THE ESPANOLA FORMATION:
A PROTEROZOIC CARBONATE
NORTH OF LAKE HURON, ONTARIO

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NORTH OF LAKE HURON, ONTARIO

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ABSTRACT

The Proterozoic Espanola Formation (Huronian Sequence) was studied at Geneva Lake, Ontario, 45 miles north-west of Sudbury. A major lithological change exists in the Espanola Formation between this area and the type section on the north shore of Lake Huron, 75 miles to the south. Unusually pure (95 percent) microcrystalline limestones and dolostones occur in almost equal abundance to the calcareous siltstones which are the characteristic lithology of the formation in its type section.

The existence and position of a fine grained deposit such as the Espanola in a stratigraphic sequence which consists mostly of glacial and periglacial deposits is unusual. It is suggested that this fine-grained deposit was an integral part of a cycle of deposition resulting from glacial advance and retreat and that its sedimentary basin was created by marine transgression in response to a glacial retreat. Spatial distribution of the Espanola Formation suggests that its sedimentary basin may have consisted of at least three environmental zones. At least one of these zones may represent a glacial melt-water lake.

A microfossil search was carried out with negative results. This made speculation necessary in determining the origin of the calcareous fraction of the Espanola Formation. A mechanism is suggested whereby calcium carbonate is precipitated inorganically, as a result of photosynthesis by anaerobic bacteria. This mechanism can be observed in

the present. If it is true, then the Espanola Formation may represent a time marker for the first presence of free oxygen in the atmosphere.

ACKNOWLEDGEMENTS

- Dr. M. J. Risk and Dr. P. M. Clifford, of the Department of Geology, McMaster University, acted as my thesis advisors.

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CHAPTER ONE

THE ESPANOLA FORMATION - THE PROBLEM

I. INTRODUCTION

The type section of the Lower Proterozoic Huronian rocks is exposed intermittently along the north shore of Lake Huron, Ontario (hereinafter referred to as the North Shore). This sequence was studied as early as 1887 by W. Logan and periodically since then (notably between 1925 and 1935) by the Canadian Geological Survey and the Ontario Department of Mines. The war-time discovery of radioactive uranium in the Bruce Formation (Figure 1) did as much to support further geological research as it did to open up post-war industry in the area. The Espanola Formation is noneconomic, but because of its stratigraphic position immediately above the Bruce Formation, it has been extensively studied, not only in the North Shore type section area, but in the Elliot Lake area, where production of uranium is presently taking place.

II. PROBLEM

In the Geneva Lake area, seventy-five miles north of the North Shore and one hundred miles east of the Elliot Lake area (Figure 2), outliers of Huronian sediments occur in great tilted fault blocks involving an Archaean basement of granite and greenstones. This area was mapped in 1920 by Quirke (Geol. Survey Can.) and again in 1929 by Osborne

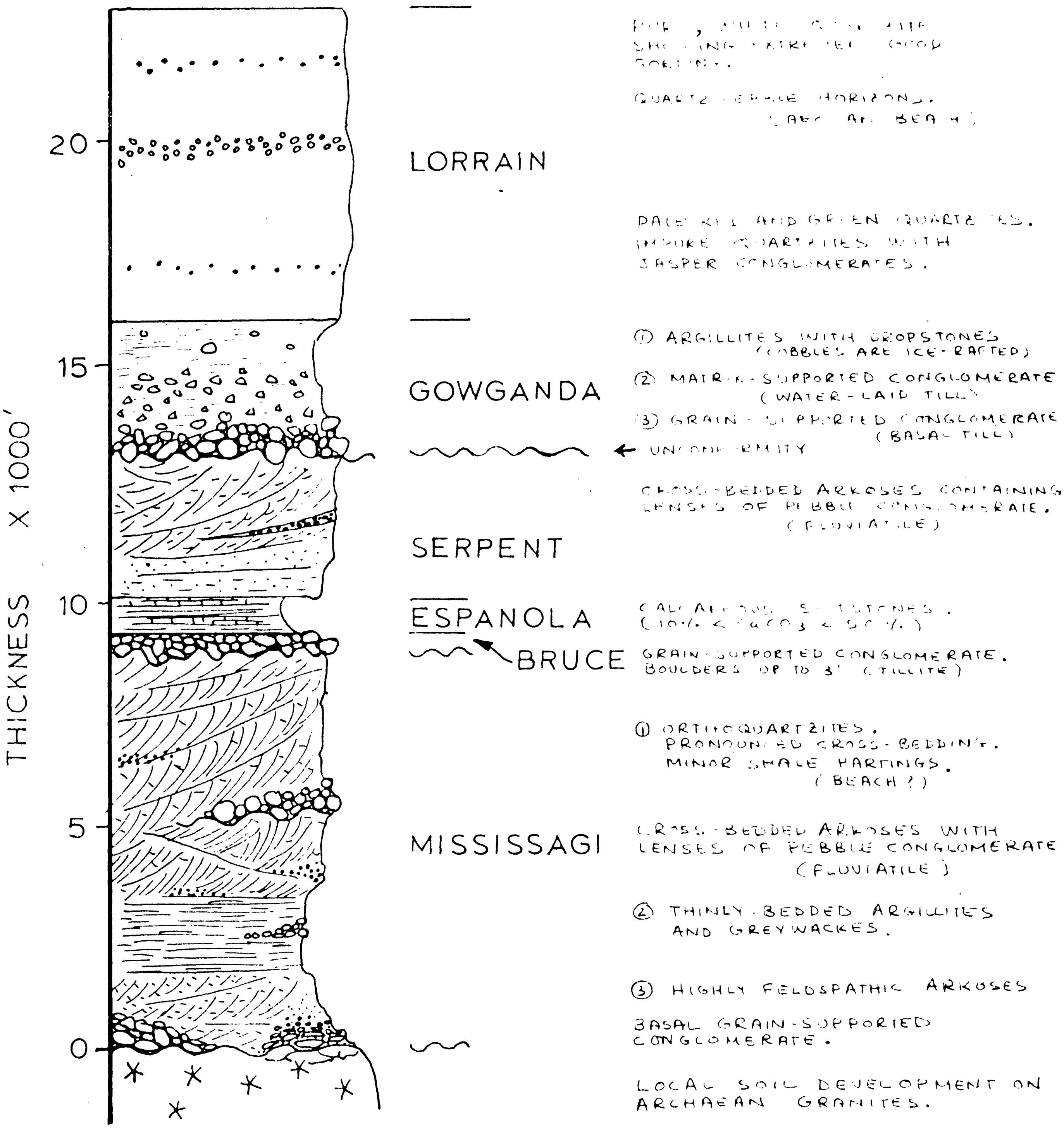

FIG. 1 - NORTH SHORE
GENERALIZED HURONIAN SECTION

after Collins (1925)

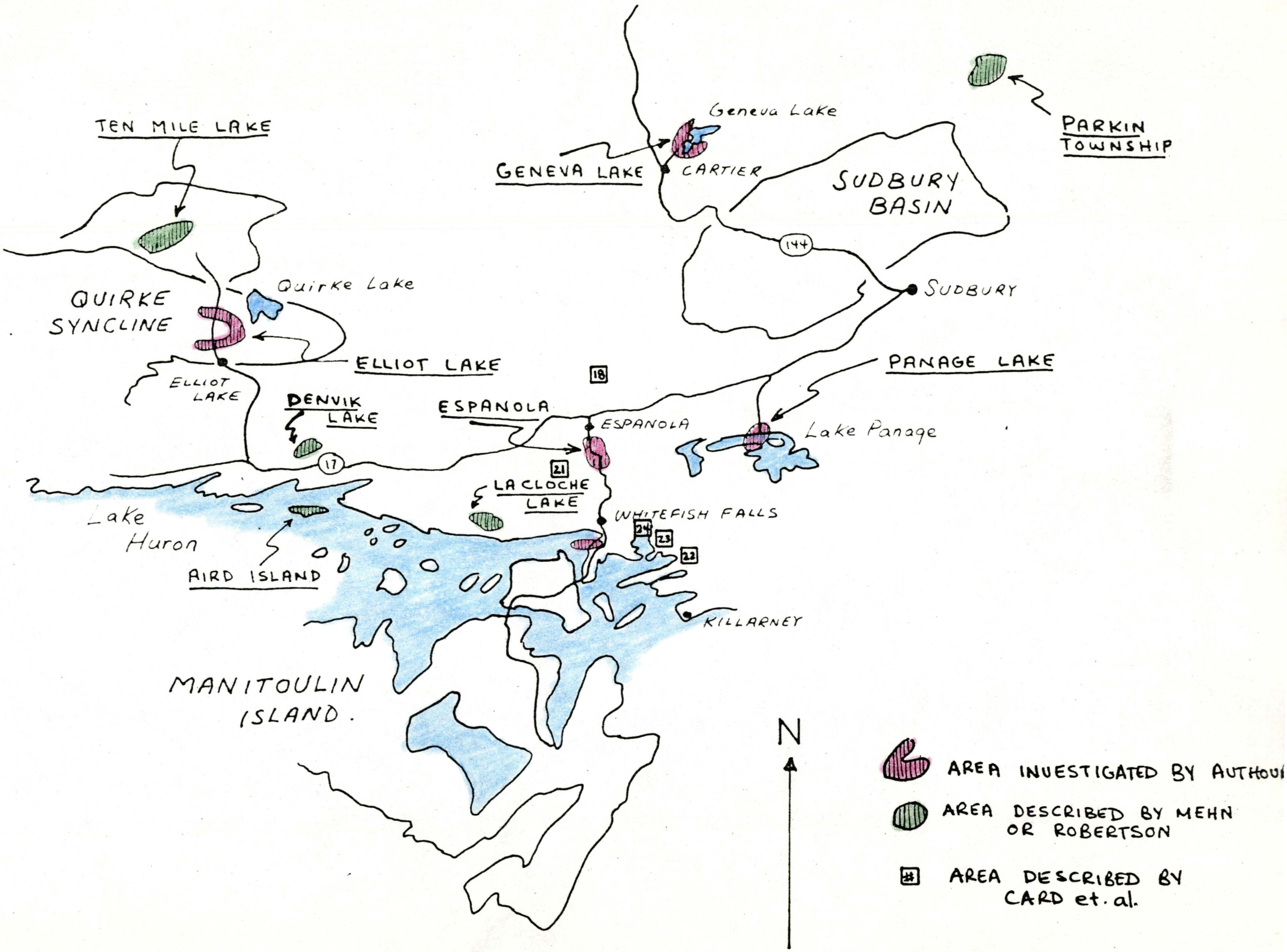

FIG. 2 - INDEX MAP

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(Ont. Dept. Mines). In 1973 Card (Ont. Min. Nat. Res.) studied a region including Geneva Lake, but his findings are as yet unpublished. Card (personal communication, April, 1974) substantiated the earlier findings of Quirke (1920) and Osborne (1929) that the Espanola Formation near Geneva Lake is exposed in at least six good sections, and consists of calcareous units of which approximately 50 percent are pure carbonates. This differs from the type section of the Espanola Formation on the North Shore in which the predominant lithology is a calcareous siltstone. Card, like Quirke and Osborne, did not study the Espanola Formation in detail but he indicated that it merited further investigation.

The occurrence of the Espanola Formation is anomalous within the framework of the Huronian sequence. This sequence consists of 5000 to 30,000 feet of conglomerates, fine-grained sediments and coarse-grained clastics (Figure 1) and is interpreted by most authors as having had a glacial/periglacial origin (Chapter 2). The Espanola carbonates are significant in that they are difficult to explain as deposits in a cold water, periglacial environment.

Carbonates are rare in this era of the geologic time scale. They are known to exist in the Proterozoic and these occurrences have been documented (Chapter 5). Seldom have carbonates been recorded prior to this era, so it is possible that the more than 2 billion year old (Young, 1967) Espanola Formation represents one of the oldest known carbonate deposits (Young, 1973).

III. PURPOSE

The purpose of this paper is:

(1) to investigate and describe in detail the Espanola Formation at Geneva Lake and thereby document its difference between this area and the type section on the North Shore;

(2) to measure Huronian sequences other than that at Geneva Lake in an attempt to determine the distribution of the Espanola Formation and thereby create a stratigraphic framework in which it may be possible to explain its existence in a glacial/periglacial environment;

and (3) to examine samples and search the literature in an attempt to account for or to speculate on the origin of the calcareous fraction in the rocks of the Espanola Formation.

IV. THE APPROACH

The six stratigraphic sections at Geneva Lake, noted by Card, were studied with respect to gross lithology and structure, and correlated with sections on the North Shore and near Elliot Lake (Chapter 3).

Detailed laboratory work (Chapter 4) involved: the study of thin sections to determine the petrology; the extraction of insoluble residues to study the clastic fraction of the samples and perhaps recover some microfossils; and, the analysis of several specimens under a scanning electron microscope to determine microstructures and again to search for microfossils which might give a clue to the cold water origin of the Espanola carbonates.

Finally, in Chapter 5, speculations on the origin and possible significance of the Espanola carbonates are presented based on ideas gleaned from the literature search.

CHAPTER TWO

THE HURONIAN SEQUENCE

This chapter describes the Huronian sequence in the North Shore and Geneva Lake areas, and outlines its regional environmental interpretation.

I. NORTH SHORE - TYPE HURONIAN SEQUENCE

The typical basal Huronian Formations outcrop along the North Shore in east-west trending synclines and anticlines. They were first extensively described by Collins (1925) although more recent works (Robertson et al, 1972; Card et al, in press) have elaborated on his work particularly in regard to petrology and Series/Formation definition.

Figure 1 illustrates the generalized type Huronian section. It is divided into an upper Cobalt Series and a lower Bruce Series on the basis of an undisputed unconformity between the two. It does not include the locally underlying Sudbury Series which was not recognized as Huronian in age until recently (Roscoe, 1973).

The Bruce Series has, at its base, the 9000 foot thick Mississagi Formation. This formation consists of a basal conglomerate member grading up through an arkosic sandstone member with frequent greywacke, argillite and conglomerate beds and lenses, into an uppermost member of low feldspathic quartzite showing pronounced cross-bedding, conglomerate horizons and minor shale partings. Unconformably overlying this is the Bruce Formation, a grain-supported conglomerate up to 300 feet thick, containing unsorted boulders, cobbles and pebbles in a greywacke matrix. It is interesting to note that the Bruce conglomerate does not contain any boulders of the underlying Mississagi Formation. Conformably above the Bruce is the Espanola Formation, up to 1200 feet of dark calcareous siltstones with minor (5 percent of formation's stratigraphic thickness) interbeds of purer limestone and dolostone, followed by 3000 feet of massive, cross-bedded siltstones and sandstones of the Serpent Formation.

The Cobalt Series unconformably overlies the Bruce Series, and consists of a lower Gowganda Formation and upper Lorrain Formation. The Gowganda Formation has a lowermost boulder conglomerate member grading up into a series of matrix-supported cobble and pebble conglomerates, then up into a series of argillites and greywackes containing occasional dropstones. This formation grades up into the massive quartzites and quartz-pebble conglomerates of the Lorrain Formation which is up to 7000 feet thick.

II. GENEVA LAKE - A GENERALIZED SEQUENCE

Figure 3 shows the geology of the Geneva Lake area (modified after Osborne, 1929). It also indexes the area's six measured stratigraphic sections (R, L, G1, G2, BN, BS) which are used to define the generalized section described below and illustrated in Figure 4.

