic acids. The colder the water, the more CO_2 is dissolved in it, so that melt waters of firn fields would be expected to be the most destructive solutional agents of the carbonate rocks. However, there is greater chemical weathering in the tropics than in cooler regions because of greater soil CO_2, concentrations and larger amounts of organic acids. The lithology and structure of the limestone and the depth and length of percolation in fractures and pore spaces, are probably more important in controlling the rate of denudation by solution of carbonates. The different amounts of dissolved $CaCO_3$ found under the same climatic conditions seems to confirm the above statement. Weyl (1958), assumes solubility to be constant in time and space and discusses the problem in relation to rock porosity and the penetration distance of unsaturated fluid in the capillaries.

Calcite is dissolved in five steps:

1. Solution of $CaCO_3$.
2. Partial dissociation of the dissolved $CaCO_3$ into calcium and carbonate ions, $CaCO_3 \rightleftharpoons Ca^{++} + CO_3^{--}$.
3. Reaction between carbonate ions and dissolved carbon-dioxide will form bicarbonate ions in the following way.

   a) $CO_3^{--} + H^+ \rightleftharpoons HCO_3^-$,

   b) $H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$,

c) CO_2 (aq) + $H_2O \rightleftharpoons H_2CO_3$ - Carbonic acid

Or d) CO_3 (aq) + CO_2 (aq) + $H_2O \rightleftharpoons 2HCO_3^-$

4. At a gas liquid interface there may also occur:

For calcite -

$CaCo_3 + H_2CO_3 \rightleftharpoons Ca + 2\ HCO_3^-$

For dolomite -

$Ca\ Mg\ (CO_3)_2 + 2H_2CO_3 \rightleftharpoons Ca^{++} + Mg^{++} + 4HCO_3$

5. The last step is transport by diffusion and flow. The rate of solution is greatest when the first 4 steps are present contemporaneously, and may then be expressed as the rate of transport.

For calcite the rate of solution is not limited by the rate of dissociation at the solid-liquid interface, although this is not true for dolomite.

In a porous material the same is true, but the rate of solution increases with the flow velocity, until saturation is reached, after which further velocity increase will not cause more solution. A change in the temperature or CO_2 content would of course change the situation. The fluid in a capillary or fracture moves by laminar flow until the capillary radius becomes 1mm, when turbulence sets in. To obtain a penetration distance of 1cm, the radius must be $.73 \times 10^{-8}$ cm/cos θ.

No penetration exists from .02 mm capillary, while .25 mm size allows penetration for one meter. At 1 mm radius the penetration distance is .5 km. The penetration distance is independent of the rock and depends only upon the size of the capillary and flow velocity.

When the solubility of rock specimens is studied a direct connection between porosity, permeability, macro and micro-structure and texture is relatively easily seen, even by the naked eye. It is therefore desirable to investigate the relationships between these and the superimposed features first.

Porosity and Permeability

Definition: Porosity is the volume percentage of pore spaces, enclosed between mineral grains of the rock (R.M. Garrels, A Textbook of Geology, 1951).

Porosity is influenced by several factors: e.g. grain size distribution, presence or absence of cement material, uniformity of crystals in shape, etc. Perfectly round grains of equal size with open pore spaces would have a porosity of approximately 48%. The volume of a sphere may be expressed by the formula:

$$Vs = \frac{\pi}{6} \text{diameter}^3$$

If each grain be placed in a circumscribed cube of Vc diameter^3, their ratio would be:

$$\frac{Vs}{Vc} = \frac{\frac{\pi}{6}\text{diameter}^3}{\text{diameter}^3} = \frac{3.14}{6} = 0.52$$

therefore, each sphere would have half the volume of such a cube and slightly less than half the space would be made up by openings. The porosity would not be affected by the size of the spheres.

In nature, of course, such idealized behaviour is not found. However, the more uniform are the grains, the closer are the porosity values to the ideal situation. A rock made up of grains of different sizes will gradually have lower porosities, as the finer grains are likely to fill the spaces between the larger grains. The lowest porosities are measured in rocks in which the grains are interlocking. The average rock porosity in outcrops is about 10%.

The following formula has been used to calculate the volume percent of voids enclosed between minerals of 25 carbonate rock specimens, collected on the Niagara Escarpment at the four sample sites:

$$Pt = \frac{Vt-Vm}{Vt} \times 100 = 1 - \frac{Vm}{Vt} \quad \%$$

where Pt is the total porosity, Vt is the total volume of the rock sample, and Vm is the volume of the minerals in the sample.

To obtain the necessary data, two pycnometers were constructed from measuring cylinders:

1. for measurement of total volume: a 40 ml mercury-filled cylinder was equipped, fitted with a perforated stopper. Three nails fixed in the stopper held down the sample in the mercury.

The calculation was:

$$Vt = \frac{Hg_o}{D\ Hg} = \frac{WHg- \quad Sw\ Pw\ Hg- \ (Pw+Sw)}{DHg}$$

Where Vt = total volume, Hg_o is the weight of overflowed mercury, SwPwHg is the weight of pycnometer with mercury and sample, Pw is the weight of pycnometer, Sw is the weight of the sample, and DHg is the density of the mercury. WHg is the total weight of mercury, and Sw Pw Hg - (Pw + Sw) is the weight of mercury after overflow.

Another pycnometer was needed in order to make the Vm values calculable. The measuring cylinder was equipped with a special glass stopper that had a tubulas central continuation, to allow the overflow of fluid during operation. The weighed dry pycnometer was filled with boiled distilled water at 21°C. to the calibration mark, and was weighed again. A powdered sample of the same weight as that used in the total volume determination, was placed in the emptied and dried pycnometer, which was then filled with water to mark, and weighed. The volume of the grains was then calculated in the same manner as the Vt values:

$$Vm = \frac{Wo}{Dw} = \frac{Ww - Sp\ Wp - (p - s_p)}{Dw}$$

Where Vm is the volume of grains, Wo is the weight of overflowed water, Dw is the specific weight of water at 21°C, Ww is the weight of total water, Sp Wp is the weight of the sample, water and pycnometer, after the water overflowed, p is the weight of the pycnometer and sp is the weight of the powdered sample.

Knowing the values of all Vt and Vm the porosities were calculated, and are listed in table 10. The relation between porosity and solubility of carbonates is obvious, but has some peculiar features. Rocks of higher pore space volumes are generally considered to be more susceptible to solutional weathering than are those with lower pore volumes. However, the best developed lapies formation is reported to be in low-porosity massive limestones (Bögli, 1951; Howard, 1963; etc.).

In the analyzed dolomites of the Niagara Escarpment, deeper and wider features developed in the high-porosity rocks than are found in the massive ones of the same mineral content. It seems to the writer that alternating higher- and lower-porosities in a rock tend to facilitate stylolitic recrystallization, and that changes in texture are more important than are the absolute values of the porosities. Higher- and lower-porosity zones within the same sample lead to the superimposition of higher- and lower-solubility features. Samples 14 and 15 are two adjacent zones of the same specimen separated by a minute stylolite. They have porosity values of 13% and 15% respectively, the more porous specimen housing a shallow, 1 cm deep groove. The zone of 13% porosity has developed a protruberance of width less than 1 cm. (These features are described in detail as reversing lapies in the next chapter.) Samples 13 and 12 came from a completely exposed boulder with pore-volume values of 25% for the protrusion and 26% for the groove. The channel is deeper in the latter sample and shallower in the former. (The latter sample was a protrusion on the boulder, indicating that higher absolute porosity does not always lead to a negative feature, although the higher porosity zone within a sample will have a groove formed in it.) Such protruberances left on an outcrop are due to the presence of larger stylolites, while the shallower grooves in the sides of the positive feature are related to smaller stylolitic planes. The porosity differences between the two is often as small as two percent (Figure 6).

Sample numbers 6 and 7 also represent a groove and protruberance topography with 8% porosity for the negative feature and 5% for the positive form. This 3% pore volume difference appears, however, to be much greater to the naked eye, as the surface openings of pores in the 8% section of the rock are much wider than in the 5% section. This fact does not in itself mean a great difference in the porosity, as the wider pores may be fewer in number and shorter in extension, than those with small cross-sections (Inter-crystalline porosity). The permeability, is, however, probably greater in the 8% zone, as the ground water moves in the zones of least friction. This kind of secondary permeability is also important in lapies formation in addition to that created by the fracturing of the rock.

The most important perhaps is the difference between porosity values of adjacent zones, the greater this difference is, the deeper the grooving, regardless of the absolute values of the porosities. For example: samples 6 and 7, with porosities 8% and 5% respectively, have grooves twice the depth of those of samples 8 and 9, which have porosities of 12% and 15% respectively.

31a

RELATIONSHIPS BETWEEN STYLOLITES, POROSITY AND REVERSING-LAPIES

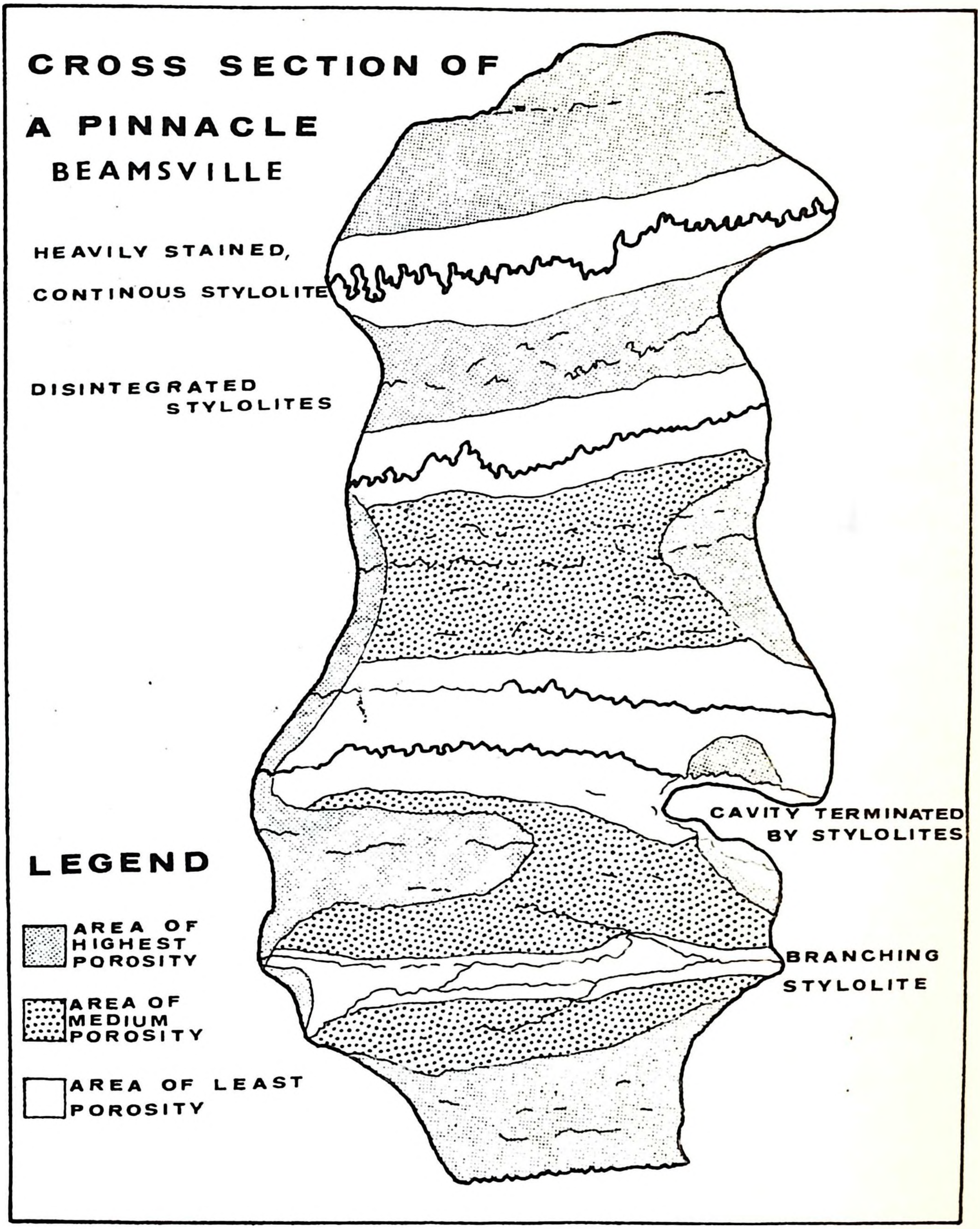


FIG.6 NATURAL SIZE

Samples 1 and 3 are from different parts of the uppermost 1 foot of the dolomite layer, with little visible porosity and alteration. This portion of the rock contains many short, but unaltered microstylolites, which seem to be the cause of overall lower porosity values. The immediate vicinity of a stylolite is usually of low porosity and permeability, and when stylolites are numerous in a relatively small space, the overall porosity may be lowered by their presence. There is also a strong probability that having an iron silicate coating on their surfaces may also increase the resistance to chemical weathering; e.g. in the case of sample number 1. Sample number 2 is from an area of deep weathering at the clay fill contact of a small cave, and shows 32 percent porosity. This indicates a great increment of weathering rim-formation under the effect of constant moist conditions. It also shows that karstification does not stop completely once clay residuals have filled a solutional cavity. The weathering rim is thinner or missing where the rock is now exposed bare, regardless of the texture and mineralogy. This is due to its soft rotten texture being unable to withstand the effects of surface erosion.