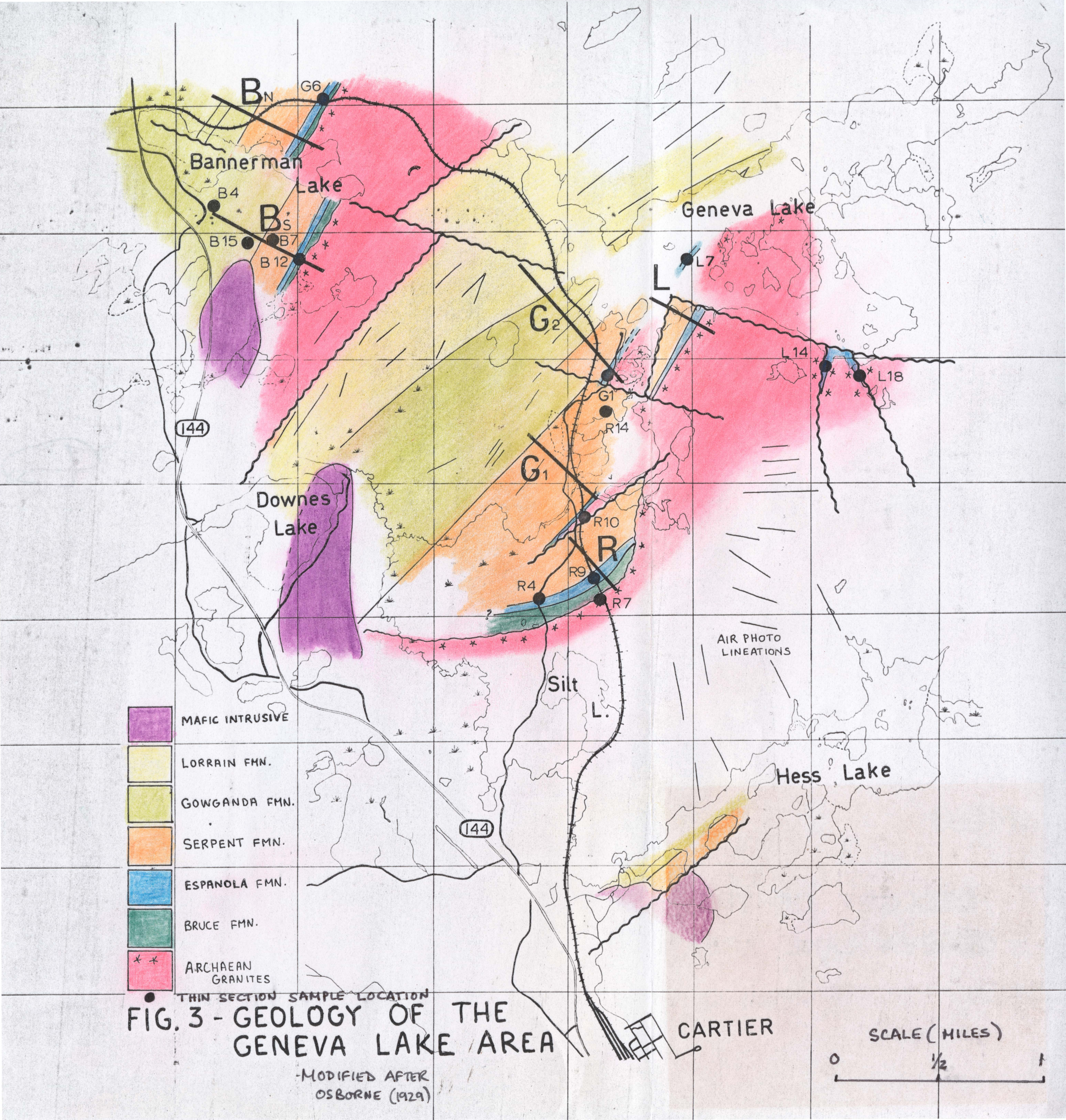
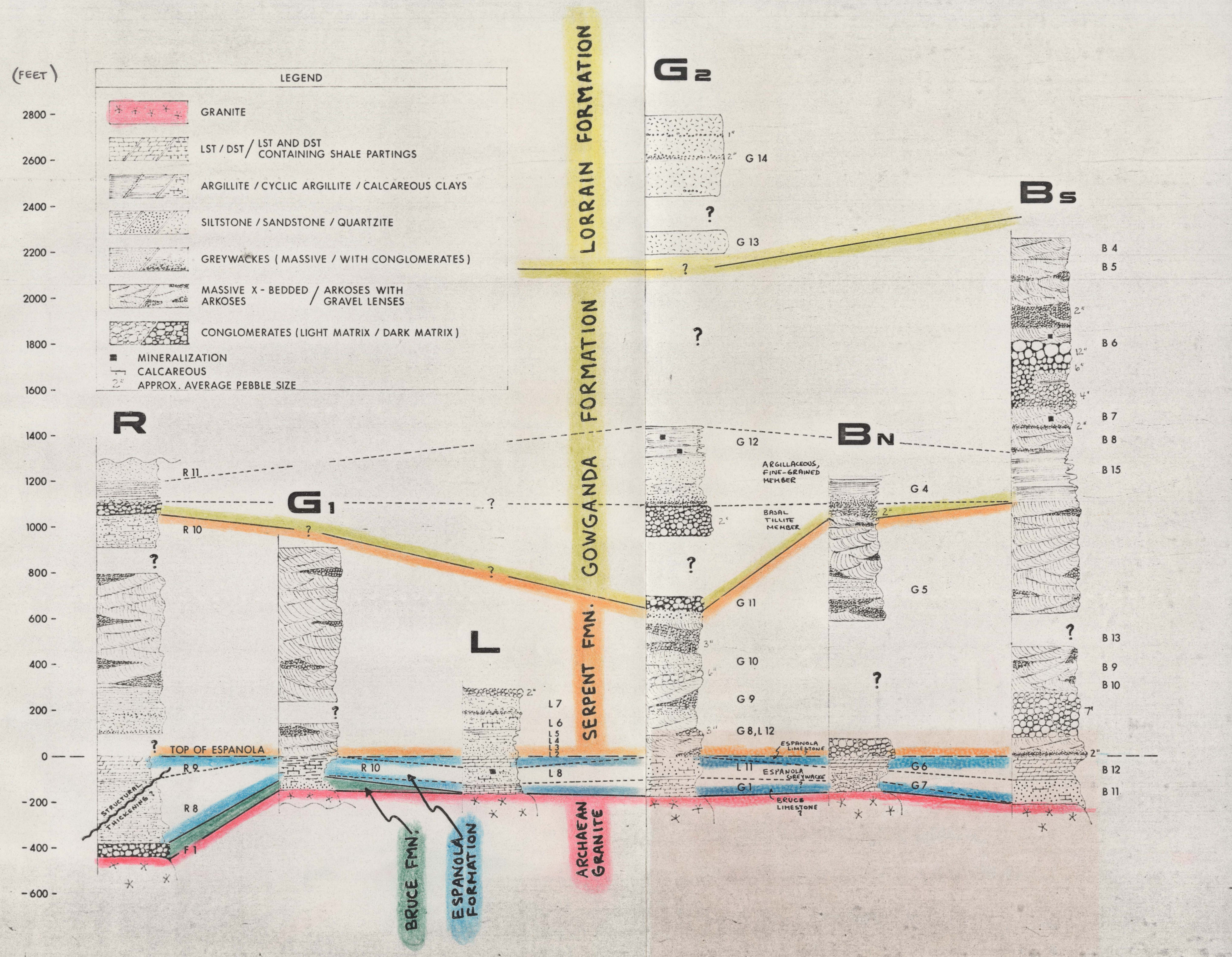


FIG. 3 - GEOLOGY OF THE GENEVA LAKE AREA

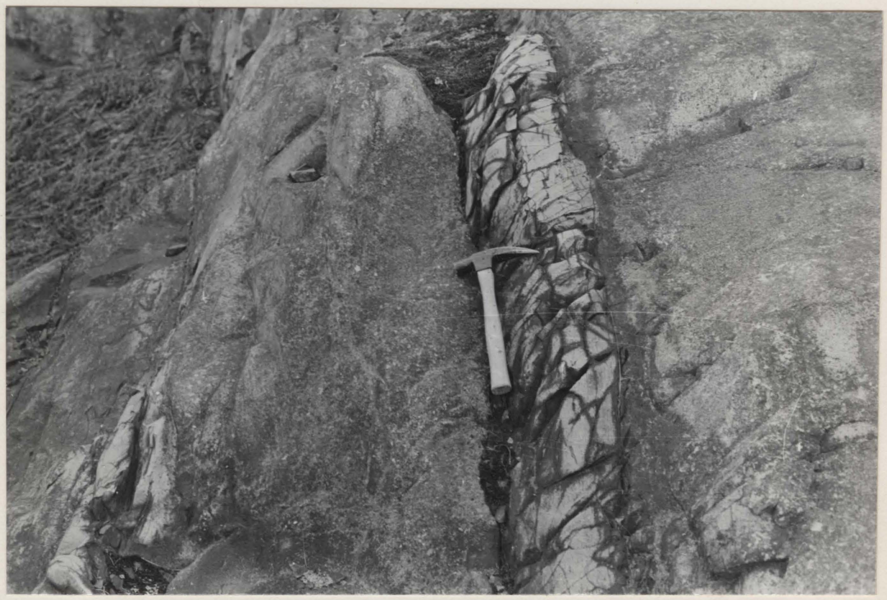

(FEET)
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
-200
-400
-600
LEGEND
GRANITE
LST / DST / LST AND DST CONTAINING SHALE PARTINGS
ARGILLITE / CYCLIC ARGILLITE / CALCAREOUS CLAYS
SILTSTONE / SANDSTONE / QUARTZITE
GREYWACKES (MASSIVE / WITH CONGLOMERATES)
MASSIVE X - BEDDED ARKOSES / ARKOSES WITH GRAVEL LENSES
CONGLOMERATES (LIGHT MATRIX / DARK MATRIX)
MINERALIZATION
CALCAREOUS
2" APPROX. AVERAGE PEBBLE SIZE
LORRAIN FORMATION
GOWGANDA FORMATION
SERPENT FMN.
ARCHAEAN GRANITE
BRUCE FMN.
ESPANOLA FORMATION
R
G1
L
G2
BN
BS
R 11
R 10
R 9
R 8
F 1
STRUCTURAL THICKENING ?
TOP OF ESPANOLA
L 7
L 6
L 5
L 4
L 3
L 2
L 8
G 14
G 13
G 12
G 11
G 10
G 9
G 8, L 12
L 11
G 1
G 4
G 5
G 6
G 7
ARGILLACEOUS, FINE-GRAINED MEMBER
BASAL TILLITE MEMBER
ESPANOLA LIMESTONE
ESPANOLA GREYWACKE
BRUCE LIMESTONE
B 4
B 5
B 6
B 7
B 8
B 15
B 13
B 9
B 10
B 12
B 11

The basal Mississagi Formation (Bruce Series) is not found near Geneva Lake. Locally, 50 feet of grain-supported conglomerate and a 30 foot sandstone unit are present, but it is unlikely that these represent the only surviving outliers of the 9000 foot thick Mississagi Formation that is found on the North Shore. It seems more probable that this clastic unit is either a remnant of the conglomeratic Bruce Formation or a basal unit of the calcareous Espanola Formation. No erosional interface is found between this clastic unit and the overlying calcareous units of the Espanola Formation. In most sections in the Geneva Lake area, the 200 - 400 foot thick Espanola Formation lies unconformably and directly on the older Archaean granitic basement. In all cases, it consists of well-defined beds of light grey calcareous siltstone, which weather white, as well as abundant (up to 50 percent) limestones and dolostones. These latter two lithologies are relatively pure ($CaCO_3$ > 75%) with shale partings and secondary siliceous and calcareous fillings in the fractures and the joints. They have locally been metamorphosed to marble.

Conformably overlying the Espanola Formation is the Serpent Formation, 600 to 1000 feet of predominantly cross-bedded arkoses with lenses of arkosic pebble conglomerates (Plate 1). In the Geneva Lake area, the Serpent Formation is not as fine grained as in its type section along the Serpent River on the North Shore, but it has remarkable textural continuity between measured sections. Locally, there is a 100 - 200 foot thick basal cobble conglomerate unit. This unit differs from the conglomerate found in the Bruce Formation by its light-colored arkosic matrix.

PLATE 1 - SERPENT FORMATION

Both photographs illustrate mg-cg arkoses, parallel laminated and cross-bedded with lenses of a fine-pebble conglomerate. These are interpreted as fluviatile deposits (possibly braided stream).



Overlying the Serpent Formation is the 500 - 800 foot thick Gowganda Formation. This consists locally of a 0 - 500 foot thick basal, grain-supported cobble conglomerate with a dark matrix, overlain by 200 -300 feet of fine-to-medium-grained parallel laminated argillites, siltstones and sandstones. These clastics differ from those of the Serpent Formation by their lack of cross-bedding. It is interesting to note the cyclic argillites (thin section B15) and the parallel-laminated argillites which contain dropstones (Plate 2), both of which occur in this stratigraphic position. The overlying members of the Gowganda Formation are found only in one stratigraphic section (Figure 4) and appear to be a series of matrix-supported conglomerates (Plate 3) and grain-supported conglomerates (Plate 4) with cross-bedded arkoses at the very top of the formation.

The generalized Huronian sequence is capped by the Lorrain Formation, whose contact with the underlying Gowganda Formation was not found. The Lorrain Formation consists of 1200 feet of quartzites, generally pale green or red, white or buff. The lack of impurities in these quartzites and the uniform grain size frequently makes it difficult to discern any primary bedding (Plate 5). Where bands or horizons of conglomerate are found in the Lorrain Formation (approximately halfway up section) the pebbles are composed of quartz, quartzite or "Jasper" - a hematite-rich chert. Bands of these pebble conglomerates are generally very thin and discontinuous, and the pebbles are usually less than two inches in diameter (Plate 6).

PLATE 2 - GOWGANDA FORMATION

Argillites containing 'drop-stones' indicate ice-rafting of pebbles and cobbles.

PLATE 3 - GOWGANDA FORMATION

Matrix-supported conglomerate, with laminated argillite matrix indicates glacial, till-like deposition below water level.

PLATE 4 - GOWGANDA FORMATION

Grain-supported polymictic, unsorted conglomerate is a classic glacial tillite deposited above water level.


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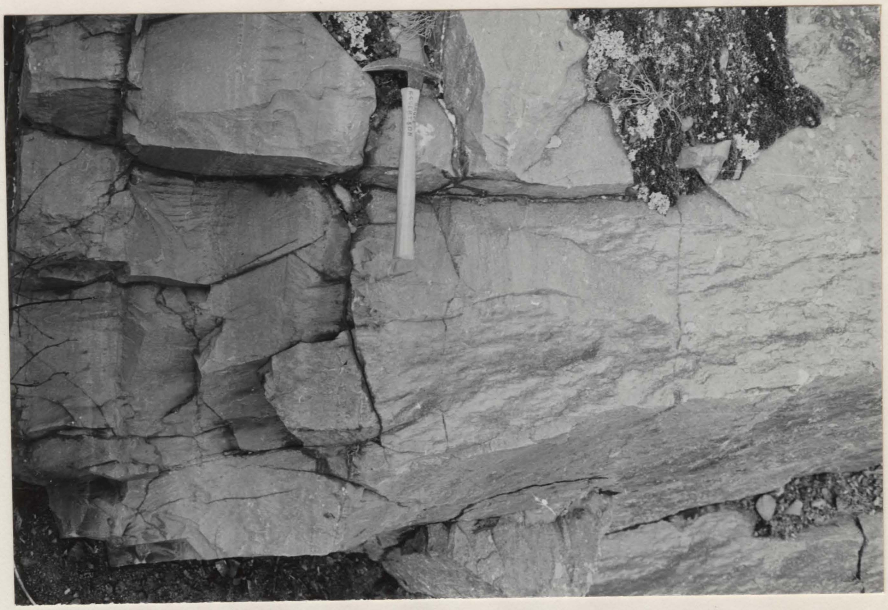
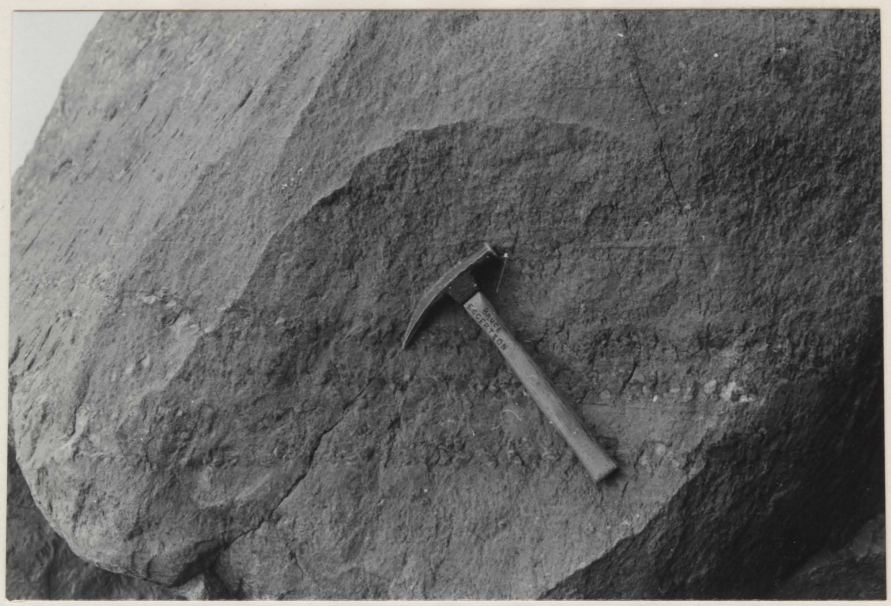
PLATE 5 - LORRAIN FORMATION

Lack of impurities in these quartzites (possibly reworked by beach and dune processes) makes it difficult to discern bedding. In fact, stratigraphically "up" is to the left.

PLATE 6 - LORRAIN FORMATION

Stringers of Jasper (Ferric chert) pebbles are common in the Lorrain Formation. They suggest periodic high energy input not associated with an aeolian environment.





III. ENVIRONMENTS OF DEPOSITION OF THE HURONIAN FORMATIONS

At the end of the 19th century, W. Logan noticed the till-like appearance of both the Bruce and the Gowganda conglomerates. In 1907, Coleman suggested an ice age during the Proterozoic. Since then, much work has been done with the purpose of substantiating the glacial origin of these rocks. The glacial theory is so well established now that Young (1970) correlated these Huronian glacial/periglacial deposits with reported glaciogenic sediments in other parts of North America and suggested an extensive Proterozoic glaciation.

Cassyhap (1969) described three cycles of glacial/periglacial sedimentation within the Huronian sequence; each cycle starts with the deposition of a basal tillite conglomerate over which fine-grained and then increasingly more coarse-grained cross-bedded sediments are deposited. A generalized cycle is described below. The sections in Figure 5 certainly suggest some cyclicity in sedimentation.

1. Basal Conglomerates

Along the North Shore, three basal conglomerates are present in the Huronian sequence and are the base of the Mississagi Formation, the Bruce Formation and the base of the Gowganda Formation. In 1931, Collins and Quirke observed the nature of the three different types of conglomerate (Plates 2, 3 and 4) and did not miss the importance of ice-rafting to the origin of "dropstones" in the overlying laminated sediments. In 1971, Lindsay explained the difference between the "grain-supported",

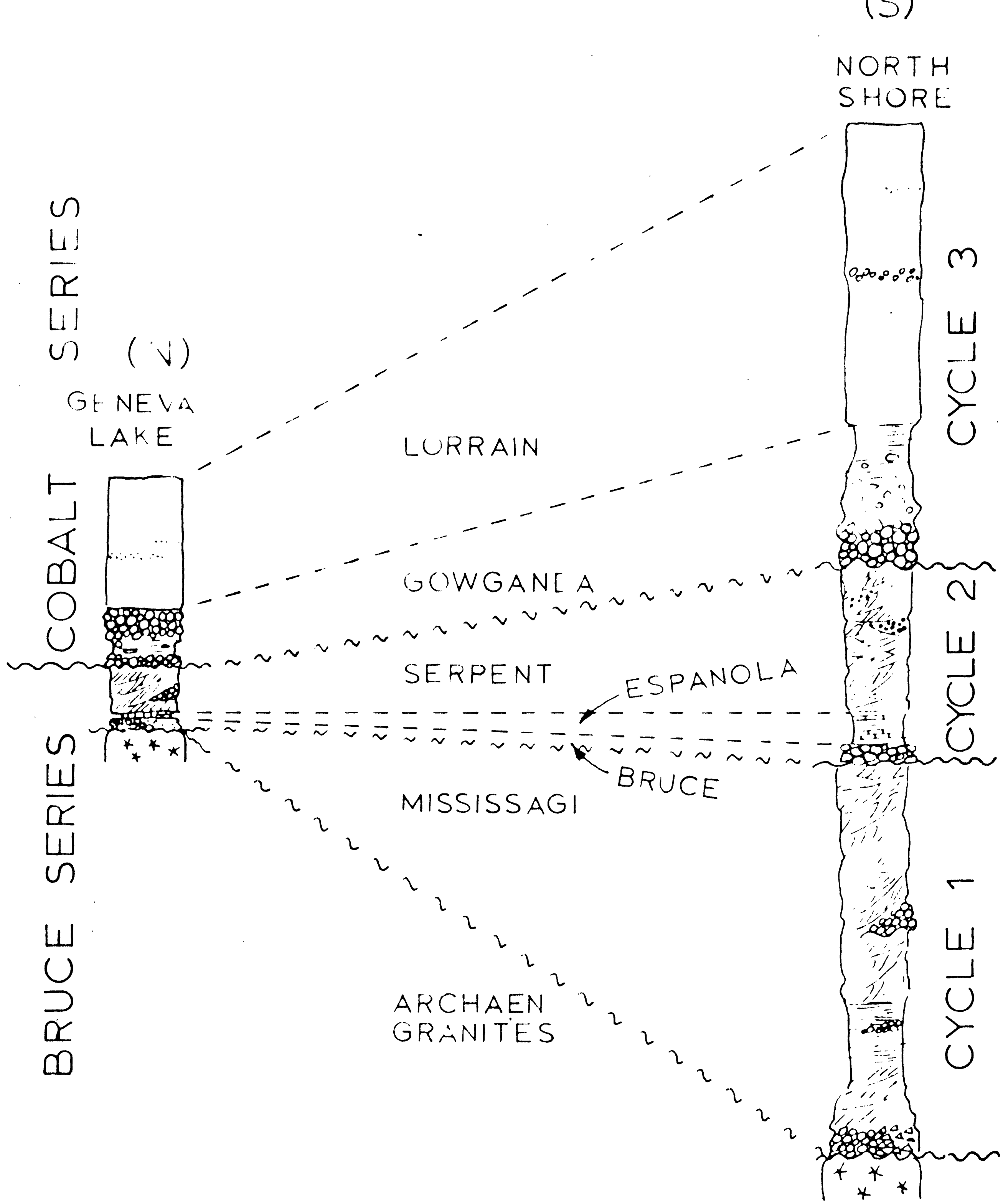


FIG. 5 - CORRELATION OF GENEVA LAKE SECTION

"matrix-supported" and "dropstone" types of tillites as a function of an increasing amount of water at the depositional interface between the ice and the sediments. Striated pebbles were later reported in several O.D.M. regional reports, and striations were found in Archaean granite where it directly underlies the Gowganda at the south end of Lake Timagami, Ontario (Lindsay, 1969). The lensitic character of the conglomerates, their lack of horizontal continuity and the fact that neither the Bruce nor the Gowganda conglomerates contain pebbles of the underlying formations all indicate a possible glacial "tillite" origin (Wood, 1973).

2. Fine-grained, Parallel-laminated Deposits

The basal conglomerates pass upwards into fine-grained, parallel-laminated deposits. In the Mississagi Formation, argillite overlies the basal conglomerate. In the Gowganda Formation, greywackes and argillites, including interbedded cyclic deposits overlie the basal conglomerate. Above the basal Bruce conglomerate, lies the fine-grained, parallel-laminated Espanola Formation which consists of thinly bedded carbonates and calcareous siltstones.

Cassyhap (1969) explained these fine-grained varved or thinly bedded units as marine deposits resulting from a post-glacial transgressive sea. This model holds only if the rise in sea level resulting from the massive melting of ice were to compensate for the isostatic rebounding (buoying) of the landmass following a glacial retreat. Should this not have been the case, these fine-grained sediments may be explained in terms of lacustrine deposits in a large periglacial basin or basins. The presence of cyclic argillites in the Gowganda Formation near Bannerman Lake might be "varves" indicating seasonal changes in this periglacial lake or marine basin.

3. Coarse-grained, Cross-bedded Deposits

The fine-grained sediments pass stratigraphically upward into more coarse-grained deposits. In the Mississagi Formation cross-bedded arkoses overlie the argillites and grade upwards into low-feldspathic sandstones, also cross-bedded. Above the Espanola Formation, the Serpent Formation consists of arkoses in large cross-bedded sets. Above the Gowganda Formation, the Lorrain Formation consists of pure quartzites.

The cross-bedded arkoses of the Mississagi, Serpent and Gowganda Formations contain lenses of pebble conglomerates and the occasional horizon of fine-grained sediments (Plate 1). They resemble modern continental, possibly fluviatile deposits (Cassyhap, 1966; Young, 1967). The Gowganda Formation is somewhat unique in that it quickly passes stratigraphically upward into the Lorrain Formation, a clean quartzite and quartz-pebble conglomerate no longer lensitic. Because of its excellent grain rounding and sorting and its dune-size cross-bedding, the Lorrain has generally been viewed as an aeolian deposit. The presence of rounded pebbles of up to two inches in diameter, which are difficult to explain in an aeolian environment, has led to an alternate hypothesis that this formation represents a beach deposit. Young (1973) describes the Lorrain Formation as a deposit resulting from combined aeolian and beach processes.

Casshyap (1966) interprets the whole of the Mississagi Formation as a fluvial deposit, but its petrographic and textural similarities to similar rocks within other glacial cycles stratigraphically above it should warn against such a conclusion. The occurence of a thick basal dark-matrix conglomerate and fine-grained sediments (mostly argillites) between the conglomerate and the arkoses above is similar to the Bruce - Espanola -Serpent transition.

4. A Working Model

In a glacial/periglacial environmental framework, the Huronian sequence can be explained as being the deposits resulting from an ice sheet, whose three periods of advancement and retreat are recorded in the three cycles within the sequence. Each cycle is represented by a basal tillite conglomerate deposited by the advancing ice sheet, overlain by fine-grained, parallel-laminated sediments deposited in the deep water of a glacial lake or marine basin (if physically possible) or both. Each cycle is terminated by coarser-grained, cross-bedded clastics deposited in a continental (possibly glacio-fluvial) environment. The clean, well sorted quartzites of the Lorrain Formation possibly represent reworking of these clastics by combined aeolian/beach processes (Figure 6). Similar glacial/periglacial cycles have been described by Moorman (1974) in a section of Proterozoic rocks in Western Canada, and by Foyn (1937) in a section, which includes carbonate rocks, in the Spitzbergen Islands, Norway.

Figure 5, which correlates the generalized Geneva Lake section to the type Huronian section on the North Shore, illustrates that all

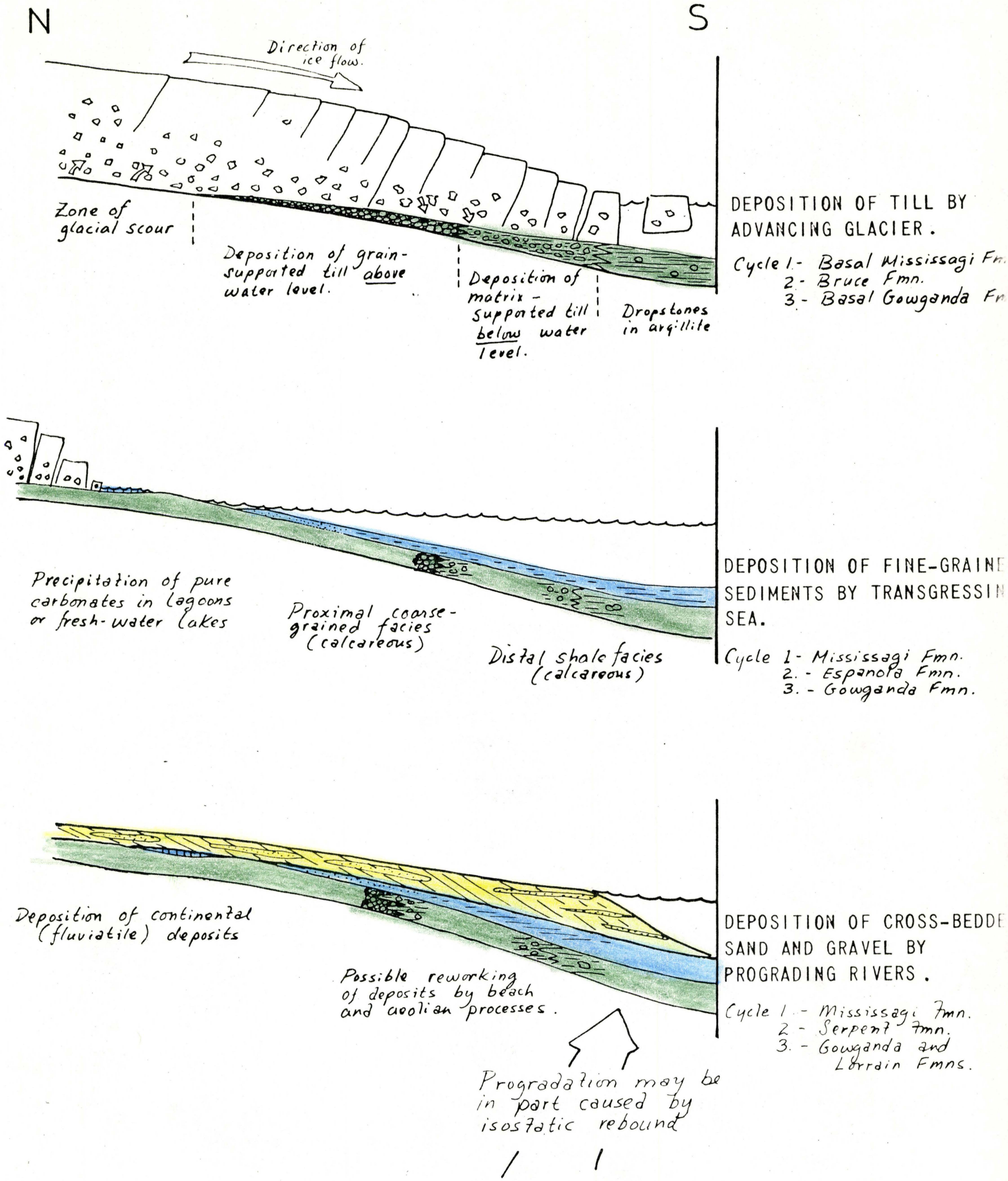


FIG. 6 - ENVIRONMENTS OF HURONIAN DEPOSITION

A WORKING MODEL BASED ON TERNARY CYCLICITY WITHIN THE HURONIAN SEQUENCE.

the formations thin stratigraphically towards the north. This is especially true of the lower formations, one of which (the Mississagi Formation) is missing from the Geneval Lake section.

In southern Ontario, most of the Pleistocene glacial/periglacial deposits record only the last (Wisconsinan) ice advance. Remnants of earlier ice advances are found only locally since southern Ontario is considered to have been an area of scouring during the earlier glacial advances. The absence of the Mississagi Formation at Geneva Lake might therefore indicate that this area may have been an area of scouring, either during deposition of Mississagi sediments to the south, or during the following ice sheet advance at which time the sediments would be re-incorporated into the second ice sheet.

It has been suggested that the basement rocks to the north were constantly rising during these glacial/interglacial cycles. A constant paleocurrent direction to the south and south-west (Young, 1968; Cassyhap, 1969) and the presence of breccias, slumping and clastic dykes in the Espanola and Serpent Formations (Chapter 3) suggest the likelihood of such tectonic movement. This would help to explain a generally north to south ice advance and help to explain the wedging out of all the formations to the north.

CHAPTER THREE

THE ESPANOLA FORMATION - REGIONAL ASPECTS

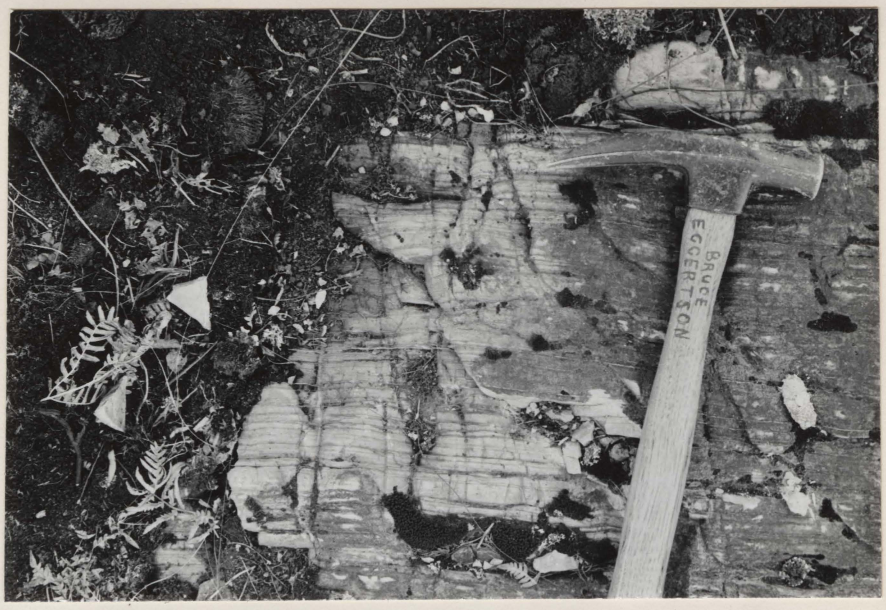
I. REGIONAL COMPARISON OF GROSS LITHOLOGIES

It is evident from the foregoing descriptions in Chapter 2 that the Espanola Formation near Geneva Lake is both similar to and different from that of the type section on the North Shore. Stratigraphic sections of the Espanola Formation were measured at Geneva Lake and in three areas to the south and west: north of the town of Elliot Lake, south of the town of Espanola, and at Moose Point, south of Whitefish Falls. An additional section was observed near Panage Lake (Figure 2) which is related to the section near Espanola. These measured sections are described below with respect to lithology and are compared with a generalized section of the Espanola Formation at Geneva Lake.

1. Espanola Formation at Geneva Lake

Sections of the Espanola Formation exposed at Geneva Lake consist of 100 - 200 feet of calcareous siltstones and sandstones with an almost equal thickness of unusually clean, almost pure limestones and dolostones giving a total stratigraphic thickness of 200 - 400 feet.

In the six stratigraphic sections measured at Geneva Lake (Figure 4) there is an upper carbonate member of up to one hundred feet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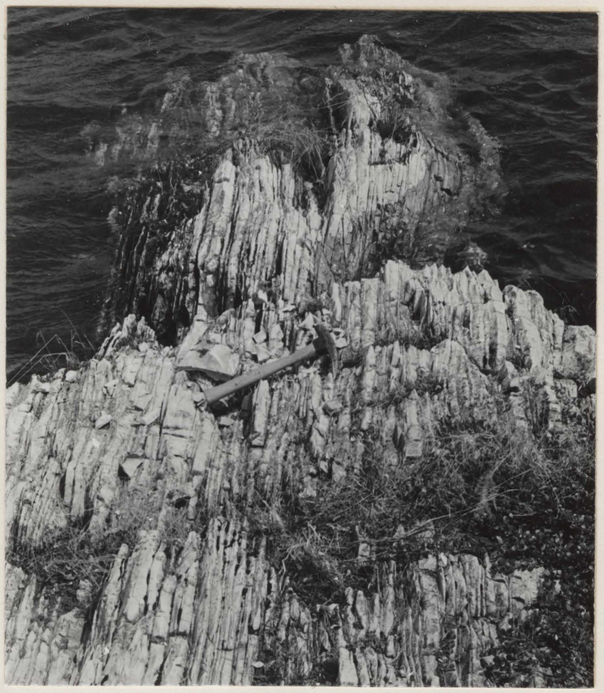


in thickness which consists predominantly of thinly bedded microcrystalline dolostones with lesser amounts of micritic limestones. Both lithologies are unusually pure (90 - 95 percent carbonate), slightly siliceous, and contain shale partings (Plate 7). Disseminated pyrite is common in this member (Thin sections R9, B12).

Conformably underlying this is a 100 - 200 foot thick calcareous clastic member with grain size varying from silt size (Thin section R8) to coarse-grained sand size (Thin section R10). This member has a carbonate content of about 20 percent and also contains disseminated pyrite.

Where this clastic unit does not lie directly on the Archaean basement, there is a lower carbonate member present which has a maximum stratigraphic thickness of up to 100 feet. This member is predominantly pure limestone, consisting of 80 - 85 percent sparry or microsparry calcite and contains angular grains of quartz silt and some shale partings (Thin section G1).