Sample number 5 is apparently unaltered and its 4% porosity is related to recrystallization (dolomitization in this case). Samples 16, 17 and 18 are almost impervious with relatively high porosity values of the two latter cases (2, 20 and 11% respectively). While no grooving is present in these rocks, small cavity and pit formation is abundant in the two high porosity samples, which are often terminated by short stylolites.

Sample number 16 has developed grooves only one centimeter deep and a few centimeters long. They are almost perfectly parallel with one another. These features are superimposed on stylolites of vertical (to bedding) orientation. Rill-lapies are also present in number 16 on the slopes of glacial grooves.

Sample numbers 23, 24 and 25, almost impervious layers from Dundas, have porosities of 11, 12 and 11%, and are fine-grained rocks with closely-packed stylolites and micro-stylolites. All kinds of lapies-formation are present in them, but all of them are smaller in size than those developed in the highly porous and permeable samples elsewhere. These samples may lead one to presume that the speed of lapies-formation increases with increasing permeabilities, if porosity is also increasing at the same time. These are secondary porosities and permeabilities, due to the solutional process itself.

The relationship between internal structure and the changing volumes of pore spheres will be discussed with the textures.

The permeability, especially that of secondary origin, is highly important to the process of karstification as joint and bedding planes are natural routes of percolating and flowing waters within the carbonate rocks, ~~in addition to intercrystalline voids~~. Probably a much greater amount of material is removed due to high permeabilities than due to high porosities. The two are, however, well related, as increasing porosities generally are associated with increasing permeabilities. The porosity indicates the amount of water that the rock may hold when completely saturated. Permeability is expressed as the mean diameter^2, and is related to the mean size of voids, which in turn depends upon the grain size distribution. Increasing grain size, therefore, means increasing permeabilities, while this is not influencing the porosity values. In the carbonates the difference between porosity and permeability is not great however, as the solutionally enlarged pores and passages are all large enough for through penetration. These are secondary porosities, present only in near-surface and outcrop rocks.

The simplest way to measure permeabilities is to measure the amount of water of known hydrostatic pressure that flows through unit cross-sectional area of a rock in a given time interval, i.e. the rate of flow under standard pressure, differential, through unit length and cross section area (increased pressure increases the permeability of most rocks).

To obtain relative values of permeability for dolomites of the locations studied, one inch diameter cylinders were cut of ten typical specimens and drilled to half an inch depth, using a half-inch diameter hard steel drill. The cups were then filled with alizarin red (a calcite-staining fluid) and the time of through penetration was noted for each sample. The appearance of the stain on the sides and at the bottom afforded a measure not only of the permeabilities of the samples, but also indicated the preferred directions of penetration within the rocks. The following are the results obtained (Table 11).

The first two samples show deep solutional features, while the third is slightly grooved between stylolites. In samples 4 and 5 there is a peculiar type of lapies formation, in addition to deep trenches parallel to the vertical wall of the escarpment. It consists of parallel grooves of half an inch in depth and width, and a few inches in length. They are superimposed on small irregular stylolites, which are oriented perpendicular to the bedding planes. Sample number 5 also has joint-oriented rill-lapies development (described in the next chapter) on 15° ice grooved slopes (Photo. 23).

Sample numbers 6, 7 and 8 have developed solutional pits (bedding-lapies), small dolines (few feet wide and deep), and trench-lapies most of which may be attributed to the presence of joints and to the stylolites, and thus give rise to secondary permeability.

Sample number 9 with little permeability or porosity is a very dense rock, chemically not much different from the other samples, but having only slight solubility. Number 10 is almost impervious with relatively high porosity. Lapies development in this layer is very good, due to thin bedding and fracturing, and the presence of clay bands causes much lateral separation between the individual beds as they are less resistant to erosion than the surrounding rock.

Table 11 illustrates a wide range of initial permeabilities, which in some examples do not display the expected karstic features

But the samples represent only a small section of a great rock body and most measure initial permeabilities in only one orientation (vertical to bedding). Greater penetration may be possible along the bedding planes or along stylolites, e.g. samples 6 and 7. Generally when high permeability and high porosity coincide, the lapies development is faster but not very long lasting as overall decomposition of the rock is fast and collapse features will soon occur, e.g. at Beamsville and in the uppermost layers of the Dundas strata. The grain size distribution may also be important; a fine grained rock is of low permeability but not necessarily of low porosity. Solution in such rocks is restricted to the surface until larger pores are opened. These increase the permeability.

Rock textures

Texture analyses were carried out on rock slabs and thin sections, and the following generalizations may be made for the Beamsville samples: all are medium to fine grained, buff-weathering and recrystallized to sugar-like textures for the greater part, with a few fossil moulds. The recrystallized material in voids and in fossil moulds is of bright, clear rhombohedral grains, coarser than those in the matrix. Dolomitization appears to be related to the presence of iron silicate and iron carbonate concentrated on the surfaces of stylolites. In some samples, dolomite rhombohedra replace the iron-stained material leaving only broken and fading remnants of stylolites with voids, shaped after the replaced stylolite.

The Beamsville texture type is well suited to the formation of small karstic features (reversing & double lapies). In a cross section this appears evident to the naked eye. Zones of alternating higher and lower porosities are attributed to a peculiar dolomitization process. Stylolites in the centre of a lower porosity section or a zone are heavily coated with a ferruginous material and are continuous. This zone projects to the surface as a protruberance, while the higher porosity zones have fading and disintegrating stylolites or iron speckles with groove development. Viewing the same specimen with a binocular microscope (Figures 7a and 7b), the crystal grains in the vicinity of the stylolites are more closelypacked and sometimes interlocking, while in the adjacent higher porosity zone they are loosely packed, and their shapes are rhombohedral or subhedral and then are of coarser size. The stylolitic columns here have almost disappeared, leaving pores oriented in their place.

The heavily coated stylolites often cut the faded portions of replaced features. This fact leads the author to believe that the continuous, more pronounced stylolites are younger than those that are disintegrated or completely recrystallized. The process is probably attacking the stylolites one by one, until the dolomitization is complete. Then a groove is formed in the place of a protruberance (reversing lapies). Stylolites formed after complete recrystallization may be left in one piece, or may split along the plane due to ground water action.

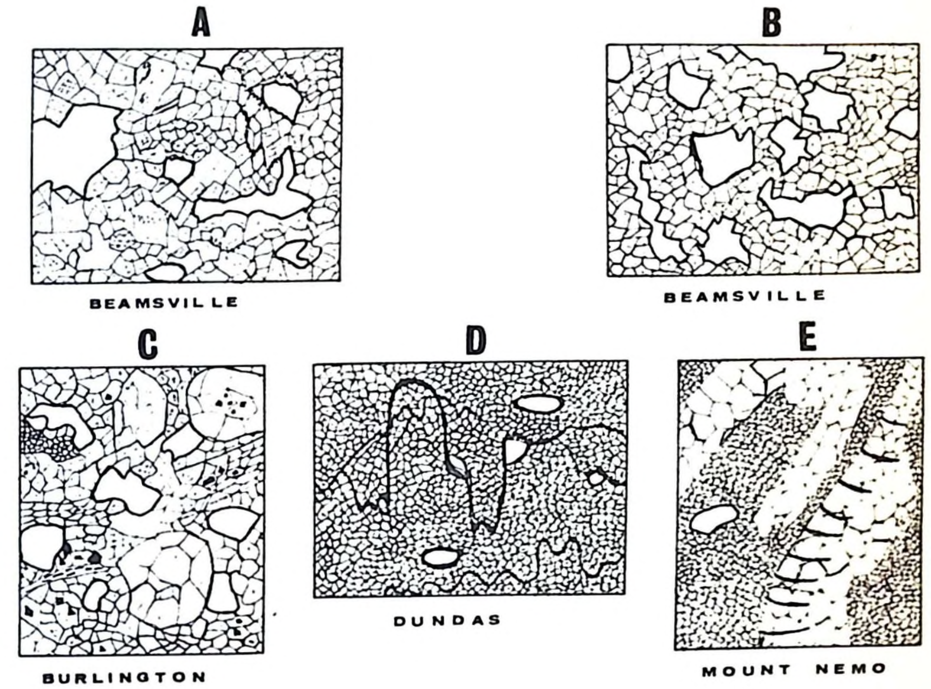
The initial orientation and size of stylolites becomes important when small features are described because the circulating waters within the rock may often have to change their routes, finding insoluble materials in the way on the surfaces of these features. While they are usually subparallel to the depositional bedding, stylolites may have just about any kind of orientation (even vertical), and may be curving or branching, cutting one-another, etc. The superimposed lapies may therefore display forms varying from thin plane ledges to neatly carved erratic sculptures (Photo. 22). When a great number of stylolites of varying sizes and orientation are present in carbonate rocks, richness of form may develop on the exposed surfaces.

In the section, the morphological relations seem less obvious, as it is impossible to bring a larger stylolite under the observing lens together with the karstic features. But the progress of dolomitization is revealed in the crystal shapes and freshness. Only a large number of such sections would prove what has been suggested. Figure 7a and 7b are of two most frequent texture types from the Beamsville rocks and Figure 7c is a Burlington sample in this section. Figure 7d is a typical Dundas specimen, with complete recrystallization, and unaffected stylolites, while Figure 7e is an example of dolomitization by fossil replacement in the Mount Nemo rocks.

Those Beamsville specimens that show the least surface weathering contain short, thinly-coated stylolites in great number, regularly distributed and oriented: they have lower porosities and are less permeable than are those with larger stylolites of varying orientation. This is because dolomitization along such minute features may not be possible in continuous and well-defined zones and the related intercrystalline porosity is therefore relatively evenly distributed: the differences are too small to appear on the surface as grooves. Very shallow pit-like depressions and minute cavities are often found in relation with micro-stylolites on surfaces of these rocks.

The Burlington rocks are also highly porous in general, but zoning (in varying layers of porosity) is not present in the same manner as in the Beamsville dolomites. In thin sections they appear to be less evenly grained and contain more impurities (possibly clay materials).

TEXTURE TYPES:



A BEAMSVILLE

B BEAMSVILLE

C BURLINGTON

D DUNDAS

E MOUNT NEMO

FIGURE 7.

Stylolites less frequent in the Burlington samples, undulating instead of the rod-like projections of Beamsville, so that a bumpy surface is exposed when the rock is split along them. This surface strongly resembles those limestone surfaces often found under a soil or snow cover, or on an exposed bedding plane which has been altered by solutional processes, and is described as the beginning of rinnen karren by Bögli (1951), and as bedding-lapies by the present writer (next chapter). The affected surfaces here are coated by iron-rich clayey materials.

In thin sections as well as in rock slabs, the Burlington outcrops display a variety of clay and/or shale layers interbedded with the dolomite layers (some of which might have been left by relatively even solution of stylolitic nature, while some are possibly depositional). Cavities, parallel or normal to bedding planes are superimposed on these clayey layers, with undulating roofs and floors (Photo. 3). The grain size is medium-fine (as in the Beamsville rocks), with rounded and interlocking calcite and anhedral to subhedral dolomite crystals, the latter being fine grained. Ferruginous material in fine grains or speckles is usually associated with recrystallization in lense-shaped patches. These are probably the cause of the small holes or pits with iron-stained coating, found in the vertical walls of the escarpment and in the walls of the trench-lapies.

The Mount Nemo specimens show fine grain size in thin section with a few vertical stylolites which split into tiny lapies on exposed surfaces. The exfoliation is greater in these massive rocks than in the highly porous ones.

At Dundas, the rocks are medium to fine, uniformly grained, with closely spaced stylolites and micro-stylolites, and much organic material. They are covered with glacial drift of 5 to 10 feet depth. In thin section, they contain anhedral to subhedral crystals and round voids with calcite rims, indicating selective void creation by solution of allochems, in this case, fossil remains. The solution and collapse-solution features here are due to the presence of stylolites and fractures, as elsewhere, but dolines in relation to secondary solution joints are most important, and develop upward and downward at right angles from stylolite surfaces. (Double-lapies, Figure 9.)

Relationships between Karstic Features and Rock Chemistry

The mineral components and solutional weathering have long been thought to be related (Eckert, 1895; Lindner, 1930, etc.). Alternating more or less pure limestone beds were thought to be the cause of differential rock-weathering, with the aid of continuous voids and fractures through which the solutions could enter and be transported. The most important impurities were said to be silica and clay materials (residual and depositional), the amounts of which were expressed in terms of limestone solubility. While this approach is still valid and useful, it is beginning to be obvious that structural elements, the internal texture, the processes of recrystallization (with the related porosities); zoning etc. are much more important than is the mineral composition of the whole rock. It is, however, vital to remember that certain minerals are associated with particular textures, just as crystal shapes are related to mineralizing processes, and that the packing of mineral grains will in-

DEVELOPMENT OF SECONDARY JOINTS IN ASSOCIATION WITH STYLOLITES

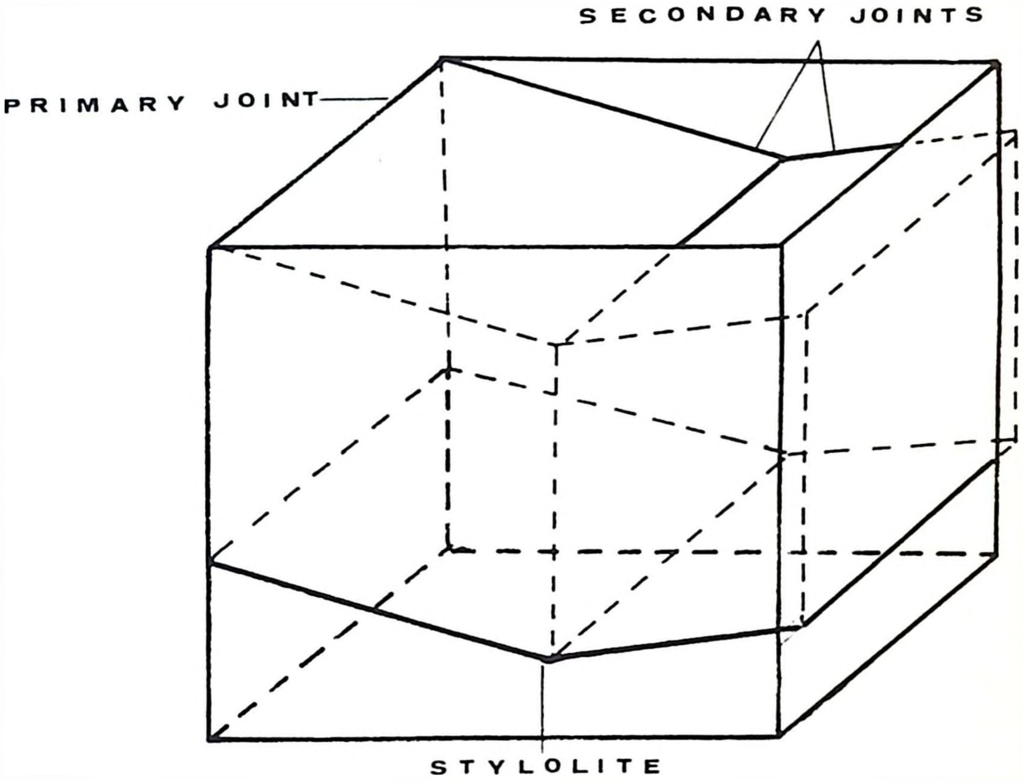


FIG.9

fluence the porosity and permeability. Better lapies may develop in high-purity rocks (deeper and wider), because the accumulation of residuals will not choke or slow down the feature development, and karstification may be a much longer-lasting process if the small amount of residuals are cleared away by waters moving in the fractures and along the bedding planes. The variation in the amounts of the mineral dolomite in the limestone or dolostone (dolomite) rock, is also believed to influence the degree of development and the frequency of lapies within a given area; the features being less well developed and more widely spaced with higher dolomite content. This is true of only those lapies which are not controlled by joints (some bedding lapies and rill-lapies). The changing amounts of dolomite mineral may have significant effect upon solubility if the rock is not dolomitized to a high degree, but the pure dolostones of the Niagara Escarpment (90% or higher dolomite content) create uniformity, as far as the variations of percentage dolomite are concerned. Alternating calcite and dolomite layers may have the same effect as alternating zones of higher and lower porosities have, however.

To reveal some of the relation between the physical and chemical parameters of the rocks, the same twenty-five samples which were used in porosity measurements, were subjected to chemical analyses, by the "rapid" method (Shapiro and Brannock, 1962). The results are listed in table 12.

It is immediately obvious that all samples are almost completely dolomitized, as the total amount of dolomite in each is about 90%, or greater. Table 13 illustrates the nomenclature of sedimentary calcite and dolomite carbonates.

Table 13

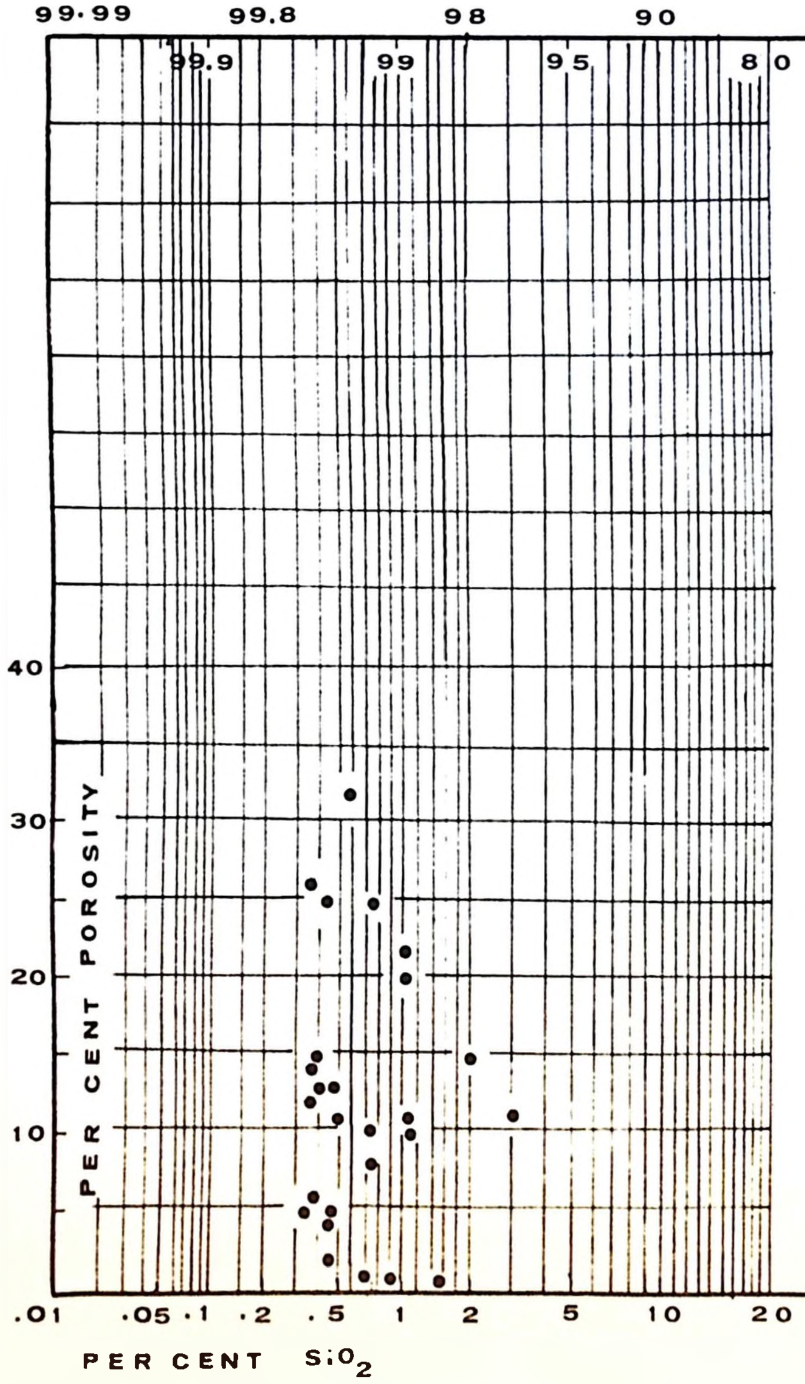
Type	Per Cent Dolomite	Approx. MgO Equivalent Per Cent	Approx. $MgCO_3$ Equivalent Per Cent
Limestone			
High-Calcium)	0-10	0- 1.1	0- 2.3
Magnesian)		1.1- 2.1	2.3- 4.4
Dolomitic limestone	10-50	2.1-10.8	4.4-22.7
Calcitic Dolomite	50-90	10.8-19.5	22.7-41.0
Dolomite	90-100	19.5-21.6	41.0-45.4

(After Pettijohn - Sedimentary Rocks)

The variation from one sample to the other is relatively little, as far as chemical composition is concerned.

Comparing variation of chemical content with variation of porosity of adjacent zones of a sample: zones of higher porosity were generally found to have a slightly higher content of dolomite and Fe_2O_3, than the surrounding areas of lower porosity, the latter being somewhat enriched in SiO_2 and CaO. In one sample, an enrichment of CaO together with lower SiO_2 content, was associated with deeper groovings than those developed on zones of higher percentage of dolomite and lower percentage of silica (e.g. numbers 6 and 7) from the same specimen, the grooved and protruding parts respectively).

The variation in the SiO_2 content may be related to zoning porosities and grooving (Figure 8). In every sample where the more and less resistant parts were separated for analysis, increase of silica is associated with a lesser amount of solution (see numbers 6 and 7, 8 and 9, 10 and 11, 12 and 13, and 14 and 15). Interestingly, the higher concentration of silica is always present in the zone of less porosity and finer grains, except for the voids caused by recrystallization on the stylolitic plane, which is the very centre of the same zone.



RELATION BETWEEN POROSITY AND SIO_2 CONTENT

FIG. 8

An increase in the total amounts of silica (or iron silicate) and dolomite may promote slight differences in weathering, as in samples 8 and 9. Generally, the depth of grooving is little influenced by the amounts of more or less soluble minerals.

Chapter 5.

THE GEOMORPHOLOGY OF LAPIES ON THE NIAGARA ESCARPMENT.

Lapies Types of the Sample Areas

The lapies found at the four studied sites are nearly same in appearence as the major kinds described by Bögli, but some of them are of different origin, and two previously undescribed types were also found. On the basis of appearence, origin, structural and lithological influences, the following classification is suggested:-

A. Forms located by tectonic or orogenic fractures or lithological features.

Larger Scale.

- 1) Trench-lapies (kluft karren, cutters).
  - a) Sinuous type
  - b) Straight-walled type
- 2) Bedding-lapies, (rinnen karren, dendritic cutters).
- 3) Rubble karren, (degraded form types 1 or 2).

Intermediate.

- 4) Double or subsequent lapies, (previously undescribed).

Smaller scale.

- 5) Simple groovings.
- 6) Reversing or inverting groovings, (subsequent to type 5 above-previously undescribed).

B. Forms created by high gradients on bare rock surfaces.

- 7) Rill-lapies, (rillen karren).

Features classified as 'larger scale' may also be represented at small scale. But any simple count of continuous features in a simple area would yield mean lengths of many feet and mean depths of greater than one foot. 'Smaller scale' features are, in the mean, substantially smaller than these dimensions and do not range so considerably in dimensions.

Trench-lapies are merely solutional enlargements of major joints. The sinuous type is developed along tension joints: the straight-walled type is associated with those joint sets considered to be of shear origin. Sinuous trench-lapies are usually wider and shallower than are the straight walled type, and contain greater numbers of subsiding features along their courses as well as in their vertical walls. There are intermediate types: Sinuous lapies are reworked by gravitational movements in the vicinity of the vertical faces of the escarpment. Because of this local factor, the two types are not always distinguishable, (see Photos. 4,5, 6, and 7).

In cross-section, the main difference between the two types is that the straight downward extention of sinuous trenches is limited to a single rock layer. When the underlying bedding plane is reached, the water may move laterally in until it finds another joint extending downwards. Such lapies therefore are sinuous in cross-section as well as on the plan, provided that the downward continuations are close together. Straight-walled lapies usually have a straight downward continuity through two or more rock layers and are also straight in plan view. (Photos. 8 and 9)

At Beamsville, the depths of trench-lapies were measured at several locations, (principally at intersections of joints), in order to establish the thicknesses of the surface layer. The resultant thickness-contour-map, (Figure 10), reveals one valuable fact: the thinning of the rock is greatest at the greatest concentration of joints. Some of these joints are due to the increasing solution and the thinning itself. It is, however also true that the depressed areas coincide with the intersection of

Photo. 4/ Typical trench-lapies (Beamsville).