2. Espanola Formation Near Elliot Lake

This section, exposed on the Quirke Lake syncline north of Elliot Lake, was studied in detail by Young (1973). It has an overall thickness of 480 feet (Figure 7) and conformably overlies the Bruce Formation, a matrix-supported conglomerate at this locality.

The uppermost 100 feet consists of a sandy, rust-coloured dolostone which is commonly cross-bedded and contains some interbedded argillites.

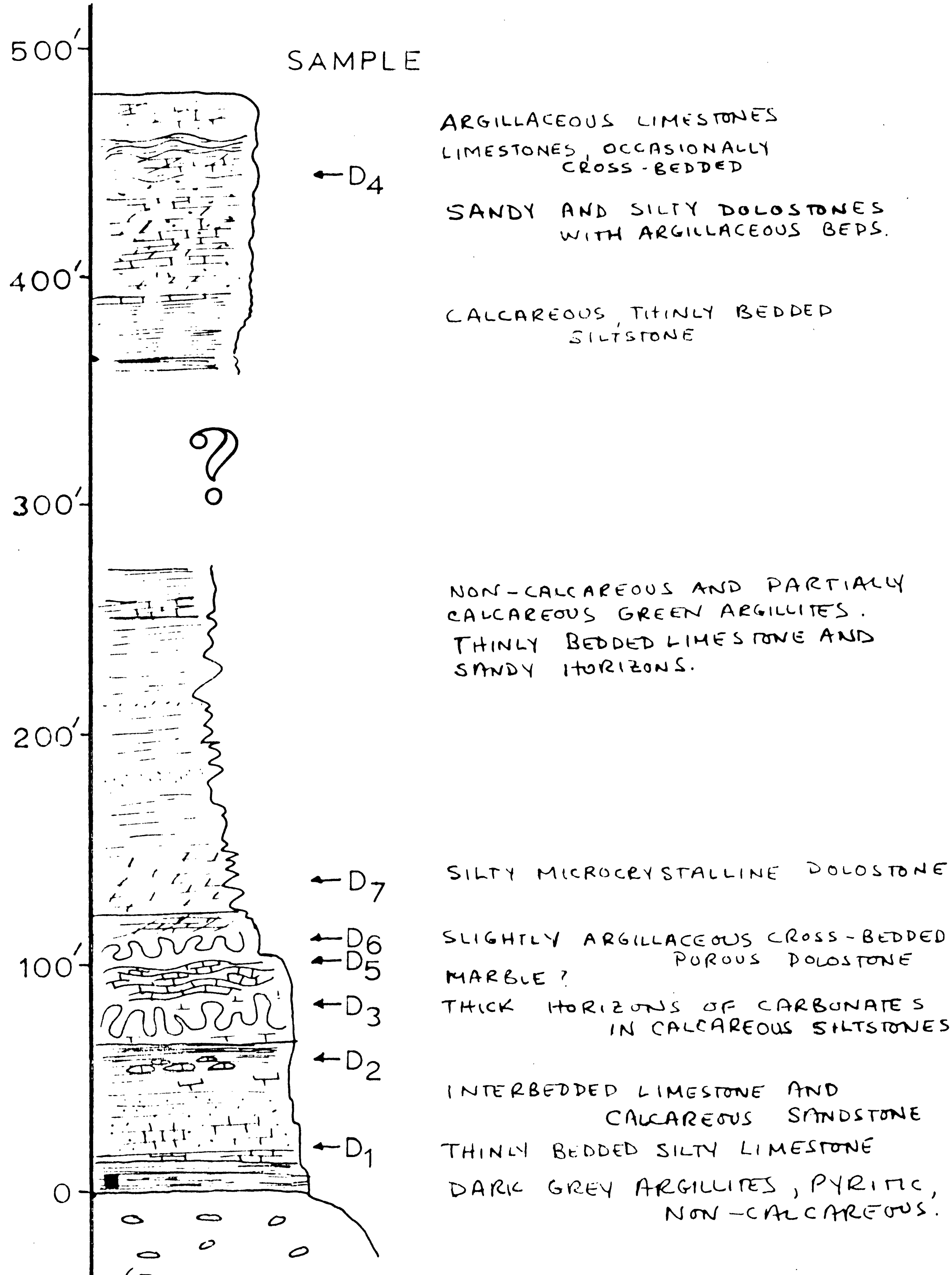


FIG. 7 - STRATIGRAPHIC SECTION OF ESPANOLA FMN. NEAR ELLIOT LAKE

The middle 275 feet is partly obscured but consists of a series of finely laminated argillites with intercalated sandy horizons. This unit is irregularily and alternately calcareous and non-calcareous.

The bottom 100 feet is a silty limestone with minor beds of pure limestone.

In gross lithology, this section is similar to the section at Geneva Lake except that the upper and lower carbonate members near Elliot Lake are considerably thinner and less pure. From a structural point of view, the beds in this section are extensively bondinaged (Plate 8) in contrast to the Geneva Lake section where simple block faulting is the major mode of deformation (See Section II).

3. <u>Espanola Formation On Moose Point</u>

Moose Point, a promontory into the Bay of Islands just south of Whitefish Falls, displays in outcrop a complete vertical section of the Espanola Formation (Figure 8). The conformable contact with the underlying Mississagi Formation (cross-bedded quartzites at this locality) can be observed. The section is overlain by cross-bedded quartzites which may represent an uppermost fluvial member of the Espanola Formation (Young, 1973), a basal member of the Serpent Formation, or even a faulted section of Mississagi Formation.

The total stratigraphic thickness of the Espanola Formation at Moose Point is 1200 feet. The dominant lithology is a fine-grained calcareous siltstone in which the calcareous material is disseminated throughout the fine-grained matrix or occurs as calcite nodules which weather easily to vugs (Plate 9).

PLATE 8 - ESPANOLA FORMATION - ELLIOT LAKE

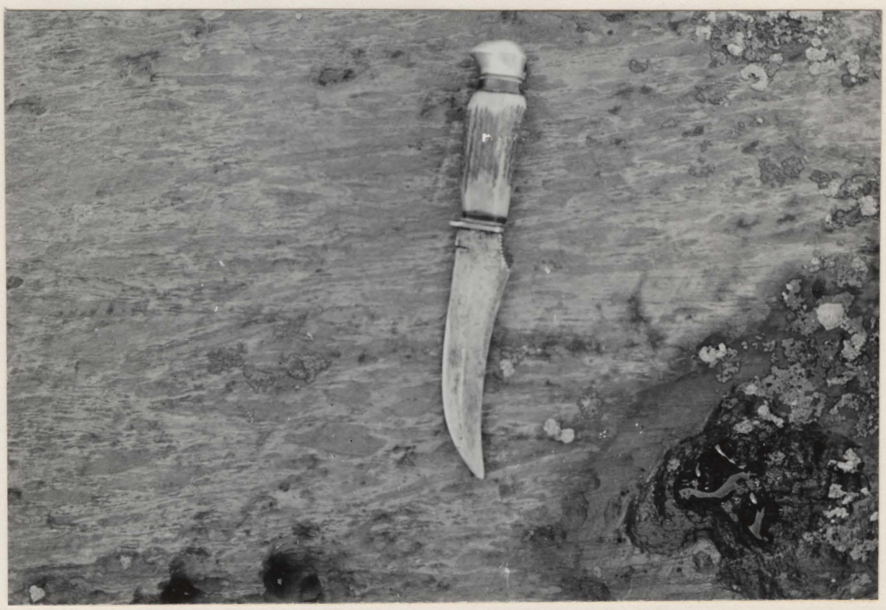
Intense pinch-and-swell, boudinage, and sympathetic folding are seen in this textbook outcrop north of Elliot Lake in the Quirke Syncline. The beds are alternately 70% carbonate and calcareous siltstone.

PLATE 9 - ESPANOLA FORMATION - MOOSE POINT

In the calcareous siltstone lithology common on the North Shore, vugs are exposed on a weathered surface where calcareous boudins have been eroded.

PLATE 10 - ESPANOLA FORMATION - MOOSE POINT

An unweathered surface shows the intense boudinage of the thinly bedded carbonates and siltstones.

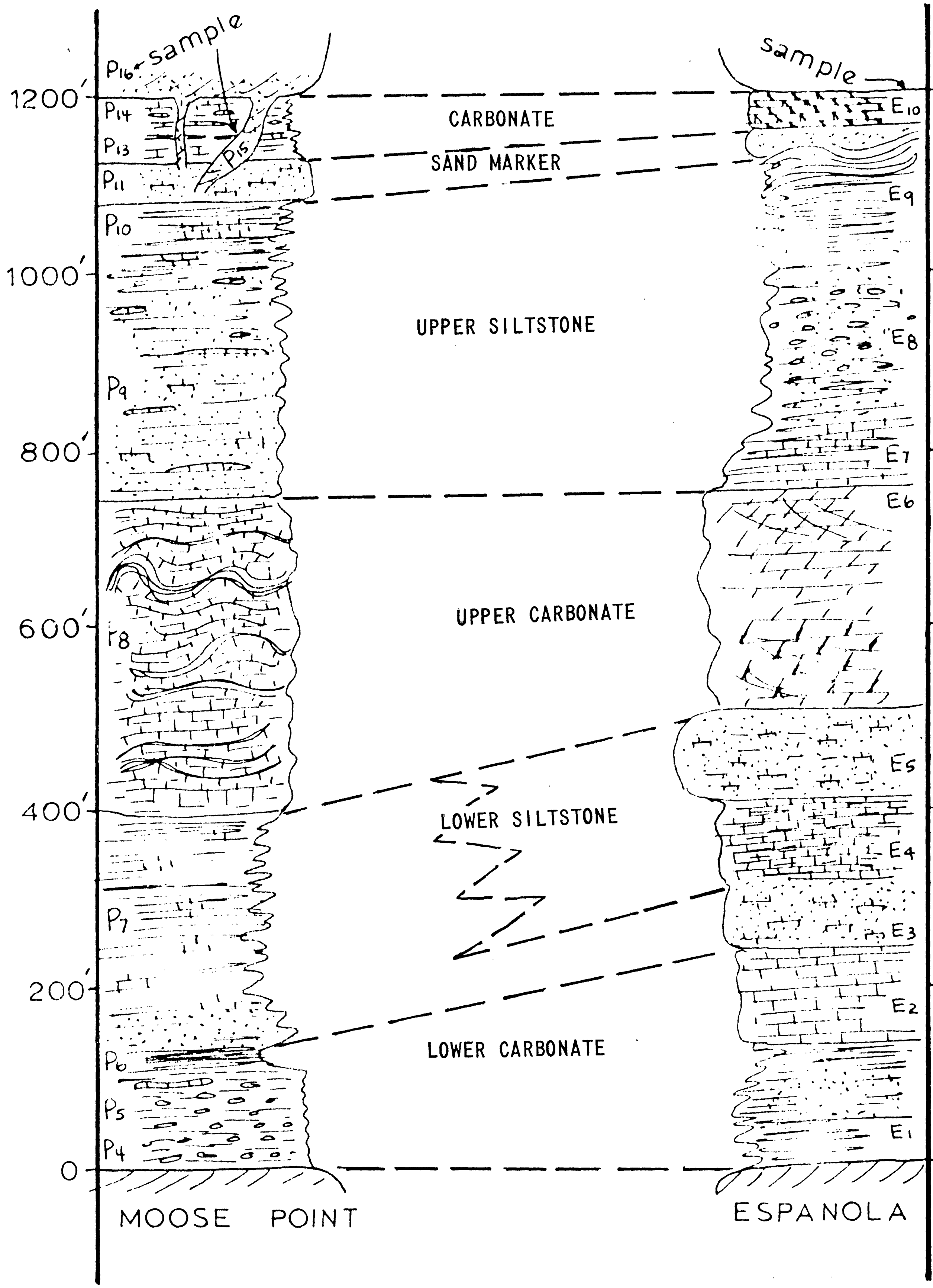


The section has two zones, one near the middle and another at the top of the section, in which the beds become less silty and the carbonate fraction exceeds 50 percent, although only in the middle zone are 75 percent pure limestones ever found. Locally, where these carbonate beds are thin, they have boudinaged within the siltstones (Plate 10). This contrasts to both the Geneva Lake and Elliot Lake sections in which pure carbonate lithologies are a major component in the total stratigraphic thickness.

4. Espanola Formation Near Espanola

In gross lithology, the 1200 foot thick section of Espanola Formation, measured south of the town of Espanola, is similar to that at Moose Point. The two sections are, in fact, located on the adjacent limbs of two parallel anticlines. The Espanola Formation near Espanola (Figure 9) consists of the same calcareous siltstones and sandstones found on Moose Point. The sections are different only in so far as the apparent average grain size in the bottom 500 feet of the Espanola section is coarser (medium sand size) than that at the bottom of the Moose Point section. In addition, the gross lithology appears to be more calcareous in the Espanola section than in that at Moose Point.

The gross lithology of the Espanola Formation near Espanola is similar to that of the middle member of the formation at Geneva Lake, but has no pure carbonate member similar to that which is found at Geneva Lake and Elliot Lake.



FIGS. 8&9 - STRATIGRAPHIC SECTIONS OF THE ESPANOLA FMN. ON THE NORTH SHOR

A stratigraphic section at Panage Lake is located along strike 15 miles to the east of the section at Espanola. Because of poor outcrops of the Espanola Formation in the section near Espanola, the section at Panage Lake was also investigated. No new or different stratigraphic or lithological data were obtained from Panage Lake, but structures were very well exposed (See Section II).

II. DESCRIPTION OF STRUCTURES IN THE ESPANOLA FORMATION

1. Small Scale Sedimentary Structures

Although most of the Espanola Formation is horizontally bedded (both the pure and argillaceous lithologies), cross-bedding and ripple laminae are commonly found in the coarser-grained units. Young (1973) mentions a locally scoured surface in the Espanola Formation which is associated with an overlying flat pebble conglomerate. All three of these structures indicate that at least part of the Espanola Formation was re-worked in a moderate to high energy environment. The only other sedimentary structure found in the Espanola are desiccation cracks (?) in the limestone at Geneva Lake (Plate 11).

2. Local Tectonic Structures

Whether as a result of continual continental uplift to the North during the time of Huronian deposition or as a result of buoying in response to isostatic rebound following the retreat of an ice mass,

PLATE 11 - ESPANOLA FORMATION - GENEVAL LAKE

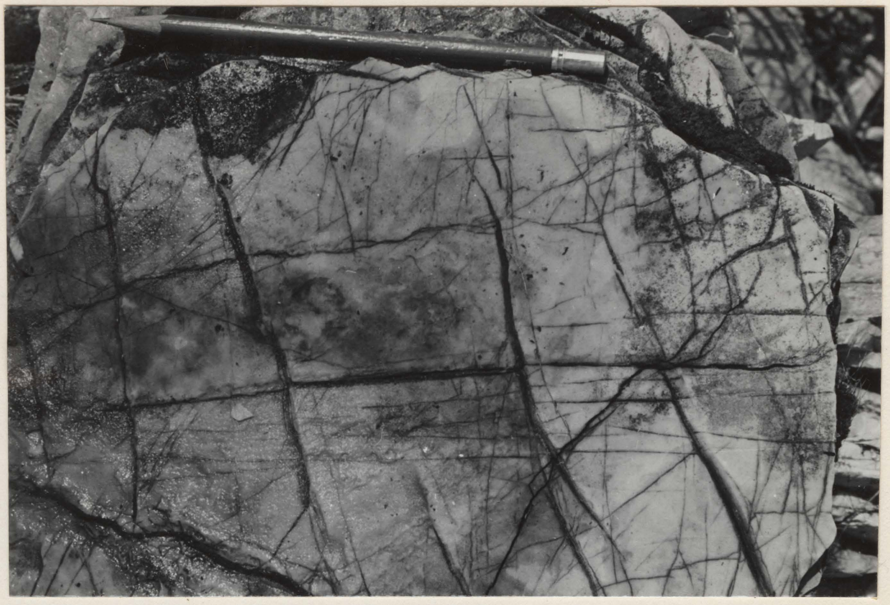
A bedding surface of the pure limestone found at Geneva Lake, shows heavy fracturing. It has been suggested that these might represent, in part at least, former dessication cracks.