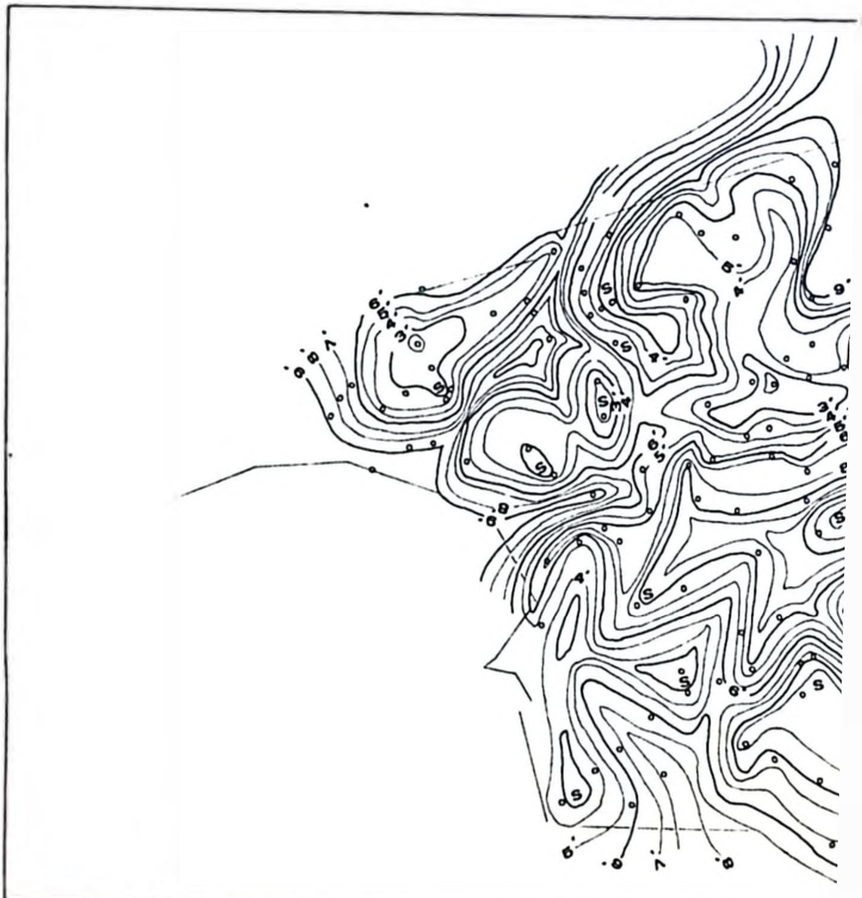
Photo. 5/ Trench and shear-lapies being reworked by gravity slumping (Beamsville).

Photo. 6/ Straight-lapies meeting an
intermediate type,
(Beamsville).

Photo. 7/ Deep crevasse along the
vertical cliff,
(Beamsville).

Photo. 8/ Straight walled trench-lapies (Beamsville).

Photo. 9/ Sinuous trench-lapies in cross-section, (Beamsville).



THICKNESS CONTOUR MAP
BEAMSVILLE

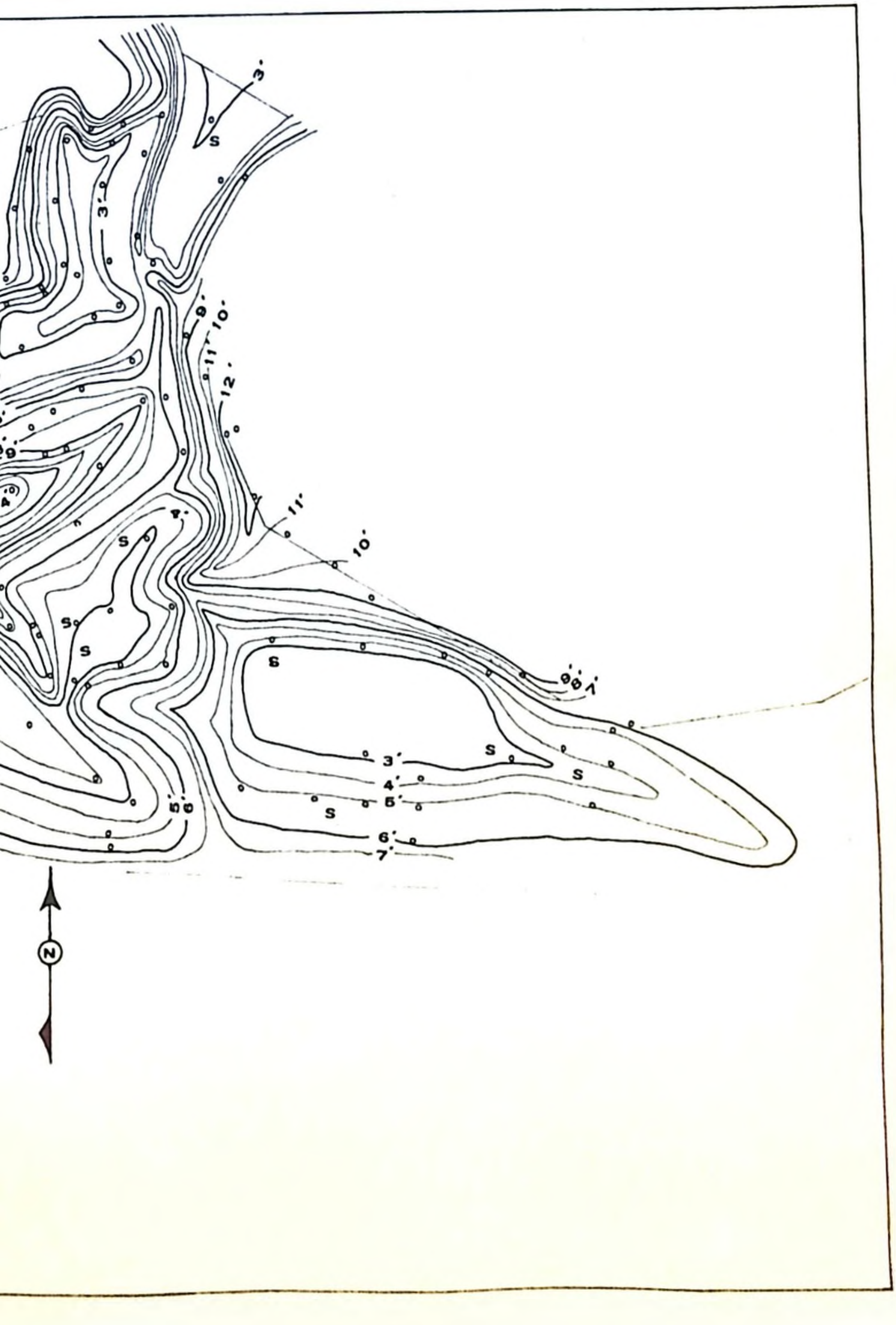
BASED ON LAPIES
DEPTHS

DRILL HOLE ...... ○
SINKING AREA .. S
CONTOURS .... ~3' 2'

CONTOUR INTERVAL
ONE FOOT

0' 30'
SCALE

FIGURE 10


3'
S
3'
9'
10'
11'
12'
9
4'
4'
S
11'
10'
S
S
S
9'
8'
7'
3'
S
S
4'
5'
S
6'
7'
5'
6'
N

the main joint systems, and also are localized by them. The secondary (gravity and solutional-fractures) make their own contributions to the speeding of the process involved. The most frequent lapies depth is 9' for the trench type, while the shear-types measure up to 25'. There are intermediates of various sizes, being transitional in appearance also, (i.e. in width, bearing and sinuosity).

Gravitational slumping contributes much to widening of the joints in the vicinity of the vertical slopes of the escarpment. This is most extensive at Beamsville, where the movements are due to a small fold in the carbonates over fragile shales, reversing the regional dips. Its effect is clearly visible within a 100' zone along the edges, and seems to diminish at approximately 300' back from the vertical face. The widths of the trenches vary with the sinuosity of the joints and with the distance from the face, but the latter is not well pronounced. Both the width and the depth of the channels increase at joint intersections. These points greatly resemble cave entrances and probably lead to small room-like cavities, (Photos. 10 and 10a) which by roof collapse also cause localized depressions. Photo. 11 is a minute natural bridge, left by the same process, found at the Burlington site.

Depressions may also be formed as a result of thinning of one or more layers by removal of low resistance shale interbeds, or by solution of the carbonate along joints and bedding planes of the various kinds described above. Figure 11 illustrates the step by step development of ~~shear and~~ trench-lapies to form such depressions and caves.

Photo. 10a/ Cavity formation at the intersection of enlarged joints. (Beamsville)

Photo. 10b/ Cavity formation at the intersection of enlarged joints. (Beamsville)

Photo. 11/ Minute natural bridge.
(Burlington)

DEVELOPMENT OF TRENCH-LAPIES

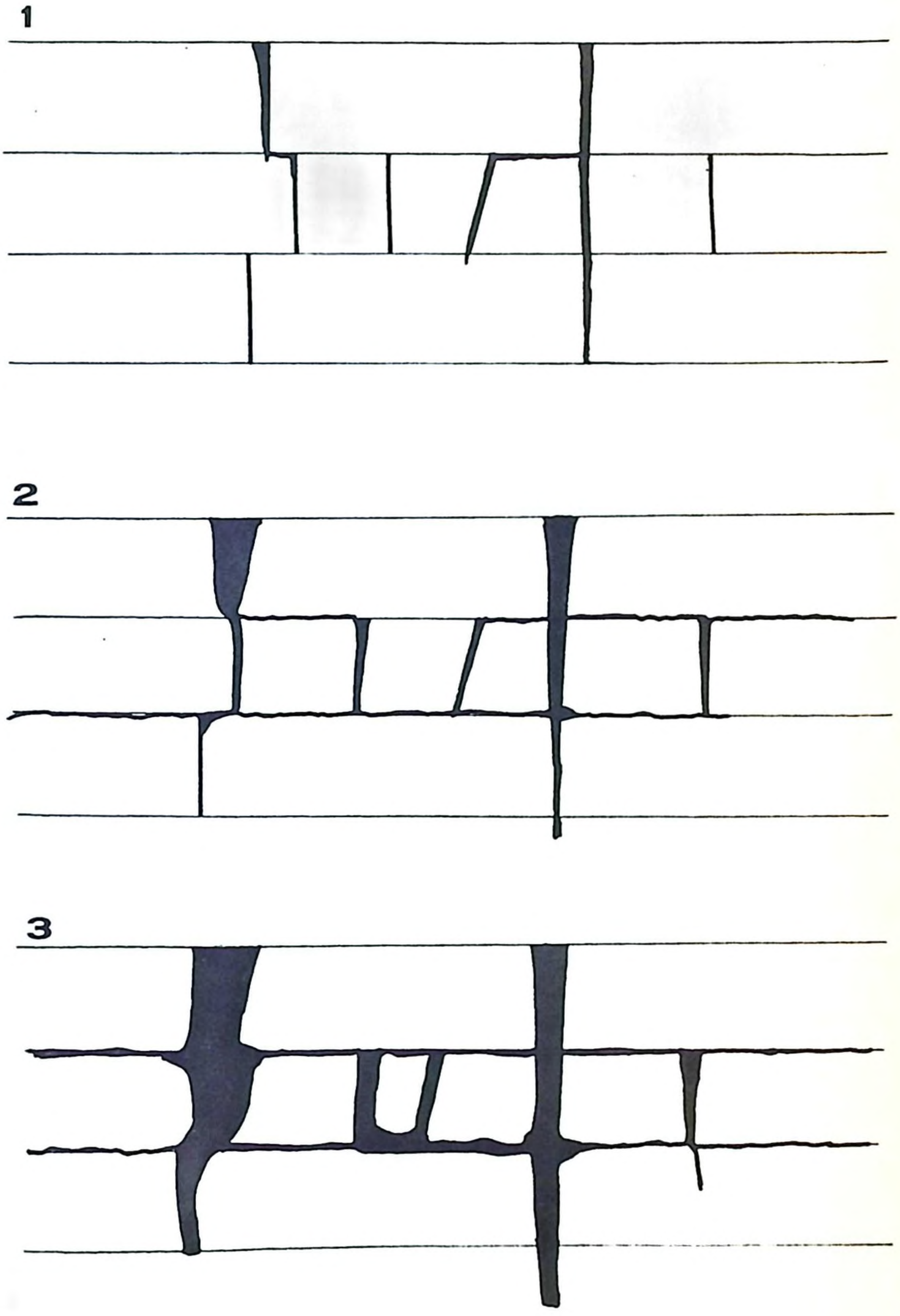


FIG. 11

Figure 12 is a theoretical illustration of joint enlargements in the underlying layers contemporaneously or non-contemporaneously, in a homogenous strata with the relative measurements of the amount of the missing rock from the lapies and from the caves in cross-section.

1. The water enters the rock through pores and enlarges a joint at 1.
2. The solution penetrates further between two beds and enlarges 1a and 1b.
3. The solution at 2 begins, the amount of water increases along the second bedding plane, and a cave may start to form. The development of 3 may be contemporaneous or non-contemporaneous, with 1, 1a and 1b.

Photo. 9 illustrates a situation, where the middle section of a trench-lapies is older than the upper. There seems to be a greater amount of solution along the joints than along the bedding planes, in general, as joints are the usual places of water entry and may be closer to acid sources. The insoluble materials deposited between beds may also hinder the solution processes. This kind of lapies development is similar to cave formation in more than one respect, and bears relationship to doline formation as well. Figure 1 illustrates the step by step growth of a channel-system which develops from lapies to caves, caves to lapies, as caves and lapies together may create surface depressions. (Photos.: 12a, b and c) represent evidences of the same.

Figure 13 (1) shows the beginning of solution in the walls of joints and at the intersections of bedding planes and joints. Figure 13

Photo. 12 a, b, c, Development of a triangular depression at the intersection of joints. (shear, tension, secondary joints and and rock removal along bedding planes, are all involved in the process. (Beamsville)

a

b

c

FIG.12

JOINT ENLARGEMENT IN
DIFFERENT LAYERS,
CONTEMPORANEOUSLY OR NON-CONTEMPORANEOUSLY

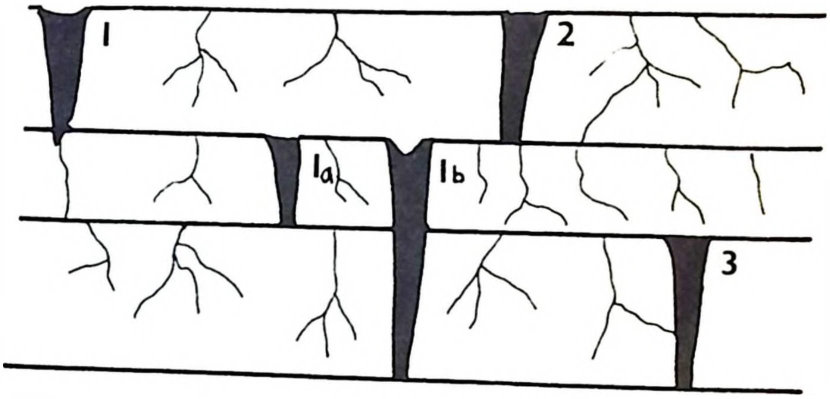


FIG.13
STEP-BY-STEP GROWTH OF A CHANNEL-SYSTEM
TO PRODUCE LAPIES, CAVES & DEPRESSIONS

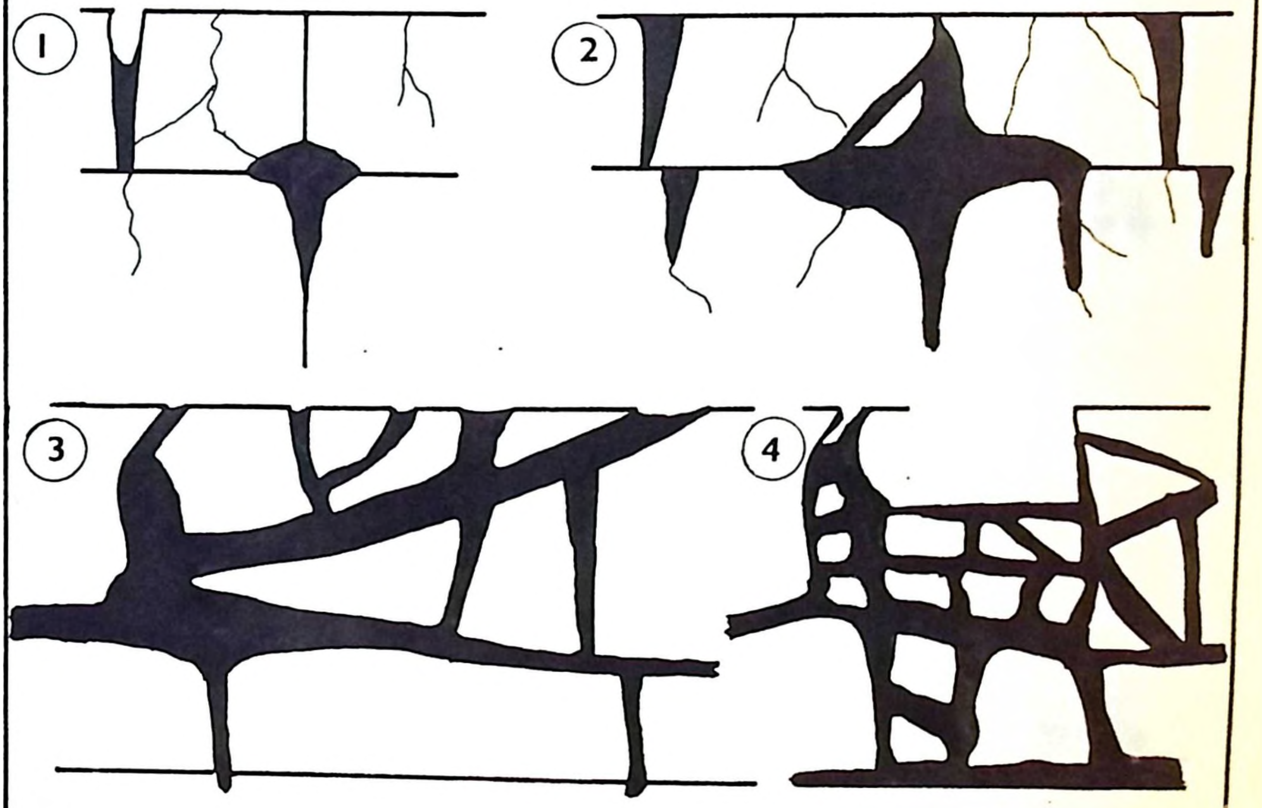
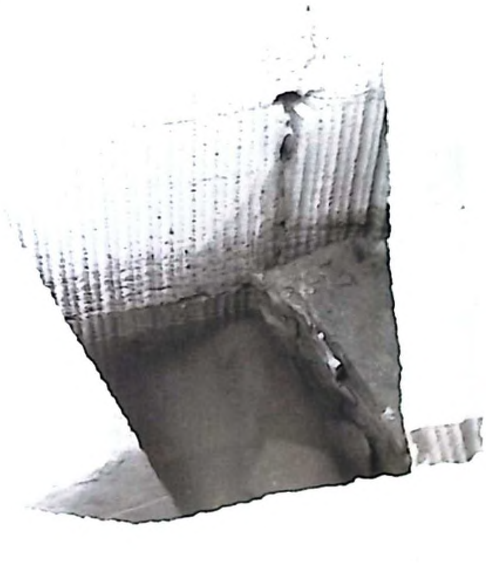


Photo. 13 a/ Illustration of rock removal along joints and bedding planes in an early stage. The depth is 12' from the topographic surface.
(Beamsville)

Photo. 13 b/ Cave formation in different levels in contemporaneous development.
(Beamsville)

1965

1965



(2) the number of trench-lapies increases on the surface, and caves are connected with the growing lapies. Figure 13 (3) the size and number of channels indicate a well developed stage. The outcropping and buried strata are being divided into large blocks and boulders, with very severe splitting where the beds become too thin to withstand the force of gravity. Finally, collapse will take place into the cavities, and dolines are formed. These dolines may continue to deepen further providing that the accumulation of residuals is not too fast to temporarily choke the downward movements of boulders. Solution itself may not be stopped at this point because the water still can circulate in enlarged pores and in the oxidizing zone (weathering rim) of the channel walls. The stage of development in Figure 13 (4) is obvious in the highly porous and permeable rocks of Beamsville and Burlington, with greater lateral erosion and faster undermining at the latter locality, because shale interbeds are present.

Bedding-lapies begin with pitting along a fracture, (usually a tension joint), following its curvings and branchings. They are circular or semi-circular, frequently with widening bottoms. They resemble jugs in cross-section and commonly become interconnected at the nearest bedding plane, after breaching the thin walls between the initially separate cavities. The water then penetrates freely along the plane, following very sinuous routes. The two layers of rock may be entirely separated from one-other by this process and yet show only pits on the surface. Collapse between pits will soon follow if accumulation of residuals is not enough to provide a support from below. Good examples of this kind of development were found at the Dundas site and at Beamsville. The pits were found on glacially polished surfaces at both locations where they had been revealed by recent removal of overburden (glacial till). (Photos.: 14a, b, c, and Photo. 15 were taken at Dundas and Photos.: 16a and 16 b at Beamsville).

It can be seen that the described pits when linked to form a continous channel may appear to be identical to trench-lapies and only cross-sections of the two would reveal the differences. When fully developed, bedding-lapies have wide bottoms with undulating floors which are usually iron stained. Trench-lapies show a gradual widening upward, invariably being narrower at the bottom than at the top, and are often V-shaped. However, some of these dissimilarities become destroyed by later erosion and gravity movements along the fracture planes, when distinction may be impossible, (Bögli, "Rubble Karren").

Some small round pits found at Dundas are not located on joints, but are terminated by the same bedding plane as the illustrated bedding-lapies and otherwise indentical to them. They show a peculiarity which remains unexplained i.e. regular scalloping in their walls all round in a continous circle. If their development started at the surface growing downwards like the other pits, they might also be the result of simple pore enlargements by solution in a highly porous zone within the lower porosity rock, (Photo. 17).

Bedding-lapies may also develop upon planes of intrastratal solution (stylolites), or upon a combination of these two types of bedding, one acting as a tributary to the other, with a knick point at the entry of a tribu-

Photo. 14 a/ b/ c/ Development of bedding-lapies from pits along joints. (Dundas)

c

b

a

Photo. 15/ Dendritic bedding-lapies.
(Dundas)

Photo. 16 a/ Bedding-lapies,
b/ (Beamsville).

b

a

Photo. 17/ Round, scalloped pit.
Dundas.

Photo. 18/ Dendritic bedding-lapies,
smoothened channels, after
the rock has become bare.
(West Virginia, U. S. A.)

Photo. 19/ Secondary (solutional) joints, Right angled to stylolite surfaces. (Dundas)

tary to the main channel. There might be several knick points along a lengthy system after the pits have disappeared, with each stylolitic plane representing one step. If the rock has become bare (or was initially bare) the sides and bottoms of these dendritic systems may be smoothed to develop U-shaped cross-sections. In this stage, it is easy to discriminate between bedding-and trench-lapies. (Photo. 18).

Both types of bedding-lapies may be forerunners of surface depressions which are completed by simple enlargement. This applies especially when the rock contains many joints (short and long) of varying orientations, in an unstable area. The instability itself may sometimes be due to solutional undermining at the bottoms of vertical walls of the escarpment. Another factor is the occasional presence of relatively widely-spaced (~1 foot apart) stylolites, which cause sets of secondary joints to form. These sets are oriented at right angles to one another and to the planes of stylolites if stylolites are parallel to one another. If the stylolites are however, developed along oblique and transverse planes, they will still create 90 degree joints with their planes, but then they will not be right angled to one another on the surface. Such joint development is due to solution of the iron-bearing minerals deposited on the stylolites by previous pressure-solution processes. Small hollows replace first the tooth-like projections, which have lost their protective ferrugineous coating; these cavities tend to enlarge vertically up and down into those portions of the rock which, to this time, appear to be unaffected by solution. Enlargement continues until another stylolitic plane, or the top surface of the rock, is reached. At this point the rock becomes to be divided into nearly cube-shaped boulders of characteristic sizes, which are likely to fall towards the center of the depression, leaving constantly-widening elongate dolines (of small sizes) in the line of tectonic joints. These dolines, once interconnected may then form rough, sinuous trench-lapies, with a tendency to collapse at intersections of joints forming dolines several times larger. Examples of this kind are abundant at the Dundas site. Photos.: 20a and b illustrate the situation.