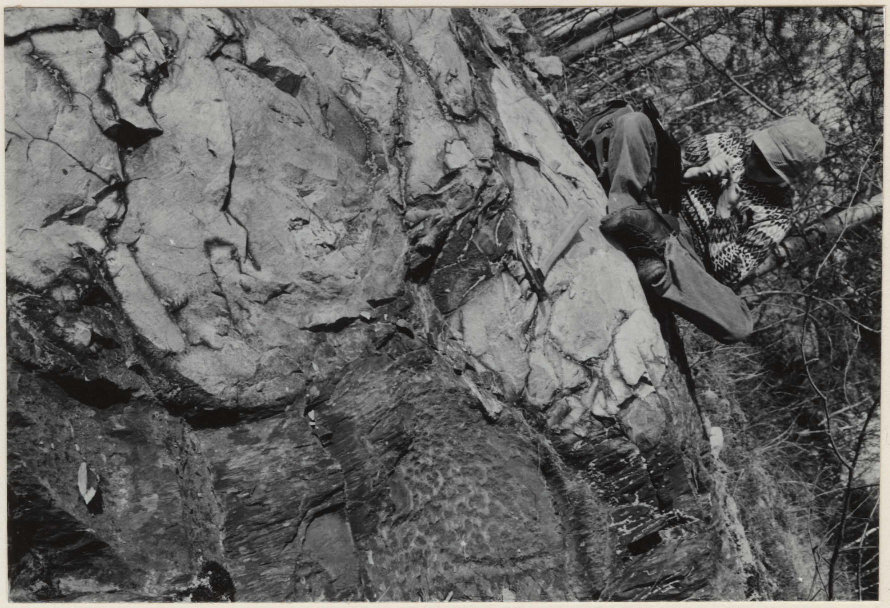
PLATE 12 - BALL AND PILLOW STRUCTURE

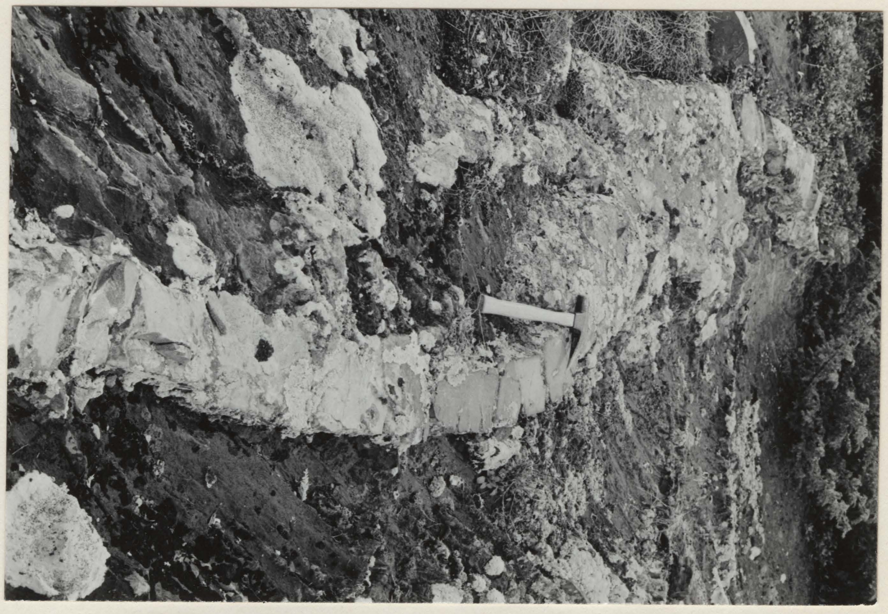
Shows loading of the Serpent Formation into the underlying Espanola Formation which was probably not fully consolidated at the time.

PLATE 13 - CLASTIC DYKE

A sand-filled vein or 'dyke' cutting sharply through beds of Espanola Formation at Moose Point, is thought to be caused by injection of underlying unlithified sands into a fracture, or by the infilling of a fracture with sand from above.







both the Espanola and Serpent Formations have characteristic structural features that give evidence of severe, short-lived tectonic mass movements.

(i) Breccias are common in the Espanola. They are well documented by Young (1973) in the Quirke Lake area, but were also found at Panage Lake and Geneva Lake (Thin section $G6_{(1)}$).

(ii) Load Structures, commonly called "ball and pillow" structures are the result of an instability created by a partially consolidated lithology overlying a less consolidated lithology in which there is a relatively high pore water pressure. A sudden tremor of medium magnitude will cause "balls" of the upper lithology (usually sand) to fall into "pillows" of the underlying lithology (usually clay, which flows around the sand balls) (Plate 12).

(iii) Clastic Dykes, of clean quartz sand, cut sharply through the calcareous Espanola Formation. These are thought to be the result of either injection of clastic material in fluid form from below as a result of loading (Young, 1973), or filling of fissures and cracks, possibly of tectonic origin, by unconsolidated clastic sediments from above (Plate 13). A sample of one of these sandstone dykes on Moose Point proves upon analysis to be similar to a sample of the immediately overlying Serpent Formation. (Samples P15 and P16).

3. Regional Tectonic Structures

In the southern exposures, along the North Shore, the regional forces which folded the whole Huronian sequence into giant parallel E-W anticlines and synclines has also left some small-scale structures in the record. The most noticeable are the boudinage and the pinch-and-swell structures which are found at Moose Point and near Elliot Lake. The boudinage of competent carbonate layers within the laminated siltstones as well as the elongated calcite nodules show an E-W elongation of about 2/1.

In a road cut just north of Elliot Lake (south limb of the Quirke Lake syncline), there are some textbook examples of intense sympathetic folding, boudinage, pinch-and-swell and accommodation features (Plate 8). Obviously, similar forces were at work here to produce the large syncline and these associated structures, although the N-S shortening is not nearly as much as to the south on the North Shore.

In the Geneva Lake area no such structures were observed. According to Osborne (1929) there is some evidence of local thickening in the Serpent Formation as a result of compressional forces, but the chief structure in this area is one of block faulting, which cannot be observed on a small scale except as numerous parallel slickensided surfaces.

III. CORRELATION AND DISTRIBUTION OF THE ESPANOLA FORMATION

Correlation of the four cross-sections of Espanola Formation measured at Geneva Lake, Elliot Lake, Moose Point and Espanola is attempted in

Figure 10. It is possible to subdivide the formation into a lower limestone member (the Bruce Limestone), an intermediate argillaceous member (the Espanola Greywacke) and an upper predominantly dolostone member (the Espanola Limestone) as suggested by Collins (1914). An uppermost sandstone member, recognized by Card (1969) and studied in detail by Young (1973) is locally present along the north shore. It is thought to represent the distal facies of a meandering river (Young, 1973) and might be related to the conformably overlying Serpent Formation. It is non-calcareous and for that reason only was not included in the measured stratigraphic sections in this chapter. Young (1973) interprets these four members of the Espanola Formation, in ascending order, as having been deposited in shallow marine, deep water marine, shallow marine and fluviatile environments. This sequence is suggested to reflect a cycle of marine transgression and regression following the retreat of an ice sheet (Young, 1973).

Because these members wedge out towards the north and are discontinuous even between stratigraphic sections in the same area (Figure 4), a subdivision of the Espanola Formation by total stratigraphic thickness and gross lithology in a spatial rather than vertical framework proved to be more useful in determining the distribution of the formation. Figure 11 is a fence diagram which includes the four stratigraphic sections described earlier in this Chapter, a section from Parkin Township described by Meyn (1973; see Figure 2) and sections measured and described by ~~Robsertson~~ Robertson (1973) at LaCloche Lake, Denvik Lake, Ten Mile Lake and Aird Island (Figure 2).

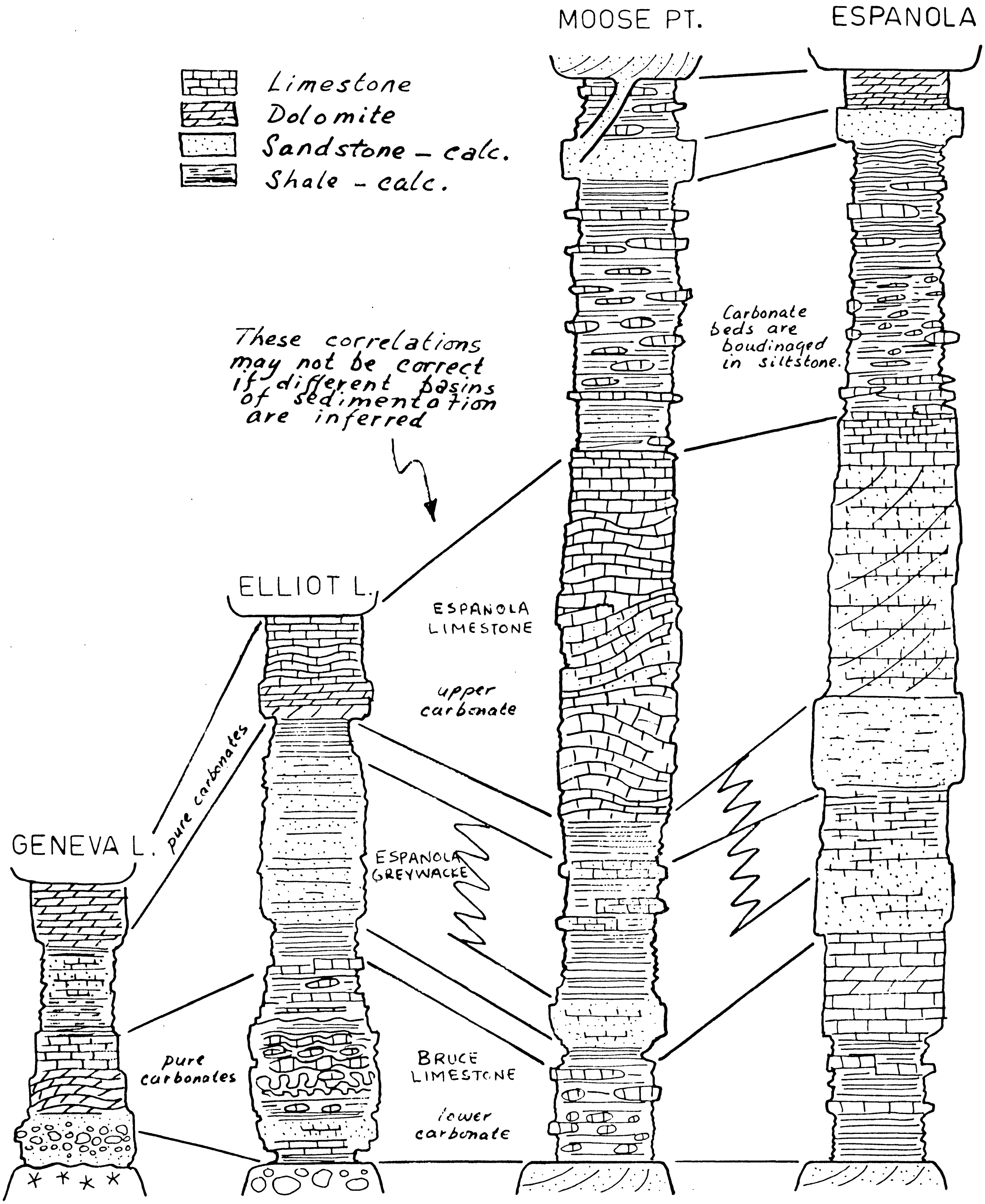


FIG.10 CORRELATION OF THE ESPANOLA

SCALE 1" = 200'

Meyn (1973) found the stratigraphic section of the Espanola Formation in Parkin Township 40 miles east of Geneva Lake to be quite similar both in total section thickness and gross lithology, to that at Geneva Lake. According to Robertson (1973) the section at Ten Mile Lake is only slightly thinner than that at Elliot Lake, ten miles to the east. At LaCloche Lake, 15 miles along strike to the west of the 1200 foot thick section at Espanola, the section is only 600 feet thick. The thickest section of Espanola Formation (1800 feet) is found on Aird Island, 20 miles along strike to the west of LaCloche Lake. Near Denvic Lake, only six miles north of Aird Island, the section wedges out completely. Five sections described by Card et al (In Print) are 15 miles to the north of Espanola (Section 18), 5 miles to the west (Section 21) and 10, 15 and 20 miles to the southeast of Espanola (Sections 24, 23, 22).

Towards the north of its outcropping area, the Espanola Formation stratigraphically wedges out and towards the south it disappears into the Grenville Front (Quirke and Collins, 1930).

Figure 12 illustrates the spatial grouping of the Espanola Formation into three areas based on gross lithology and total stratigraphic thickness.

Area "A", north of Sudbury, consists of 100 - 200 feet of approximately equal proportions of fine-grain calcareous siltstones and unusually pure dolomites and limestones.

Area "B" (near Elliot Lake) consists of 400 - 600 feet of Espanola Formation which can be subdivided into a basal and an uppermost