Double-lapies (subsequent- lapies) are of a peculiar type, as far as origin is concerned. They are superimposed on the secondary solutional joints associated with stylolite surfaces. The stylolite surfaces themselves have cross-sections like those of lapies in the early stages of pitting and undulations, and are said to be analogous features, (Propcovich 1952). The secondary joint development from such surfaces has been described above. The double-lapies may resemble bedding-lapies (rinnen karren) with V-shaped or broad flat bottoms and rounded divides. Some may be oriented at right angles to one another (if stylolites are normal to bedding planes); others vary with the orientation of stylolites. Branching stylolites may even produce radiocentric double-lapies with a central depression. (Photo. 21a & b). Double lapies are frequent on boulders that have been exposed for a long time and in the vertical walls of the escarpment. They are usually a few centimeters in width and depth, but at the extremes, range from the microscopic to several meters. The relationship between bedding-and double lapies is obvious: the water in each may use the course of the other at advanced stages of development, and each may become tributary to the other. Stylolite surfaces may also act as bedding planes.

Photo. 20 a/ Doline development due to solutional
b/ joints, (Dundas)

a

b

Photo. 21a/ Secondary joints in a boulder. (Beamsville)

Photo. 21b/ Double-lapies (superimposed on secondary joints of the same boulder.)


1 2 3 4 5 6 7 8 9 10 11

terminating pits that will eventually develop into bedding-lapies. Double-lapies are, however, different in origin from any other prevously described types and truly deserve the term "double".

Simple groovings are shallow trenches dissolved along the higher porosity zone between two stylolite surfaces by organic acid concentration, due to moss and bacteria. They are very common features indeed and appear to vary in detail with the microclimate of pores, vegetational characteristics and lithology. Moss is always present in the groovings unless they have been buried by soil after formation. With burial the forms tend to smooth out. More raw humus is present in the grooves than on the "pinnacles". Figure 6 is a cross-section of the alternating grooves and "pinnacles " formed in the sides of a larger structural-solutional "Pinnacle" left between two trench-lapies, at their intersection.

Reversing-lapies or groovings. It is very interesting that the arrangement of grooves and pinnacles" may reverse themselves in an advanced stage of development. The stylolites may split along their planes, gradually permitting solution in the deeper regions of the stylolitic seam, the organic acids and the CO_2-charged water dissolving the limonite coating left by intrastratal solution, exposing the carbonates to fast destruction. The result is a complete reversal of the form, with grooves or widened joints repleacing the pinnacles and the previously recessed sections developed into flat-topped protrusions. Reversal is very frequent on rock surfaces that are exposed to the sun and wind. They have a minimum of vegetation cover. Another criterion appears to be the size of the rod-like projections and lateral extensions of the stylolites. The micro-features would probably help the process of exfoliation without creating any solutional-grooves and the over-all resistance to chemical weathering would be lowered if the micro-stylolites were relatively evenly distributed throughout a rock layer. This would lower the porosity and permeability. This is the situation in the uppermost portion of the surface bed at the Beamsville location. The edges and corners of the separated blocks and boulders are rounded, with a slight amount of pitting between minute, short and shallow micro-stylolites.

Reversing lapies and all other features related to the presence of stylolites in the rock are greatly influenced by the angle of inclination of the stylolite to the topographic surface and to one another. If the stylolites are disrupted by dislocation of a boulder or tectonic movements, the course of water in the rock will change accordingly. Where the rearrangement is as great at 90° after the solutional processes have started, cavities will form at right angles to the previous groovings, breaching the planes of the stylolites, and enlarging in the direction of the layers of greater porosity (between stylolites). Thus, the cross-section of the cavities will be essentially the same as that of the reversing-lapies, with a 90° turn. (Photo 22). In the same time the smoothing out process of previous grooving will start to disappear. The processes of form reversing is discussed with the textures, and believed to be due to recrystallization along stylolites, by replacement of iron bearing minerals and calcite, - by dolomite.

When inter-stylolite planes become vertically oriented, the water can enter from the upper surface, as well as from the sides of the fracture wall, soaking the whole block at once like a sponge. Water entering through

Photo.22/ Cavity development in an erratic boulder, which were dislocated from the original position by 90°.

Photo. 23/ Structure contraolled rill-lapies. (Mount Nemo)

side openings meet with solutions that have come from above and the weakened stylolites are easily breached. Similar cave development is possible on a large scale in areas of near vertical dips. It is not long lasting.

Rill-lapies (Rillenkarren) in the srictest meaning of the term are scarcely present in any of the four sample areas of the Niagara Escarpment. A few poorly developed parallel channel-like features are found at early stages of development at Beamsville, being cut into the steep slopes of the escarpment. They are influenced by structure, but are unlike the other lapies in one important respect: they do not require the presence of joints, bedding planes or stylolites at the beginning of their formation. These channel-like features do however, cause enlargement of joints and bedding planes after having exposed them. Photo. 23 shows a few such channels. The growth takes place on steep slopes, and develops by backward solution-erosion. The channels cut bedding planes without much alteration. When fully developed they may become identical to trench-lapies in areas of flat dips (Flach Karren), but remain characteristic where the dips are steeper than 15°. The rock surface must be bare and the waters must concentrate into rills, in order for them to be produced. The writer has found a small number of little dendritic rill-lapies at the Dundas site on a boulder that was removed from between two beds by mining operations. Therefore its covered origin is indicated. However, this example is peculiar being very similar to bedding lapies in appearence.

Parallel rill-lapies (Photo. 24), are usually located on steep slopes, and in any kind of rock that contains minerals of different susceptibility to chemical weathering. Rocks of least homogenity will therefore harbour

Photo. 24/ Rill-lapies on steep, slopes
(Beamsville)

the best rill-lapies. Mechanical erosion and weathering may be very important in the case of those rocks which are not water-soluble in mass, but contain water-soluble minerals in considerable amounts, e.g. sandstones cemented by calcite. In similar situation solution of the cement material will release the quartz grains, which may fall out under the force of gravity, where the waters have concentrated into fast moving rills. This process may be one of the fastest acting causes of lapies, if the resulting features may be considered lapies at all. Bögli (1951) suggested the use of the term pseudo-lapies for such features, if they were developed in rocks other than carbonates.

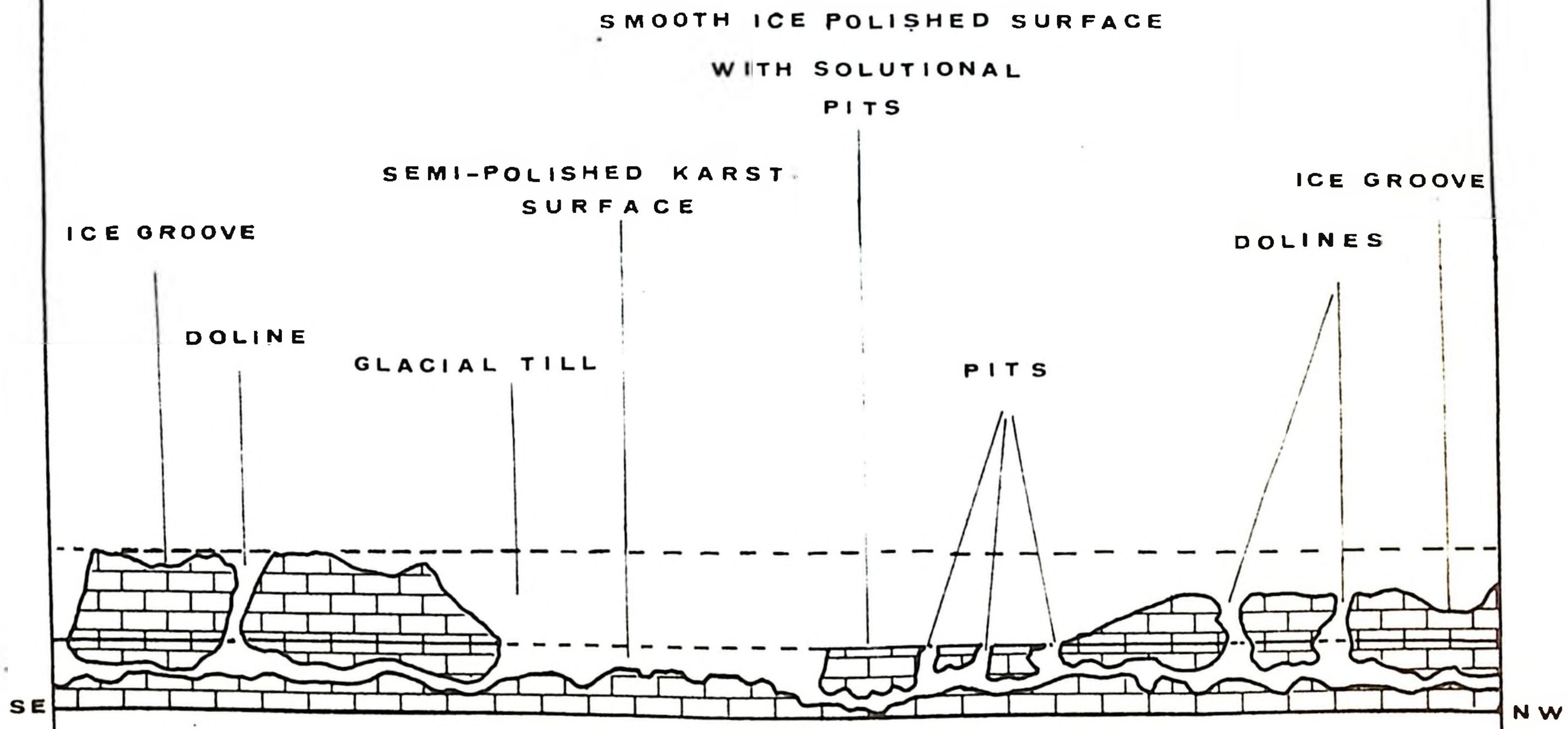
The age of the Niagaran lapies.

It might be supposed that rill-lapies are as old as the first exposure of the rock. This may be true for non-carbonates, but the karst rill-lapies are a more complicated problem because primary intrastratal solution may already have removed as much as 40 % of the rock before exposure, causing local (or zonal) weak parts similar to those described above (Stockdale, 1922). Examples found at Beamsville site appear to be of such origin, or at least in part influenced by the presence of stylolites. It is also probable that some of the features have developed under a rock cover, (or bedding plane e.g. the Dundas specimen, which could have developed before the removal of the overburden, or the overlying strata). Some rill-lapies at Beamsville are certainly of post-Pleistocene origin as they are located in the artificial walls of a stone pit, quarried about a hundred years ago. They were probably weakened by so-

lution at a much

earlier time. Difference of size (in width, depth and length) may indicate the relative ages of any lapies in the case of nearly homogeneous soluble rocks, when the original slope angles (on which their growth depend), are known.

There are geomorphological means for estimating the relative ages of these and other karstic features. All trench- and bedding-lapies of the Niagara Escarpment were found dissolved or cut into glacially polished or grooved rock surfaces, which were covered by glacial till of varying thicknesses. This may be taken as evidence of post-Pleistocene origin under an overburden. However, features exposed in the Dundas area lead to the belief that the karstification there must have started earlier. Whether they are last inter-glacial or Wisconsin is morphologically indeterminable in the examined sites. Figure 14 and Photos. 14a, b and C, illustrate the situation. Figure 14 is a cross-section of the area exposed by mining operation. The ice polished and grooved, low-permeability, dolomites have a drift cover of approximately 9'. Small solution pits terminated by the underlying bed are found on this polished surface adjacent to fresh, scarcely altered, ice scratches and gravity joints. The underlying bed has also been solutionally affected and displays a bumpy, undulating, surface with depressions under the pits and positive features elsewhere. All the solutional pits are connected (bedding-lapies) to these twisting passages. The bumpy bed surface has in places been exposed to ice erosion and is partly polished, but the undulations are still well defined and similar to the rock-covered features (Photo. 25.). A short distance from the photographed site, this layer is covered by two higher beds in situ. The



GLACIALLY ERODED KARST FEATURES

DUNDAS

FIGURE 14

Photo. 25/ Undulating karst surface semi-polished by ice movements, (Dundas)

uppermost bed contains larger depressions which are partly collapsed due to secondary joint formation. These small dolines extend down through the two rock layers, narrowing downward until they have nearly the same diameter at their bases as that found in the same layer where it is immediately under a soil cover. (Photos. 20a & b). It is therefore probable that the small solutional pits were originally the bottoms of these larger depressions, and have been partly destroyed by ice erosion. Some alteration on their edges, however, appears to be recent, evidencing that karstification is still in progress. Similarly developed small pits with dendritic appearance are also present at Beamsville on a polished surface which has been slightly altered by solution. This is related to greater porosity and a very thin cover of soil at the latter site.

It is obvious, however that not all small pits have originated the same way and at the same time. The very small, straight pipes (or pits), which are unrelated to the regional jointing, are likely post-Pleistocene in origin, and the larger ones may owe some of their alteration to later times, since the process probably is still in progress there being enough acid available in the soil cover. (pH 6.5-7.0).

Small rill-lapies of structure-oriented type, cut into the sides of glacial grooves on the top of Mount Nemo must be post-Pleistocene, but remnants of adjacent bedding-lapies show signs of having been partially destroyed by the moving ice, as the grooves were cut into them (Photo 22

All double and reversing-lapies must also be post glacial, some as young as a few hundred years old, if the intrasratal pressure solution (which caused the stylolites to form) is not considered as an integral part of the process. These features can be related to moss and bacteria life, which started only after the ice melted away.

The effect of soil-cover on lapies development.

According to Howard (1963), only cutters (trench-types of -lapies) may develop under an overburden, while bare rock surfaces are a pre-requisite of true lapies development, because rill-lapies are only found on such surfaces, e.g. on pinnacles left between cutters (trenches).

In the opinion of the writer, a cover of rock may act in the same manner as a soil cover; one actual example has been found at Dundas, where two beds have been separated by solution, (Photo. 14c). It cannot be assumed that the same types of lapies cannot develop also on a bare or nearly bare surface. Alternatively, lapies might form on now bare surface which also displays partly smoothed-out features of a former, covered condition. This is because on bare carbonate surfaces, only the solution process can be dominant; under an acidic soil cover other chemical processes may have a greater influence on the whole rock body simultaneously, giving the rock a rotten appearance when being exposed. The differing lithology may, of course, also influence the roundness or sharpness of lapies surfaces. The effect of the microstylolites has already been discussed. Impurities evenly distributed among the soluble grains cause over-all resistance to chemical weathering of any kind. Finer grain size and compactness have the same effect, whether the rock is bare or covered. Micro features indicate greater angularity, while alternating lower and higher porosities will give rise to wavy or undulating surfaces. Uneven bumpy surfaces are often the result of differential weathering caused by mineralogical change in the rock, and may also be related to, porosity or even to a lack of micro-stylolites.

It is also true that the number of small primary and secondary features are increasing with the increased exposure, creating richness of form, (if the area is protected from strong winds, which have a smoothing effect on the already-developed features). Heavy rain or trickling melt waters may also round the steep slopes, in their uppermost parts, sometimes in a short 50 years. Limestone pebbles, semi-imbedded in river terraces, nicely rounded on the exposed side while the covered side remains angular, were observed in a roadcut near Paris, Ontario.

The biological influence on lapies formation.

Some effects of biology have already been mentioned. It is probably much more significant than has been proven as yet and much experiment and statistical analysis is needed to resolve the question.

The groovings and reversing groovings described above are attributed entirely to plant and bacterial action on stylolites, and all recent karstic features owe something to organic acids. Features that may have developed during the last Pleistocene interglacial under warmer and wetter climatic conditions than those of the present, must have had even greater acid concentrations. Features may have developed during the Wisconsin ice age with a minimum of aid from biological agents but may have been just as extensive due to the action of melt waters.

The mechanical action of plant growth in joint fractures is also well known, and is described in many texts. No solution is involved in this process as the rock enclosed in the network of roots is fragmented, but otherwise is unaffected on the fragment surfaces, and remains tightly packed around large roots and tree trunks. Roots are observed growing into open lapies after they have left tight cracks higher up. This indicates that the upper fractures are due to mechanical action of growth, while lower down the roots found already widened joints, which they used without adding to the solution process. This may also be evidence that the solution process in below-surface soil conditions is almost nil in a period 50-100 years, which is the approximate age of these tree-roots, (Photo. 26).

The cyclic development of lapies

Cvijic (1924), described a theoretical lapies cycle, (page 9). But it is little applicable to the Niagara Escarpment in the manner of that author.

Lapies may have different depths in the initial stage as joints are of different depths. The destruction of the surface layer may be contemporaneous with widespread solution in an underlying bed, as was described above . Any type may begin to form anywhere within the carbonate strata, exept for rill-lapies. There is no true base level formed in carbonate rocks unless there are insoluble layers interbedded with the limestones; otherwise solution is continuous in three dimensions. Older and younger features may be adjacent and there is no rejuvenation by uplift, since the process of karstification does not stop, but is only slowed by the accumulation of residues. Completely new features may start to develop on young joints, created by gravity movements, (Photos. 13a & b.).

Photo. 26/ Tree root growing into an open fracture, which broadens downward instead narrowing. No solution is present where the same root is enclosed, in an intact joint.

However, stages of development, while intermingled over an area are clearly definable for single features. For example, bedding-lapies may start as shallow grooves or pits breaking into grooves. Intersections then become places of collapse, due to weakening of the strata by undermining along the planes of beds and vertical joints. This leads to pit and doline formation etc. The end stage is rubble karren.

The areal development is outlined on pages 3-6, and only one observation will be mentioned here. In the Beamsville area, the oldest lapies which were buried by till, are being reopened and deepened, ('rejuvenated') by gravity movements over the underlying shales.

This represents a kind of multi-cyclic effect in areal extent, but the 'rejuvenation' speeds the complete destruction of lapies, by slumping at the cliff face.

DEVELOPMENT OF BEDDING-LAPIES

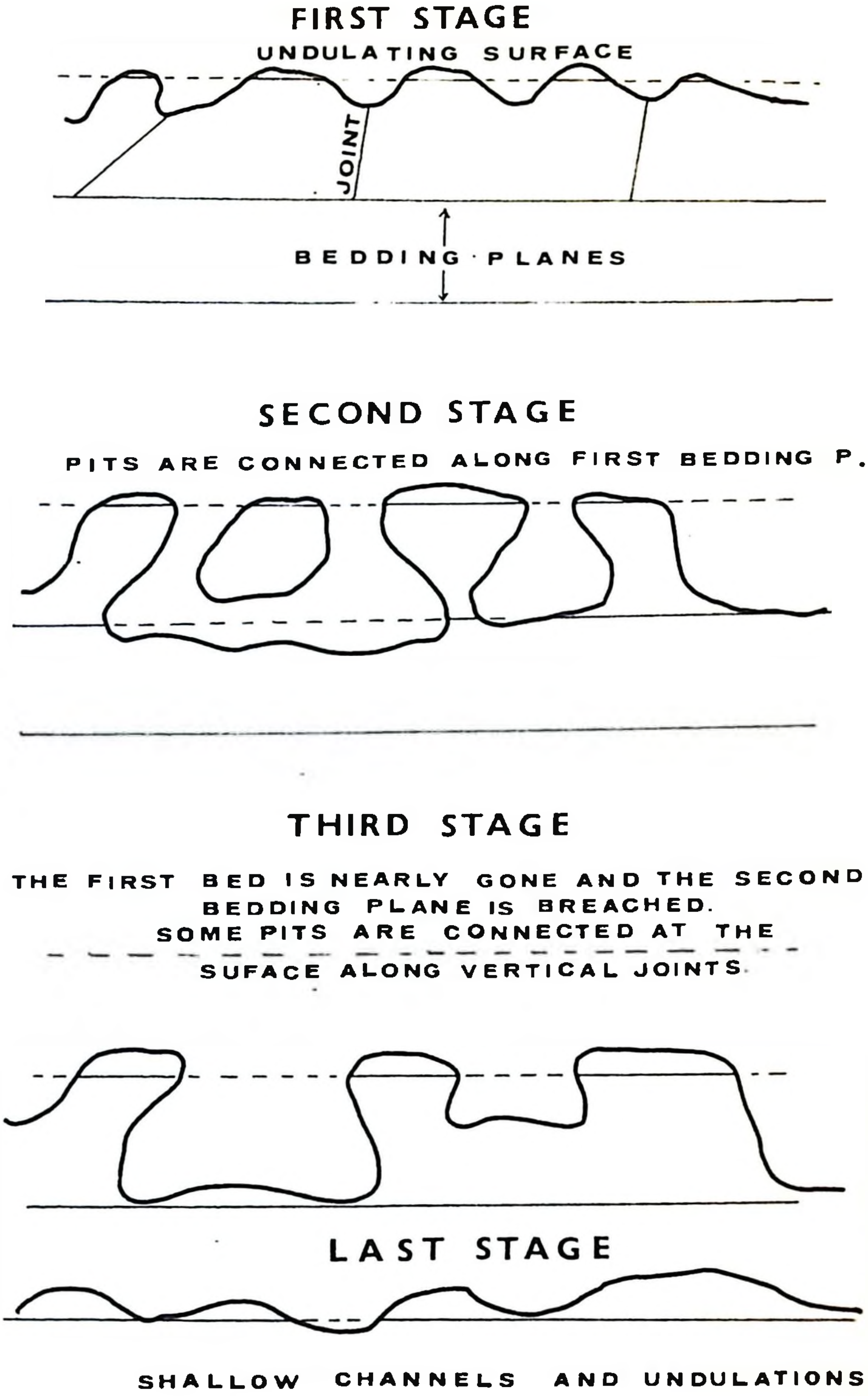


FIG.15

CONCLUSIONS

Along the Niagara Escarpment:-

1. All lapies, large or small, are structure-controlled, or a least influenced by structure. Some are superimposed on the regional jointing, some used joints as well as bedding planes to form bedding-lapies and some are related to micro-structure and rock texture.
2. The shape and size of a fracture will determine the shape and size of lapies developed on its plane.
3. The widening of joints involves solution, erosion and gravity movement in the vicinity of steep slopes, such as an escarpment face.
4. Lapies may develop on flat or inclined terrains, but most often found on the former, where the strata dips are flat or moderate, up to 20°.
5. Wide and shallow, irregular (branching and curving) trench-lapies may originate from pits along a tension joint, by breaching of the walls between pits, by upward break-through (or by roof collapse) from the surface of bedding of bedding lapies, from collapse-solutional dolines (superimposed on secondary joints), and by straight downward water penetration, ie. even solution in the walls and down to the bottoms of the lapies.
6. Fairly straight to very straight, and narrower, trench-lapies may develop by even downward penetration of tension joints by gravity movements and solutional alteration and from shear joints by the same process.
7. "Shear and tension-lapies" may start anywhere within the carbonate strata, with or without the presence of an overburden.
8. Bedding lapies are widened spaces between beds of carbonate rocks.

They start with an undulating surface, which later may develop into shallow branching channels, with irregular, flat bottoms, or by pits breaching one plane after another downward, in step-like order, and which may appear to be dendritic in a later stage. They may develop a trough-like cross-section if later exposed to rain and wind, and the knick-points may disappear, leaving evenly-grading channels. Knick points are created by styloIitic planes, usually normal to the bedding.

9. Double-lapies are superimposed small grooves on secondary solution-joints, projecting upward and downward from stylolitic surfaces.

10. Reversing-lapies are depressions and protrusions of different sizes (sometimes small cavities) in the walls of trench- and shear-lapies, related to pressure-solution planes, recrystallization of ferrous minerals and alteration of calcite to dolomite. Increasing inter-crystalline porosity reverse the lapies, and some protruberances split along the styolites.

11. Surface depressions are usually located at the intersections of two or more differently-oriented lapies by solution-erosion and by collapse, or by solutional undermining and collapse. (The latter will project to the surface by several near right-angled or right-angled gravity joints.

12. The most important lithological control is found in porosity differences, and sometimes in slight changes in mineralogy, the most important of which is the silica content.

13. Many small karst features owe their existence to the presence of styolites, which are therefore most important in the formation of such forms.

14. The age of the lapies formation is probably Pleistocene (last interglacial or Wisconsin) and post-Pleistocene as uneroded strata lying above glacially polished rock surfaces contain what are probably the upper portions of pits. These pits are similar to those now found in polished and till-covered sections of underlying layers with solution-altered and semi-polished undulating surface that continues unpolished; but weathered underneath a shiny, smooth, ice-polished and pitted surface in adjacent areas.

15. A regolith cover for lapies development is unnecessary, as every feature was found on bare rock surfaces and developed between different layers of rock. Where soil is present, the degree of weathering varies with the thickness of soil. A very thick overburden acts as a protecting cover against solution, and forms under soil cover do not generally display a wide variety of forms. This is attributed to nearly equal solution, (although the degree of alteration increases downward to a certain depth, then decreases with the growing thickness). A thin veneer of soil is probably needed to develop the maximum wealth of small forms, while a soil cover of great depth would smooth out these features.

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APPENDIX I

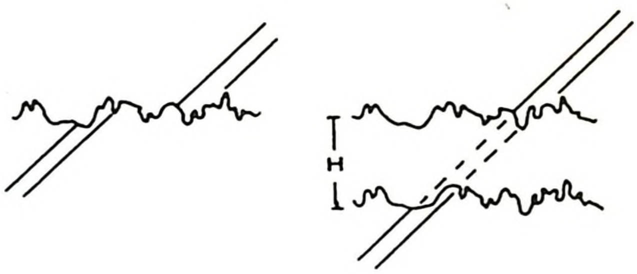
Stylolite formation, (pressure solution)

"A stylolitic seam is a surface marked by interlocking or mutual interpenetration of two sides. The toothlike projections of one side fit into sockets of like dimension on the other. In cross-section the stylolitic surface resembles a suture (Ge. Durcksuturen) or the tracing of a stylus-an oscillogram. Stylolitic seams are exceedingly common in certain types of rock". (Pettijohn, 213). Stylolites are of various sizes and orientations, but are most commonly a few cms. in amplitude, and laterally may reach several meters, usually sub-parallel to the bedding.