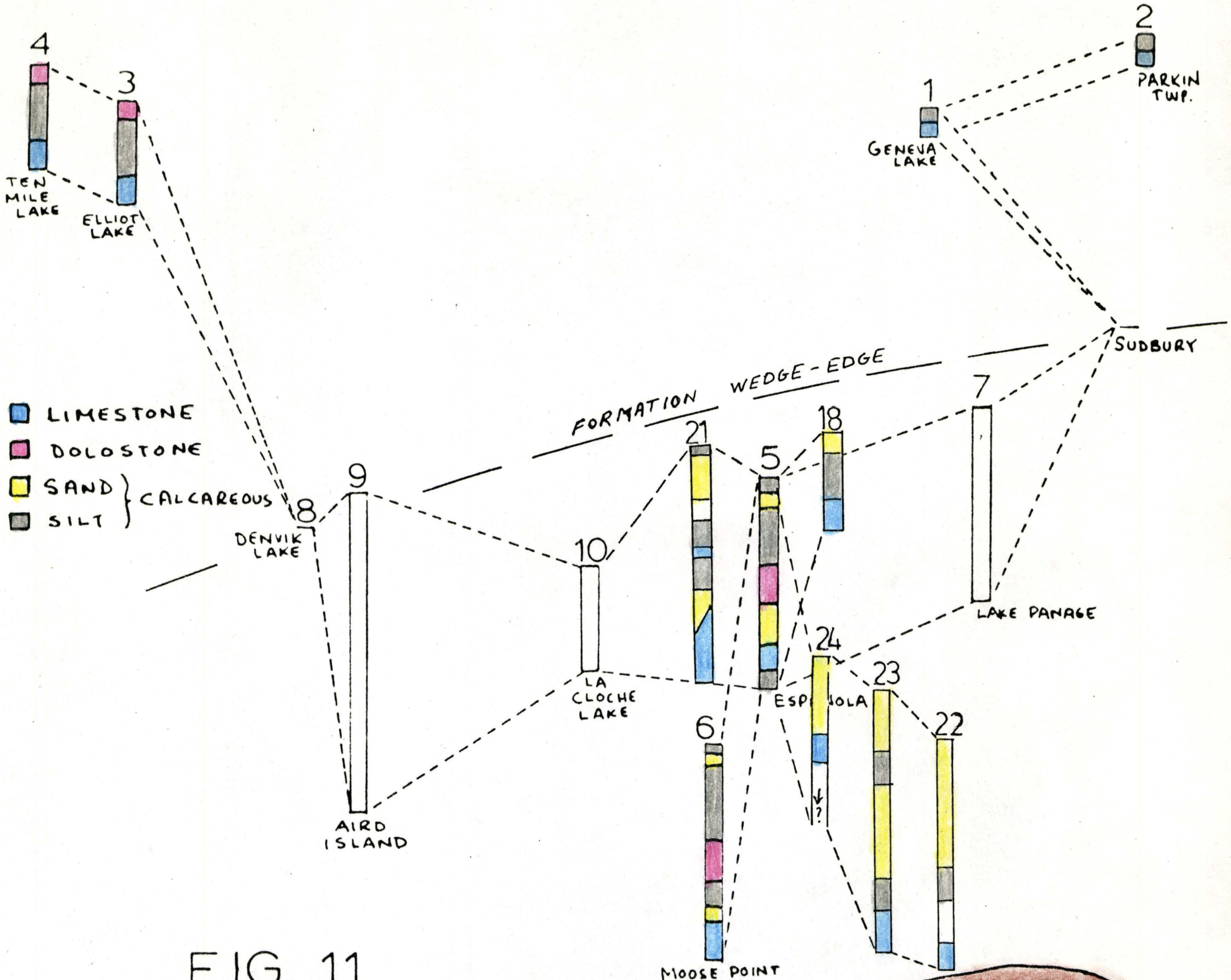


FIG. 11

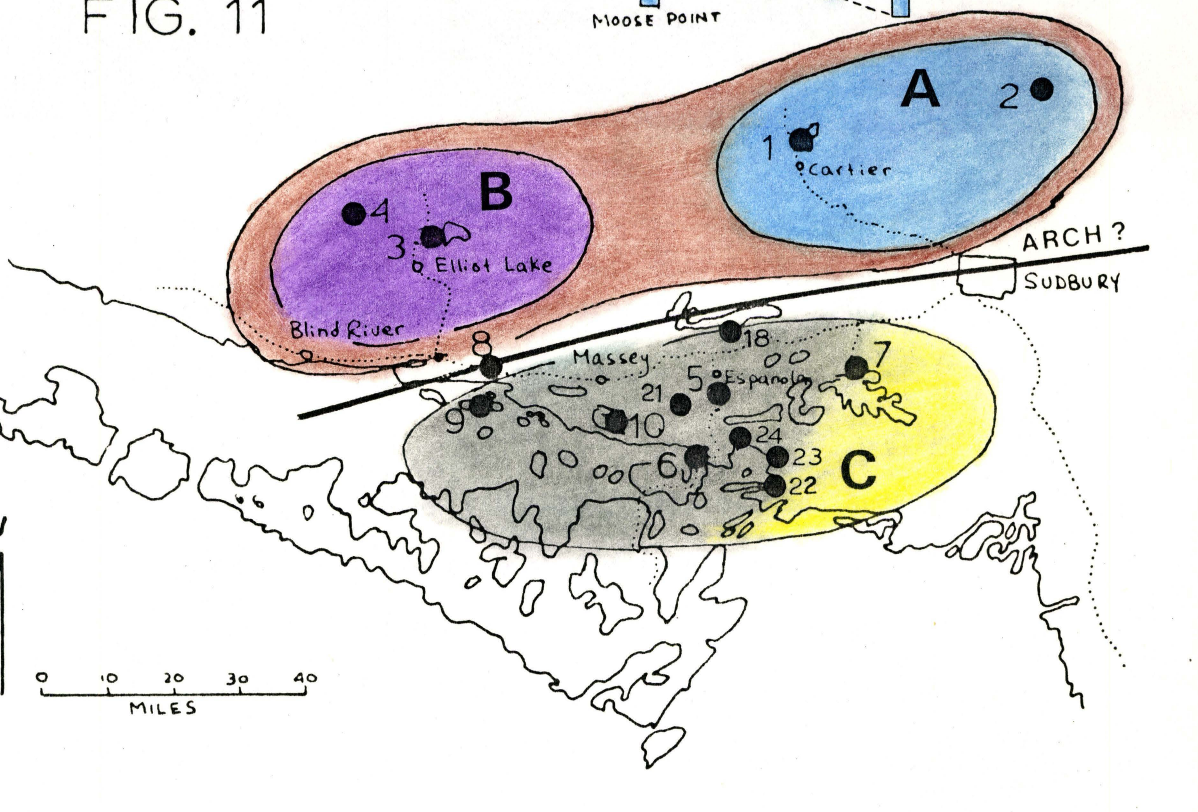


FIG. 12 - SPATIAL GROUPING WITHIN THE ESPANOLA FORMATION

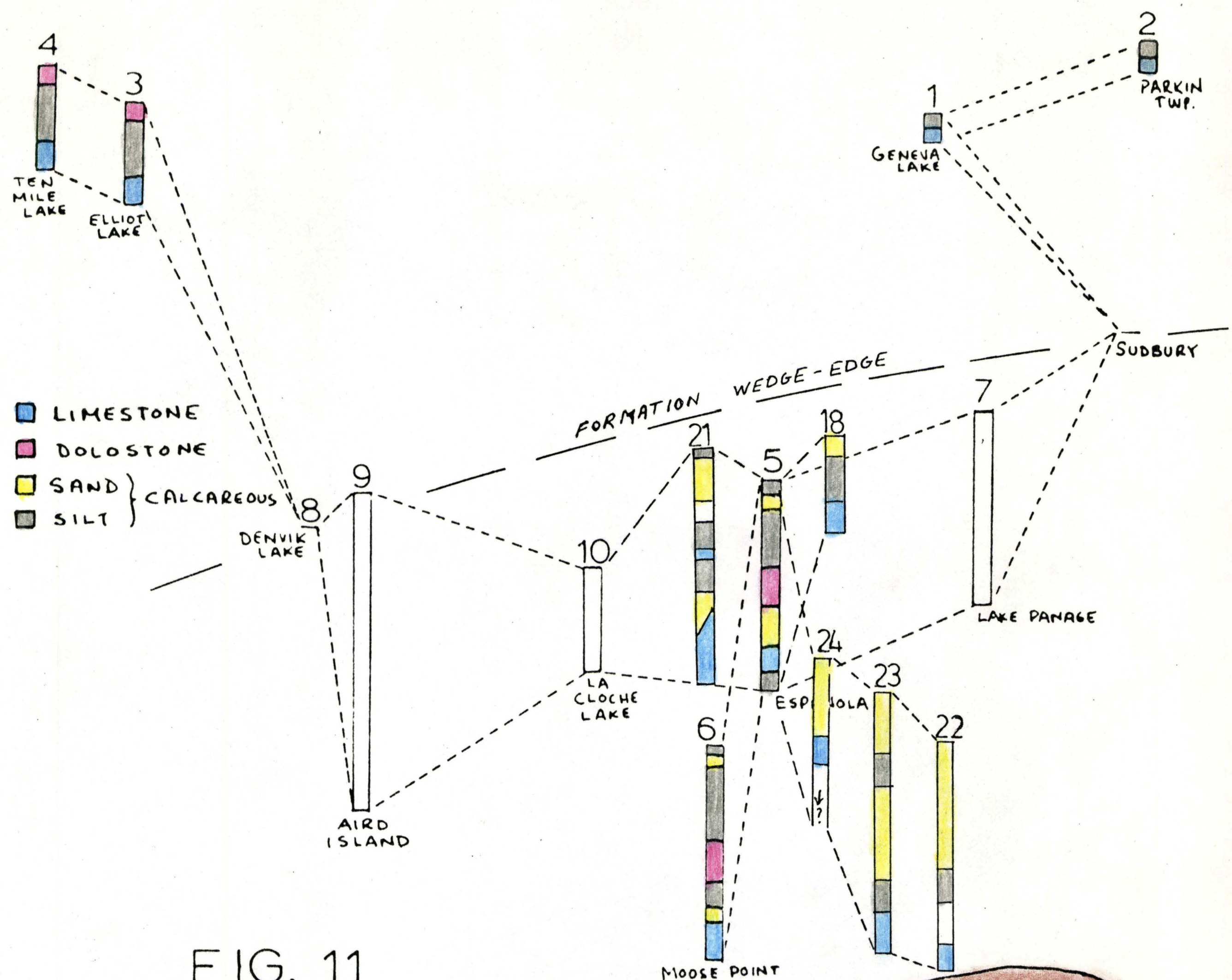


FIG. 11

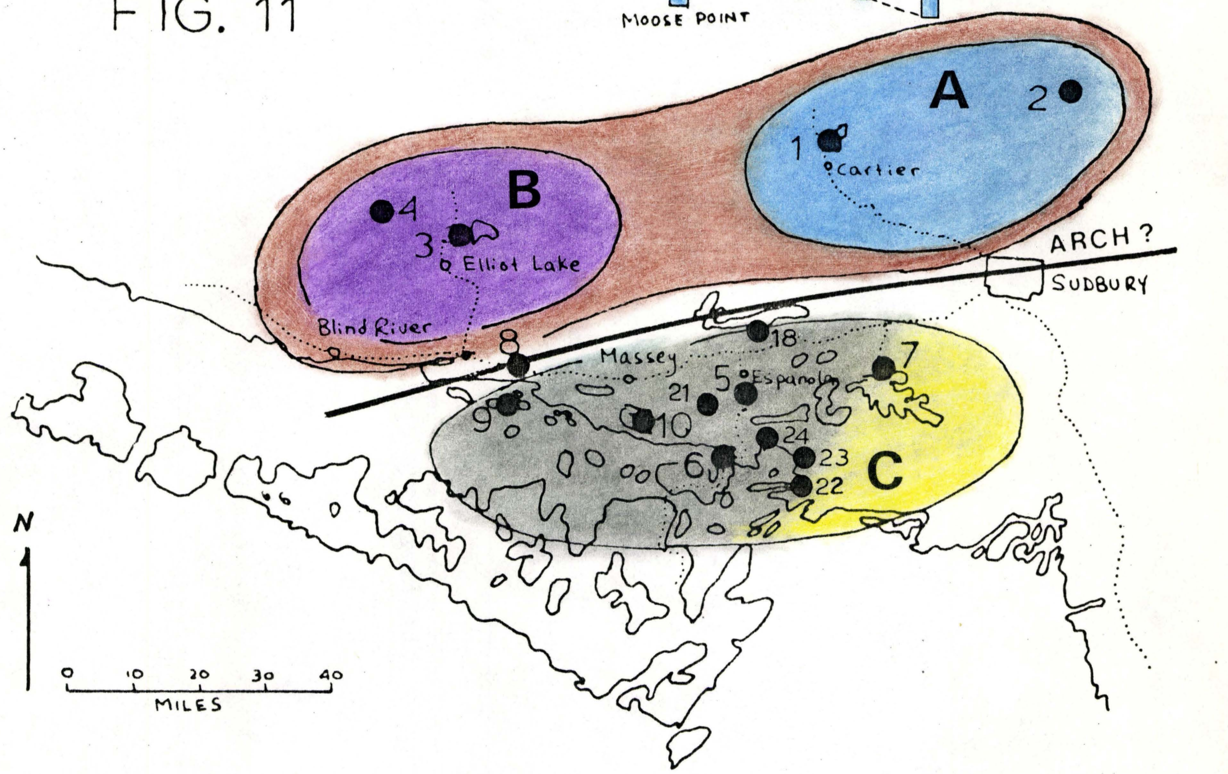


FIG. 12 - SPATIAL GROUPING WITHIN THE ESPANOLA FORMATION

pure to dirty limestone and dolostone units separated by 200 - 300 feet of slightly to non-calcareous fine-grained siltstones and sandstones.

Area "C" (south of an imaginary (hinge?) line between Sudbury and Blind River) consists of 600-1,800 feet of dirty calcareous siltstones and sandstones with minor amounts of impure carbonates. Sections 22, 23 and 24 measured by Card et al (In Print) show an increase in the sand-size clastic component to the southeast. The absence of the Espanola Formation at Denvic Lake could be an erosional feature. Alternatively, this area may have been a topographic high during the deposition of the Espanola Formation, as is suggested for the Sudbury area (Palonen, 1973), and thereby represent an area of non-deposition.

This ternary spatial grouping is useful for speculating on the nature of the basin of deposition of the Espanola Formation. It is possible that this basin could have been divided into three different sub-basins (Figure 12) or into two different basinal environments one on either side of the imaginary arch between Sudbury and Blind River. For example, it is possible that the areas "A" and "B" (Figure 12) could represent deposition of the Espanola Formation in large, shallow lakes at the same time that marine deposition of the same formation was occurring in area "C" (Lindsay, 1969).

The lithologies presented earlier in this chapter suggest three major specific environments of deposition:

(i) One in which the pure limestones and dolostones containing parallel laminae and shale partings suggest deposition in a quiet environment with little or no clastic input.

(ii) A second environment in which calcareous argillites suggest deposition in a low-energy environment in which there is a very high input of fine-grained clastics and a fluctuating input of calcareous material.

(iii) A third environment in which calcareous coarse-grained clastics containing cross-bedding, breccias and scoured surfaces, suggest deposition in a high-energy environment which has a varying input of calcareous material.

It is difficult to specifically label these environments. The first might be found in a restricted, shallow marine basin, on a stable shelf, in a restricted lagoon or even in a fresh water lake. The deposits of this environment may be organic or inorganic (See Chapter 5). The second appears to be typical of a deep marine basin; perhaps the third environment represents the shallow-water equivalent of the second. These environments are compatible with the model of a marine transgression during glacial regression, as described in Chapter Two (also Figure 6, middle).

CHAPTER FOUR

THE ESPANOLA FORMATION - LABORATORY INVESTIGATIONS

Thirty-nine representative samples of the Espanola Formation were studied in the laboratory to support the field data of this paper. Twenty-three thin sections were prepared to determine the petrology. Insoluable residues were extracted from five samples in order to study the clastic fraction of the rocks and to recovery any organic material or any microfossils which might have been preserved. Eleven samples were studied with a scanning electron microscope to determine the microtextures and again to search for microfossils. The use of the "Kevex-Ray" elemental detector, in conjunction with the scanning electron microscope, is discussed.

I. THIN SECTION STUDY

Twenty-three thin sections were examined petrographically and are described in detail (Appendix A). Care was taken to ensure that each lithology in the Espanola Formation was represented in thin section. Those from the Geneva Lake are indexed in Figure 3. The thin sections can be divided into four groups, each of which is discussed below. The first three groups are representative of the three predominant lithologies of the Espanola Formation. The fourth group contains thin sections of lithologies outside the Espanola Formation but which are important in the understanding of the Huronian Sequence.

1. Pure Micritic Carbonates (Samples R9, B12, L7, L14, G1, G6(2).)

A thin section of Sample R9 (Geneva Lake), which is a microcrystalline dolomite, shows a 99 percent pure carbonate with only a trace of detrital material. The micritic matrix is apparently primary but has been recrystallized in part to a microsparite during diagenesis.

A thin section of sample B12 (Geneva Lake), shows a microcrystalline dolomite of similar unusual purity (95 percent). Angular silt-size quartz grains (3 percent) and opaques (2 percent) are scattered randomly throughout the matrix or along lineations that represent shale partings.

In sample L7 (Geneva Lake) a pure, micritic limestone is host to a fracture which is oriented perpendicular bedding, and which had subsequently been infilled with silt-sized subangular quartz grains. The quartz appears to have been derived from a similarly quartz-filled parting that is parallel to bedding. Angular silt-sized quartz grains and opaques (pyrite?) are scattered throughout the micritic matrix, which is otherwise as pure as Samples R9 and B12. In contact with the vertical quartz-filled fracture, the micrite has been recrystallized to a microsparite.

Thin sections of samples L14 and G1 (Geneva Lake) illustrate a pure limestone with pronounced shale partings. Silt-sized quartz grains are also scattered throughout a martix which, in the case of both samples L14 and G1, consists of sparite and microsparite.

Sample G6(2) (Geneva Lake) is similarly a 95 percent pure micritic limestone with shale partings and scattered grains of silt-size quartz. In this sample, a vein is filled with sparry calcite crystals which exhibit twinning under cross-polarized light.

These six samples illustrate the uncommonly pure micritic limestones and dolostones that occur in the section of Espanola Formation near Geneva Lake. The micrite appears to be primary, and is recrystallized locally into sparite and microsparite. Angular, silt-sized quartz grains and opaques of pyrite are scatterred throughout the matrix or are concentrated in partings. Quartz and calcite-filled veins are common. Secondary micas are present in some samples and indicate that low-grade metamorphism might have place in the Geneva Lake area.

2. <u>Calcareous Siltstones</u> (Samples E2, E4, P4, P5, B15, P9, P14).

A thin section of sample E2 (Espanola) illustrates a calcareous siltstone in which microcrystalline calcite and quartz silt occur in equal proportions with some randomly scatterred chert, green mica, and opaque minerals (pyrite?).

Sample E4 (Espanola) is a calcareous siltstones in which quartz silt and green micas are enclosed in a 30 percent micritic matrix. In this sample there is 5 percent porosity which may have resulted from weathering. Porosity is not found in other samples.

Samples P4 and P5 (Moose Point) are calcareous siltstones which have been structurally flattened. Boudins can be seen microscopically to consist of sparry calcite. The boudins are set in a matrix of calcareous siltstone containing secondary micas.

Sample B15 (Geneva Lake) is a good example of a cyclic or banded claystone. It is from the Gowganda Formation but is the only sample of a calcareous rock found that was not located stratigraphically in the Espanola Formation. The bands are 2-5 millimeters and are differentiated by grain size (clay/silt). The clay-rich bands are extensively jointed at a consistent angle of 35° to bedding.

Samples P9 and P14 (Moose Point) are similarly banded calcareous siltstones. Microscopically, they consist of bands of 2-5 millimeters in thickness, which are alternately clay or silt as in Sample B15. The finer-grained bands are again jointed but because of extensive boudinaging, the constant-angle fracture pattern is lost. The banding in all three samples might represent seasonal "varves" but age dates would be necessary.

These seven samples are representative of the calcareous siltstones found throughout the Espanola Formation on the North Shore. The clastic fraction is fairly uniform in grain size except when banded, and the calcareous fraction varies from 10 to 50 percent approximately.

3. Calcareous Sandstones (Samples R4, R10, E6, E10, L18, G6(1))

Thin sections of samples R4, R10 (Geneva Lake) and E6, E10 (Espanola) will illustrate this lithology type. These four samples consisted of commonly subangular, medium sand-size, quartz grains with abundant feldspar and/or rock fragments. Samples R10 and E10 contain at least 25 percent feldspar, which defines them as arkoses. The calcareous fraction ranges from 10 to 30 percent, and accessory chert, green micas and opaque minerals are always present. Sample E6 contains limestone allochems of similar grain size to the quartz clasts present.

A thin section of sample L18 shows a recrystallized sparry calcite in which secondary sericite is almost as abundant as the carbonate fraction. This is the most metamorphosed sample taken from the Geneva Lake area.

Sample G6(1) is a brecciated calcareous siltstone, in which fractures have been infilled by calcite or by an argillaceous matrix.

4. Other Lithologies (Samples B4, B7, R14, R7)

Thin sections were made of samples B4 (Geneva Lake - Upper Gowganda Formation), B7 (Geneva Lake - Lower Gowganda Formation) and R14 (Geneva Lake - Serpent Formation). These samples are all sandstones representative of the upper fluviatile unit of the glacial cycles suggested by Casshyap (1969). All three samples contained a polymictic assemblage of grains of quartz, metamorphic quartz, feldspar and rock fragments. A matrix is present in all three samples and generally contains green micas and minor opaques.

Sample R7 (Geneva Lake) represents a pre-Huronian soil horizon that developed on Archaean granites. This horizon is overlain by a basal conglomerate unit, thought to represent part of the Bruce Formation. The clasts, noticably devoid of metamorphic rock fragments, are poorly sorted, subrounded and are supported in a chloritic matrix.

II. RESIDUE STUDY

Residue studies were done on five samples from the Espanola Formation (Samples G1, G6(2), L7, R9, D1) with the help of the staff at the Amoco Canada Palynological Laboratory. Samples were chosen to represent all major lithology types from a very pure limestone to a calcareous fine-grained sandstone.

Following dissolution in 10 Normal hydrochloric acid, the siltstone samples produced a residue of thick mud whereas the purer specimens produced a small amount of angular quartz silt. The residues were then treated with a solution of strong hydrofluoric acid to dissolve the quartz and thereby release any organic fraction.

No organic fraction was found. No algal filaments, microfossils nor any spheres or spicules which might have had an organic origin, were recovered.

III. SCANNING ELECTRON MICROSCOPE STUDY

Eleven samples (Samples D2, D7, D8, D10a, G1, G6, E4, E20, P9, R14, L14) were observed at the Amoco Research Center. These samples were prepared in the standard manner using a fresh, unetched fracture surface coated with silver. The S.E.M. was able to study the samples under various magnifications from 10X to 1000X.

1. Microtextures

Photomicrographs of the samples under study (Plates 14 to 18 inclusive) show some microstructures of the Espanola Formation.

2. Microfossils - Introduction to the use of the Kevex-Ray Elemental Detector

No microfossils were discovered in the 16 samples studied with the S.E.M.

The Kevex-Ray Elemental Detector (K-R) is an attachment of the S.E.M. It has the capability of detecting elements of medium atomic weight although it is unable to detect lighter elements such as carbon, nitrogen and oxygen. It is able to give a qualitative point analysis of elements present at a certain point, or it can map the density of any element over a surface. It is emphasized that the K-R is a qualitative tool and can be used in a quasi-quantitative manner only in the comparison of the analysis of an unknown to the analysis of a known specimen.

PLATE 14 - S.E.M. PHOTOGRAPH

Sample E10, 200X

(fine-grained, massive dolostone)

PLATE 15 - S.E.M. PHOTOGRAPH

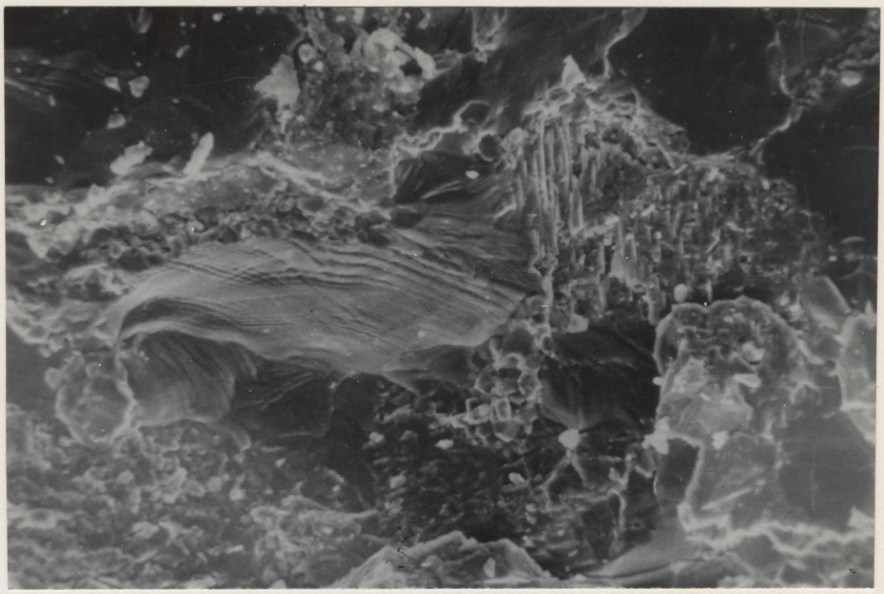
Sample G6, 200X

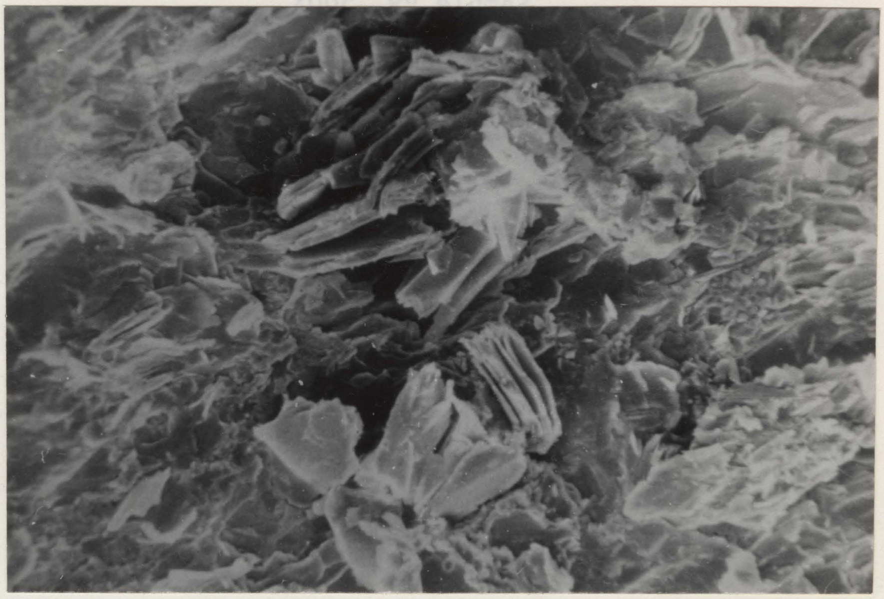
(fine-grained dolostone)

PLATE 16 - S.E.M. PHOTOGRAPH

Sample R14, 500X

(fine-grained arkose)





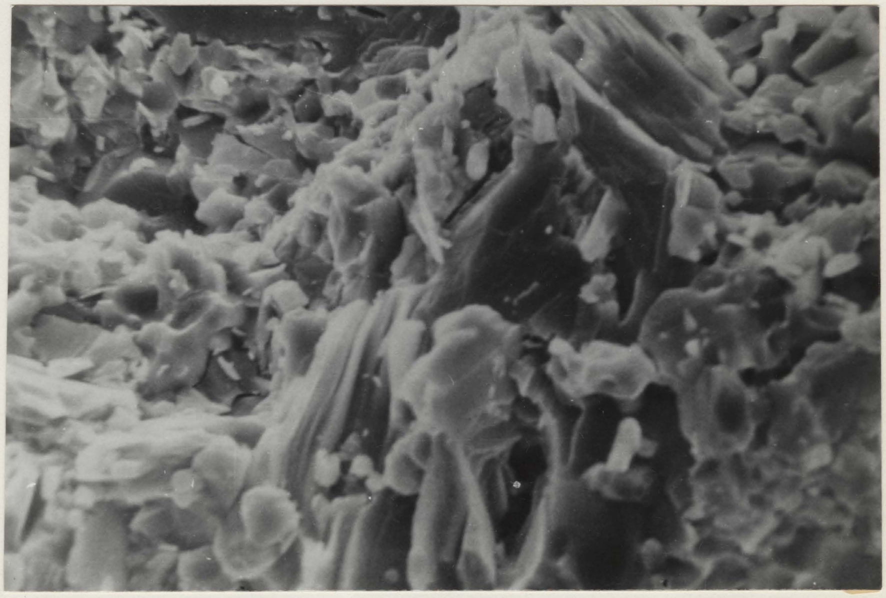


PLATE 17 - S.E.M. PHOTOGRAPH

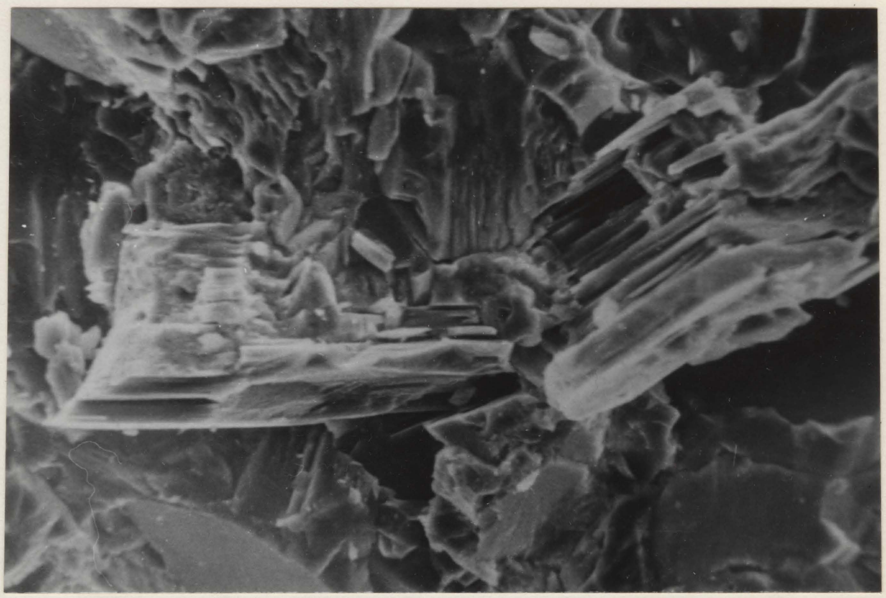
Sample D10, 500X

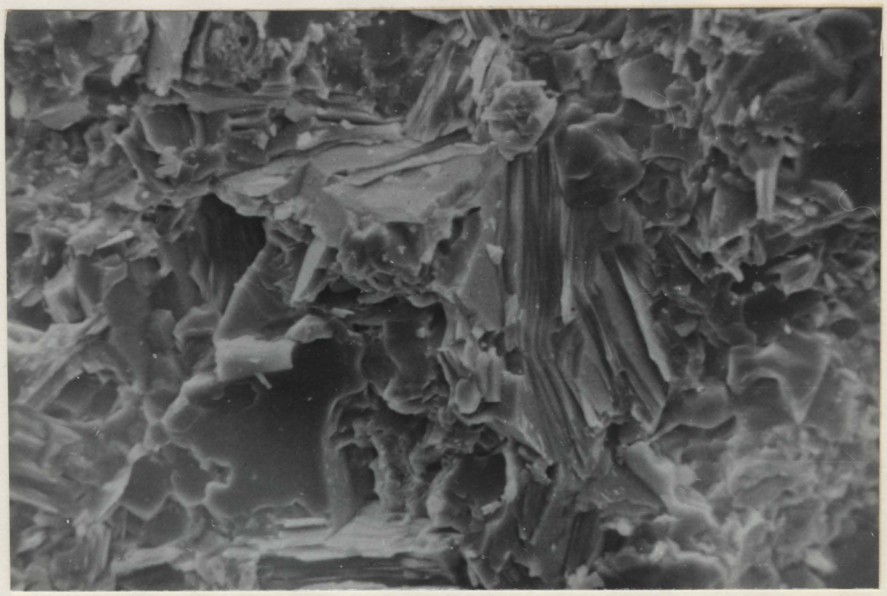
(medium-grained arkose)

PLATE 18 - S.E.M. PHTOOGRAPH

Sample P9, 500X

(calcareous argillite)





Only one sample (Sample G6(2)) of the Espanola Formation (Geneva Lake) was selected for analysis using the K-R, because of the dual grain size found in the sample. Thin section study has shown this sample to be a pure micritic limestone or marble with veins of sparry, twinned calcite. The micritic matrix contains randomly scatterred angular silt-size quartz grains. Plate 19 shows a 100X photomicrograph of this sample in the area of contact between the micrite and sparite. The difference in grain size is evident. No micas are observed in this sample.

Plates 20 and 21 show, respectively, 1000X photomicrographs of the micrite and sparry calcite vein filling, accompanied by a K-R point analysis on each. Qualitatively, the vein consists of almost pure calcite with minor phosphorous; the rest represents background "noise" inherent to the K-R. In contrast, the micrite is found to have a large amount of silica (as a result of scatterred quartz silt), magnesium and iron. Manganese and copper show readings significantly above background "noise".

Distribution maps were made of the elements iron and silica (Plate 22) in an attempt to discern any radial, spherical, linear or other anomalous arrangement of these elements that might indicate the previous existance of microfossils. Benson et al (1972) have shown that the distribution of both iron and magnesium in sedimentary rocks are generally unaffected by low grade metamorphism. Because of the migration of magnesium ions during diagesis, it was decided that a map of the magnesium distribution would be meaningless in a search for microfossils.

PLATE 19 - KEVEX-RAY

A 100X photograph of sample G6(2) showing the contact between the micritic matrix and the sparry vein-filling.

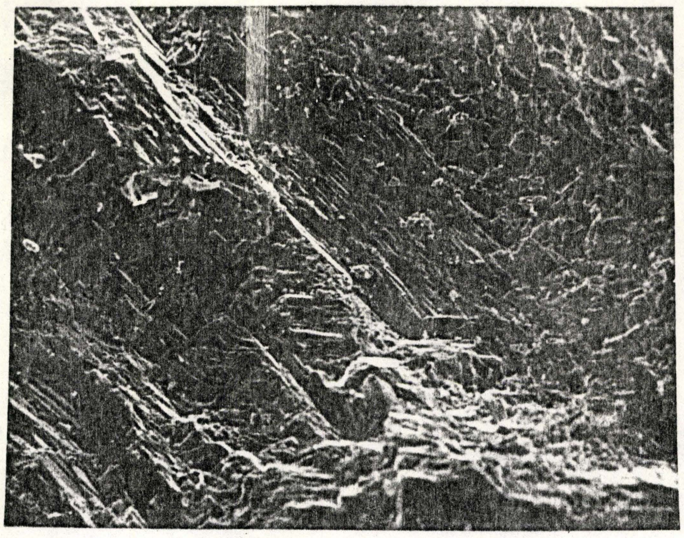
PLATE 20 - KEVEX-RAY

A 1000X close-up of the micritic fraction, with an accompanying Kevex-Ray elemental analysis. This shows silica, magnesium, iron, copper and manganese to be above "noise" level.

PLATE 21 - KEVEX-RAY

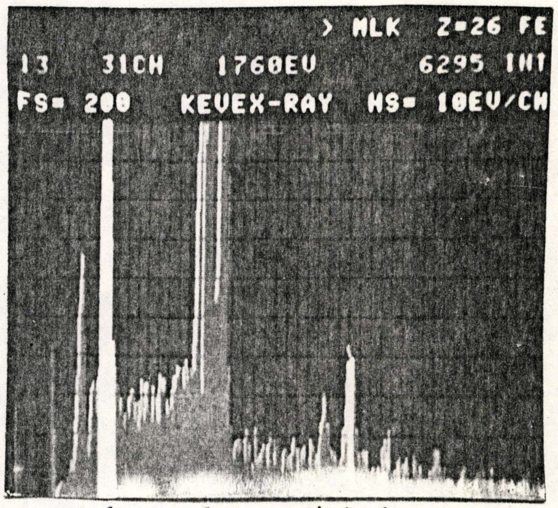
A 1000X close-up of the sparry fraction with an accompanying Kevex-Ray elemental analysis. This indicates that the vein filling is pure calcite with minor phosphorous.

VEIN

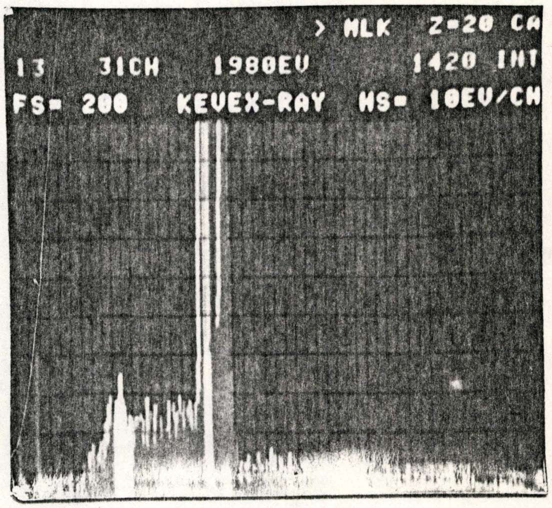


MATRIX

100 X



1000 X - MATRIX



1000 X - VEIN

The distribution of silica (Plate 22b) and iron (Plate 22c) shows a background "noise" level in the sparry calcite. The levels of both silica and iron increase significantly across the sparite/micrite contact. In neither case is an anomalous distribution of these elements found that would indicate the presence of possible microfossils.

Although the results of this microfossil search in the Espanola Formation are not encouraging, the K-R (Kevex-Ray Elemental Detector) has great potential for further work of this type.

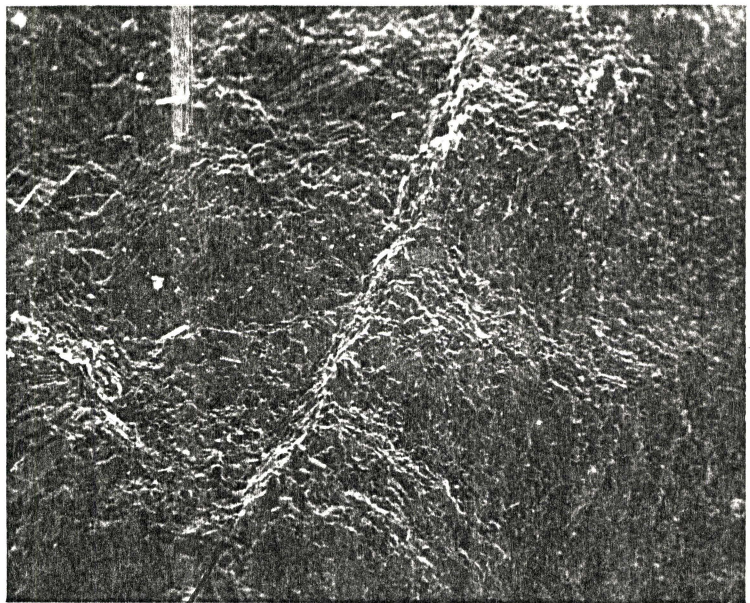
(a)

PLATE 22 - KEVEX-RAY

Distribution maps of silica (b) and iron (c) in Sample G6(2).

(b)

(c)



VEIN / MATRIX 50X

Si - SILICA

Fe - IRON

CHAPTER FIVE

CONCLUSIONS AND DISCUSSION

I. CONCLUSIONS

1. The Espanola Formation undergoes a lithofacies change from its type section on the north shore of Lake Huron, Ontario, to the study area near Geneva Lake, seventy-five miles to the north. In the Geneva Lake area, an unusually pure (95 percent) carbonate lithology is found in almost equal proportions with the calcareous siltstone and sandstone lithologies that characterize the Espanola Formation on the North Shore (Figures 1 and 4). This lithofacies change is accompanied by a 300 percent increase in the stratigraphic thickness of the formation from north to south (Figure 5).

2. The Espanola Formation can be correlated throughout its outcropping area north of Lake Huron, Ontario (Figure 10). When the formation is viewed in terms of stratigraphic thickness and gross lithology in a spatial rather than vertical framework, its distribution can be established (FIgure 11). From this, it is possible to recognize three different zones in the depositional basin of the formation which are perhaps indicative of environments of deposition (Figure 12).