According to Stockdale (1922, 1926) stylolites originate by a pressure solution process, due to the presence of circulating connate waters throughout the strata. He assumed that solubility differences within the rock will produce an undulating surface and the pressure would be the greatest on the crests and troughs, while on the sloping sides it would be a minimum. Vertical columns form accordingly with solution at the ends. Figure 16 illustrates the mechanism of pressure solution, and an estimation of the amount of rock missing due to the process.

ESTIMATION OF THICKNESS OF ROCK DISSOLVED BY PRESSURE-SOLUTION

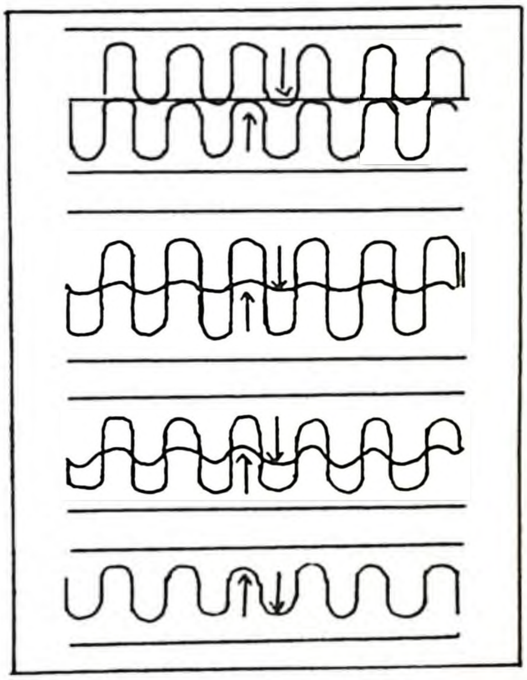
AFTER CONYBEARE, 1949.



LOWER

DEVELOPMENT OF STYLOLITES FROM AN IDEAL SITUATION.

AFTER STOCKDALE, 1922.



ARROWS INDICATE DIRECTION OF PRESSURE

FIG. 16

APPENDIX II

Table 1 Average strike directions and sum of lengths by 5° intervals, for joint set I, Beamsville.

Strike from-to	Average direction	Associated length	number of segments
S 45 W - S 49 W	S 45 W	58'	1
S 50 W - S 54 W	S 53 W	22'	1
S 55 W - S 59 W	S 56 W	104'	7
S 60 W - S 64 W	S 62 W	259'	7
S 65 W - S 69 W	S 67 W	370'	10
S 70 W - S 74 W	S 72 W	892'	15
S 75 W - S 79 W	S 76 W	390'	10
S 80 W - S 84 W	S 81 W	259'	7
S 85 W - S 89 W	S 87 W	209'	4
90 W - N 85 W	N 89 W	87'	3
N 85 W - N 79 W	N 84 W	88'	3
N 80 W - N 76 W	N 80 W	78'	1
N 75 W - N 71 W	N 75 W	77'	1

Table 2 Average strike directions and sums of lengths by 5° intervals for joint set II, Beamsville. These fractures are at right-angles to set I.

Strike interval	Average	Length	
N 40 W	N 40 W	66'	2
N 35 W - N 31 W	N 35 W	25'	1
N 30 W - N 26 W	N 28 W	135'	7
N 25 W - N 21 W	N 24 W	168'	7
N 20 W - N 16 W	N 17 W	155'	7
N 15 W - N 11 W	N 14 W	60'	3
N 10 W - N 6 W	N 10 W	75'	3

Table 3 Shear joint set III, Beamsville

90 W - N 86 W	N 87 W	21'	1
N 85 W - N 81 W	N 81 W	51'	1
N 80 W - N 76 W	N 77 W	42'	2
N 75 W - N 71 W	N 73 W	186'	5
N 70 W - N 66 W	N 68 W	85'	3
N 65 W - N 61 W	N 64 W	479'	10
N 60 W - N 56 W	N 58 W	37'	1
N 55 W - N 51 W	N 54 W	64'	4
N 50 W - N 46 W	N 49 W	53'	2
N 45 W - N 41 W	N 43 W	41'	3

Table 4 Average strike directions and sums of lengths by 5° intervals for shear joint set IV, Beamsville.

Strike interval	Average	Length	Number of segments
N 15 E - N 19 E	N 17 E	208'	5
N 20 E - N 24 E	0	0	0
N 25 E - N 29 E	N 25 E	10'	1
N 30 E - N 34 E	0	0	0
N 35 E - N 39 E	N 38 E	29'	2
N 40 E - N 44 E	N 44 E	58'	1
N 45 E - N 49 E	0	0	0
N 50 E - N 54 E	0	0	0
N 55 E - N 59 E	N 55 E	16'	1

Table 5 Dundas - set I.

N 60 E - N 64 E	N 61 E	613'	1
N 65 E - N 69 E	0	0	0
N 70 E - N 74 E	N 71 E	32'	1
N 80 E - N 84 E	N 80 E	38'	1

Table 6 Dundas - set II

N 4 E - N 0 E	N 3 E	66'	2
N 15 E	N 15 E	25'	1

Table 7 Dundas set III

Strike interval	Average	Length	Number of segments
N 74 W		30'	1

Table 8 Dundas set IV

N 35 E - N 39 E	N 37 E	213'	3
N 45 E - N 49 E	N 45 E	54'	2

Table 9 Burlington set I

S 20 W - S 24 W	S 20 W	84'	2
S 25 W - S 29 W	S 28 W	51'	1
S 35 W - S 39 W	S 37 W	83'	3
S 40 W - S 44 W	S 44 W	11'	1
S 45 W - S 49 W	S 49 W	62'	1
S 50 W - S 54 W	S 51 W	71'	2
S 55 W - S 59 W	S 55 W	255'	3

Table 10a

No.	Vt	Vm	Pt %	Description and location
1	1.67	1.58	6	Beamsville, resistant uppermost layer, with even stylolite distribution.
2	0.83	0.53	32	Beamsville, clay-fill contact of 5' depth, weathering rim .5" deep.
3	2.71	2.58	5	Uppermost resistant unit, from Beamsville, a pinnacle between two trench-lapies. Microstilolites, no grooving on surfaces.
4.	3.01	2.98	7	Beamsville, practically unaltered.
5.	3.71	3.55	4	Beamsville, apparently unaltered from 4' depth, with intercrystalline porosity, micro-stylolites.
6	4.27	3.93	8	Beamsville, grooved sample, less resistant zone, the porosity difference appears to be much greater to the eye. Pink minute stylolites.
7	2.36	2.23	5	Same sample as above, more resistant zone.
8	2.56	2.23	12	Very slightly grooved, Beamsville more resistant zone.
9	2.59	2.18	15	Same sample as 8, but the less resistant section.

Table 10b

No.	Vt	Vm	Pt %	Description of samples
10	5.94	5.28	11	Beamsville, upper unit, more soil here than at the above locations. Sample is well grooved. More resistant zone.
11	3.01	2.61	13	Same as 10, but less resistant portion.
12	2.20	1.65	25	Beamsville, protrusion from an exposed boulder, the more resistant portion, with stylolite in the centre.
13	3.51	2.63	26	Same sample as 12 but grooved. Slightly less resistant part.
14	3.50	3.02	13	Beamsville, slightly grooved, more resistant zone.
15	3.63	3.07	15	Same as above, less resistant.
16	3.59	3.52	2	Mount Nemo, pitted, fine grained with short styolites of differing orientations.
17	2.09	1.88	20	Mount Nemo, fine and coarse grained patches within. Cavernous, with ferriferous coating along cavities (1-2" deep).
18	3.42	3.01	11	Mount Nemo, from ice-polished surface, contains rill-lapies on 15° slope.

Table 10c

No.	Vt	Vm	Pt %	Description of samples
19	3.55	3.53	6	Mount Nemo, ice polished surface, crinoid stems, fossil replacement, fine grained, micro-stylolites, some pitting, no weathering rim. Only pits are lined by iron oxide.
20	2.16	2.13	1	Nelson Lookout, ultra fine grained, with stylolites. Iron oxide coating on fossil fragments, fossil replacement by carbonates.
21	2.41	2.03	16	Nelson Lookout, fine grained between coarse grained recrystallized fossils. Parallel reversing-lapies on transverse stylolites.
22	3.77	2.80	25	Trafalgar Lookout, fine- to medium-grained, almost completely recrystalized, with pits and tiny channels.
23	2.85	2.53	11	Dundas, fairly uniform grain-size. Full of micro-stylolites and stylolites. Icepolished, pitted and channelled surface.
24	3.26	2.85	12	Underlying 23, medium grained with micro-stylolites and galena veinlets, with solutional separation between the two.
25	2.92	3.24	11	Dundas, undulating, bumpy surface, Shear-lapies.

Table 11a

Sample number	Time needed in minutes	Penetration distance in inches	Porosity per cent	Description and location
1	30	1/2	13	Beamsville, medium grained fastest movement along stylolites. Relatively uniform permeability.
2	40	1/2	15	Behaviour similar to that of previous sample. Upper layer from Beamsville.
3	90	1/2	5	Beamsville, fluid seen along stylolites, and in larger pores, the two penetration routes are at right angles to one another.
4	300	1/4	2	Mount Nemo, very fine-grained with fossil moulds.
5	300	1/8	8	Mount Nemo, ultra fine-grained, crinoid stems.
6	30		11	Dundas, fine to medium grained, full of stylolites. Penetration along stylolites only.

Table 11b

Sample number	Time needed in minutes	Penetration distance in inches	Porosity per cent	Description and location
7	150	1	12	Same as above, but penetration allowed vertical to stylolite planes from weathered surface.
8	300	0	11	Dundas fine grained, stylolite free. 1/16 inch to 1/4 inch diameter solutional cavities.
9	180	1/8	1	Nelson Lookout fine grained with variously oriented stylolites. Pinhead-sized cavities.
10	300	1/4	10	Burlington, medium to fine grained, with clayey patches. 1/8 inch diameter pores.

Table 12a

No	Rock Name	SiO_2 %	Fe_2O_3 %	MgO %	CaO %	Loss on ignition
1	Dolomite	3.77	0.41	20.6	29.6	46.5
2	Dolomite	0.59	0.50	20.6	30.0	47.0
3	Dolomite	0.49	0.47	20.8	30.3	47.3
4	Dolomite	0.93	0.48	20.5	30.4	47.4
5	Dolomite	0.44	0.50	20.8	30.4	47.1
6	Dolomite	0.74	0.39	20.6	30.0	46.8
7	Dolomite	0.33	0.50	20.8	30.3	47.3
8	Dolomite	0.37	0.49	20.7	30.1	47.2
9	Dolomite	0.39	0.55	20.3	30.0	47.1
10	Dolomite	0.52	0.50	20.5	30.3	47.0
11	Dolomite	0.39	0.58	20.9	29.8	47.0
12	Dolomite	0.46	0.46	20.2	30.3	47.2
13	Dolomite	0.35	0.38	20.4	30.5	47.2
14	Dolomite	0.43	0.56	20.5	30.0	47.1
15	Dolomite	0.39	0.58	20.9	29.8	47.0
16	Dolomite	0.45	0.16	20.5	30.6	47.4
17	Dolomite	1.02	0.25	20.3	30.1	47.0

Table 12b

No	Rock Name	SiO_2 %	Fe_2O_3 %	MgO %	CaO %	Loss on* ignition
18	Dolomite	3.01	0.41	19.7	29.2	45.4
19	Dolomite	1.48	0.34	20.8	30.4	46.7
20	Dolomite	0.69	0.37	20.8	30.5	47.4
21	Dolomite	2.01	0.23	19.9	29.8	46.4
22	Dolomite	0.79	0.23	20.3	30.3	47.1
23	Dolomite	1.46	0.14	20.3	29.7	46.8
24	Dolomite	1.06	0.11	20.8	29.9	47.1
25	Dolomite	0.72	0.14	20.5	30.2	47.1
26	Dolomite	1.31	0.57	19.7	29.8	46.5 **

*Loss on ignition (mostly CO_2 and water)

**Burlington surface sample, portion of bedding-lapies; porosity of this specimen has not been determined. Undulose stylolites, subhedral and euhedral crystals.

All other samples are described in table 10.