The existence of the Espanola Formation as a fine-grained deposit within the Huronian glacial sequence is explained in the context of a marine transgression coincident with glacial retreat. Three glacial advance/retreat cycles are recognized in the Huronian sequence, each of which has associated fine grain deposits overlying a tillite conglomerate.

II. DISCUSSION

The apparent absence of microfossils in the studied samples of the Espanola Formation makes it necessary to only speculate on the origin of the carbonate matter in the formation. The approach taken involves a discussion on the origin of life which outlines the chemical conditions present during Proterozoic times, and a summary of microfossils found in other Precambrian deposits. The origin of recent lime mud is discussed because the micritic Espanola carbonates might originally have been deposited as lime muds. Evidence is outlined which enables a speculative mechanism to be presented that explains the origin of the Espanola carbonates.

1. The Origin of Life on Earth

It is believed that the earth's primitive atmosphere consisted of water, carbon monoxide, carbon dioxide, hydrogen and nitrogen (Rubey, 1951; Abelson, 1966; Cloud, 1968). Ammonia and methane may have been present at least during the earlier stages of differentiation of the atmosphere (prior to three billion years before present) (Haldene, 1954; Wald, 1964). All authors are in agreement that free oxygen did not exist in the primitive atmosphere or hydrosphere at this time.

Organic materials such as amino acids have been created synthetically in laboratories (Cloud, 1968) from gases such as have been postulated for the primitive atmosphere. It is possible that radiation energy from the sun naturally produced the same products on earth three billion years ago.

The first organisms to develop from this organic matter were undoubtedly anaerobic procaryotic heterotrophs (Weyl, 1968), which are probably related to modern anaerobic bacteria. These organisms could have survived in a shallow marine environment which was just deep enough to shield them from the sun's destructive ultraviolet radiation. Organic matter in the water around them would supply these organisms with nourishment. Haldane (1954) suggests that a primitive fermentative process was used by these first procaryotes, and that this was gradually replaced by a more complex photosynthetic process at a later date, approximately 2 billion years ago. In a time interval spanning a time of from 3 to 2 billion years before present these anaerobic bacteria evolved into efficient photosynthetic organisms (Glaessner, 1968). During the same interval, anaerobic blue-green algae may have evolved, using a primitive type of chlorophyll which would enable them to photosynthesize efficiently.

Convincing evidence is presented by Abelson (1966) that the first oceans were not acidic, but maintained a Ph of between eight and nine, with the help of buffering reactions. Solution of carbon dioxide in this primitive ocean, in the form of CO_2 and HCO_3- according to the reaction:

$$CO_2 + H_2O = H+ + HCO_3- \qquad (1)$$

would lower the pH of the water (Bathurst, 1971). It is possible that the CO_2-consuming photosynthetic process replaced the fermentative process in an effort to buffer the undesirable effects of the dissolved carbon dioxide.

Free oxygen is produced in the photosynthetic manufacture of hydrocarbons as follows:

$$x(CO_2) + y(H_2O) = Cx(H_2O)y + xO_2 \qquad (2)$$

This oxygen, which would have behaved like a poison to these primitive anaerobic organisms, had to be disposed of. The world-wide occurrence in the Proterozoic of banded iron formations is generally thought to be evidence that readily available ferrous ions accepted some oxygen (Cloud, 1968). Where such an acceptor of oxygen was not present, free oxygen escaped, possibly in solution, to the hydrosphere/atmosphere interface and built up in the atmosphere. Wald (1964) postulated an atmospheric build-up of oxygen to about 10^{-3} or 10^{-2} atmospheres before aerobic forms of life were able to evolve.

2. Precambrian Fossils

The earliest known fossils are found in the Precambrian, generally in Proterozoic rocks of approximately two billion years in age, or younger. These have been well documented (Barghoorn and Tyler, 1965; Young, 1967; Schopf, 1968; Cloud et al, 1969; Moorman, 1974; Donaldson and Delaney, 1975) although the validity of some (Hofmann, 1967) is in doubt.

In some cases, microfossil preservation has been extremely good. Individual cells and the quasi-metazoan arrangement of cells have been studied (Moorman, 1974). In other cases algal filaments have been found (Donaldson and Delaney, 1975). In all cases, apart from Hofmann's (1967) metazoan(?) fossils(?) near Elliot Lake, algae seems to be chiefly responsible for both the organic structures (predominantly stromatolites) observed. Russian geologists have recently been intensely studying Proterozoic stromatolites in an attempt to classify the morphologies, and have suggested a worldwide correlation of Proterozoic rocks on the basis of the stromatolite morphology and zonation within them (Cloud and Semikhatov, 1969; Raaben, 1969).

3. Origin of Recent Lime Muds

Near Geneva Lake, where post-Huronian metamorphism appears to be minimal, the Espanola Formation contains micritic carbonates that appear to be primary. It is necessary to look briefly at recent, unconsolidated micrites, or lime muds, in an attempt to explain the existence of micrite in the Espanola Formation.

Cloud (1962) has shown that for lime muds west of Andros Island, Bahamas, five percent is of detrital origin, 17-20 percent is of skeletal origin, and only 4-5 percent is algal aragonite. Cloud (1962) suggests that the remaining seventy percent by volume of this mud is of inorganic origin.

Cloud (1962) suggests that "whitings", spontaneous surface accumulations of aragonite needles, observed in the Persian Gulf and in Florida Bay are not the result of biological activity on the shelf floor, nor the result of ships passing through the area, but have been precipitated inorganically. This is substantiated by Kinsman and Holland (1969) who find that the concentration of Sr^{2+} in lime muds is similar to that of Sr^{2+} in normal seawater (approximately 10,000 p.p.m., or 1%). Analysis of the shells of molluscs and other shelled organisms indicates that the Sr^{2+} concentration in these tests is less than 20 percent of that in the lime muds (approximately 2,000 p.p.m.).

Drew (1914) first suggested that carbonates might be precipitated in the presence of denitrifying bacteria. Wehl (1961) suggested that carbonate precipitation is a move towards equilibrium to counteract the supersaturation of warming sea water. Deer et al (1962) indicated that carbonate deposition is enhanced by high temperatures, low partial pressures of dissolved carbon dioxide and low salinities in the carbonate-saturated water. Cloud (1962) found that the rate of precipitation of carbonates is proportional to the degree of supersaturation of sea water with respect to aragonite. In this same paper, Cloud proposed a model for instantaneous precipitation of aragonite in whitings. Blooms of diatoms, which take up large amounts of dissolved carbon dioxide from the water, will account for a sudden drop in the carbon dioxide and a corresponding rise in pH of the sea water. This would be buffered by precipitation of carbonate as aragonite needles (eg: "whitings"). Monty (1967) went one step further and sugegsted that sudden drops of carbon dioxide levels in sea water and the associated drop in its acidity might be explained by increased photosynthetic activity of anaerobic bacteria and/or algae in the water.

4. Origin of the Espanola Formation

Without direct microfossil evidence to attest to the organic origin of the calcareous Espanola Formation, a discussion of the true origin must be kept speculative. Three speculations are presented and discussed here:

(i) inorganic precipitation

Glacial melt-water is generally fresh, but hard due to an excessively high concentration of cations and minerals released during the pulverization of rock by a glacier (Smalley, 1971). If cold melt-water becomes saturated with respect to Ca^{2+} and HCO_3^- ions, then upon warming up (by definition of an inter-glacial period) the water will become supersaturated and might precipitate inorganic calcium carbonate:

$$Ca^{2+} + 2HCO_3^- = CO_2 + H_2O + CaCO_3 \qquad (3)$$

This reaction will proceed, however, only if the resultant carbon dioxide is being simultaneously withdrawn - a high pH is fundamental to the thermodynamics of calcium carbonate precipitation. In view of the evidence presented in this chapter, it is probable that anaerobic bacteria or algae did exist during this time and were capable of consuming the released carbon dioxide by photosynthesis. Free oxygen released during this process would have little effect upon the precipitation of the calcium carbonate.

(ii) organic origin

Algal structures, commonly stromatolites, which are found in Proterozoic sequences other than the Huronian Sequence, have led to a alternate conclusion that perhaps the Espanola Formation is in part, an organic deposit. Penicillus, an algal form common to the Florida Bay area, has been shown by Cloud (1968) to account for the total volume of lime muds in the area. It is possible that primitive blue-green algae might have developed by the time of deposition of the Espanola Formation. However, in the light of evidence which suggests that the hydrosphere was anaerobic during this time (detrital uraninite in the underlying Bruce formation, the presence of apparently detrital pyrite and detrital unoxydized green micas in most samples of the Espanola Formation), it is unlikely that aerobic algae, capable of calcium carbonate generation, existed by the time of deposition of the Espanola Formation.

(iii) brine concentration by selective freezing

Young (1973) presented a mechanism of inorganic precipitation from a brine that becomes increasingly more saturated with carbonates with time, due to selective freezing. However, great quantities of salt and other evaporites are not found associated with the carbonates. It is more likely to think of the Espanola Formation as an inter-glacial deposit, at which time freezing would probably not be going on.

(iv) Summary

A viable mechanism for the inorganic precipitation of calcium carbonate in the Espanola Formation has been presented. It relies upon two premises, one of which will have local significance, the other of which will have global significance.

The premise that the meltwater, from which the Espanola carbonates were precipitated, was saturated with cations and other minerals implies that the earlier "Bruce" glacial advance was of sufficient magnitude to pulverize enough fine material, for solution in the glacial meltwaters. It also implies that the sedimentary basin or basins must have been small enough that these saturated meltwaters were not diluted by unsaturated ocean water. In this context, a glacial lake environment for the deposition of the Espanola Formation is envisaged.

The second premise is that anaerobic bacteria or algae existed that could photosynthesize the excess carbon dioxide produced by inorganic precipitation of calcium carbonate. Since free oxygen is a waste bi-product of photosynthesis, the first occurrence of these organisms would be accompanied by an occurrence of free oxygen in the atmosphere. If this is so, then the Espanola Formation will represent one of the oldest carbonate deposits in the world, and may be used as a time marker in the differentiation of the primitive atmosphere.

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APPENDIX A

THIN SECTION DESCRIPTIONS

I. PURE MICRITIC CARBONATES

1. Sample R9
2. Sample B12
3. Sample L7
4. Samples L14, G1
5. Sample G6(2)

II. CALCAREOUS SILTSTONES

1. Sample E2
2. Sample E4
3. Samples P4, P5
4. Sample B15
5. Samples P9, P14

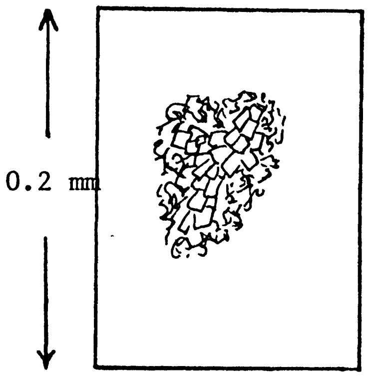
III. CALCAREOUS SANDSTONES

1. Sample R4
2. Sample R10
3. Sample E6
4. Sample E10
5. Sample L18
6. Sample G6(1)

IV. OTHER LITHOLOGIES

1. Sample B4
2. Sample B7
3. Sample R14
4. Sample R7

SAMPLE R9



 MICRITIC DOLOMITE

 MICROSCOPIC DOLOMITE (RECRYSTALLIZED)

99% DOLOMITE

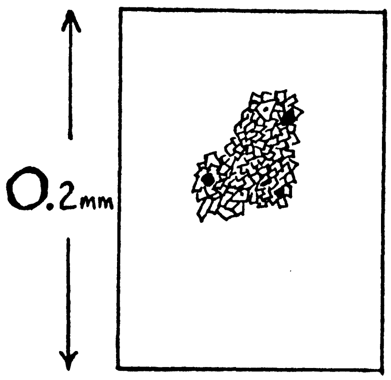
Tr QUARTZ DETRITUS

Tr MUSCOVITE

DOLOMITE

Microcrystalline dolomite, recrystallized in places to a microsparitic dolomite. Trace of detrital material.

SAMPLE B12



FINELY CRYSTALLINE CARBONATE

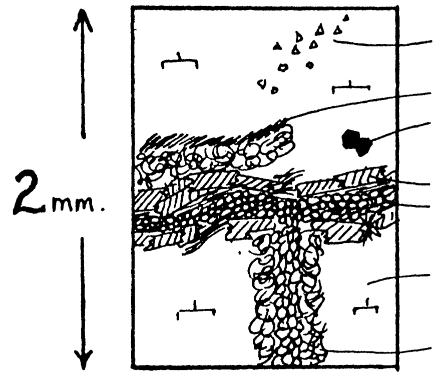
SILT FRAGMENTS

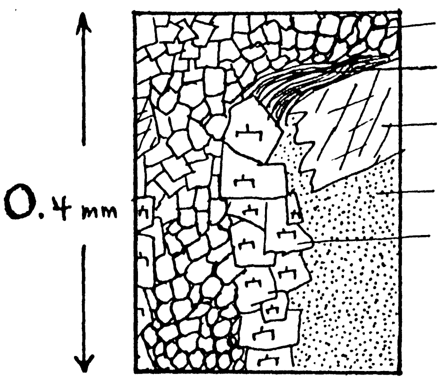
OPAQUES

95%	DOLOMITE (finely crystalline rhombs)
3%	SILT (QUARTZ)
2%	OPAQUES
100%	

DOLOMITE

Composed almost exclusively of fine-grained dolomite rhombs, with scattered silt-sized quartz and linear siliceous partings.

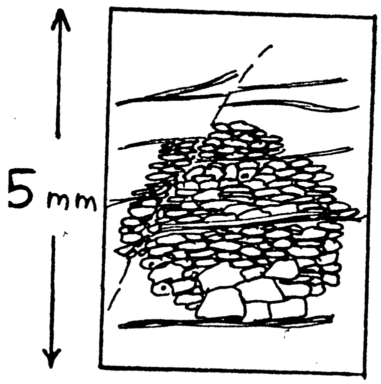




80%	CALCITE DOLOMITE
10%	QUARTZ
3%	SERICITE
5%	MICAS
2%	OPAQUES
100%	

BEDDED LIMESTONE

Mostly microcrystalline calcite (some dolomite) with horizontal partings less than 1 mm of angular quartz grains (silt-size), secondary micas and sericite. Vertical quartz partings are "mini-dikes", containing quartz grains derived from the horizontal partings. Angular quartz grains (again silt-size) are scattered throughout the micrite. Sparry and micro-sparry calcite crystals have developed around both vertical and horizontal clastic partings.



FRACTURE LINE

SHALEY PARTING

SPARRY AND MICROSPARRY CALCITE

QUARTZ CLASTS

90%	CALCITE	
4%	QUARTZ	
6%	MATRIX ALONG PARTINGS	(includes Tr. opaques) (clay minerals? limonite?)
100%		

FINELY BEDDED LIMESTONE

Fine grains of calcite, slightly imbricated parallel to fine shaley partings, about 1 mm apart. Occasional quartz clasts (silt-fine size) scattered throughout. Sample is finely fractured.

25mm

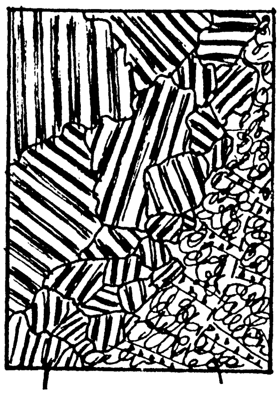
SPARRY-FILLED FRACTURE; spars are twinned rhombs of calcite/dolomite?

INCIPIENT FRACTURE

MICRITE WITH SMALL AMOUNTS OF QUARTZ SILT

PARTINGS IN MICRITE OUTLINE ORIGINAL BEDDING SERICITE AND MUSCOVITE

5 mm

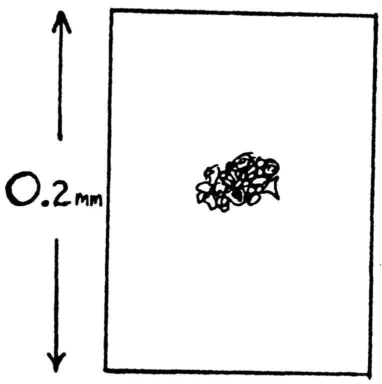


90%	CARBONATE
5%	QUARTZ SILT
5%	MUSCOVITE/SERICITE IN PARTINGS
100%	

SPARITE MICRITE WITH PARTINGS

LIMESTONE (MARBLE)

Apart from the quartz silt randomly scattered throughout the rock, and the sericite/muscovite partings in the micrite, this limestone is composed of micritic carbonates, with fractures some of which are filled with sparite. The spars are twinned, and are jointed together along stylolites. The nature of the twinning is perhaps one of calcite/dolomite, but could be an effect of metamorphism into marble.



MICRITE

CHERT

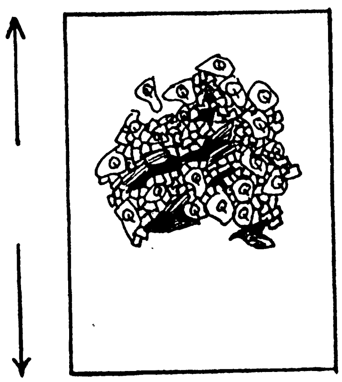
QUARTZ SILT

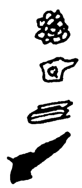
50%	CARBONATE
50%	QUARTZ
Tr	OPAQUES
Tr	MUSCOVITE
100%	

CALCAREOUS CHERTY-SILT

Disseminated micritic calcite in cherty silt.

SAMPLE E4





CARBONATE

QUARTZ CLASTS (SILT-FINE GRAINED)

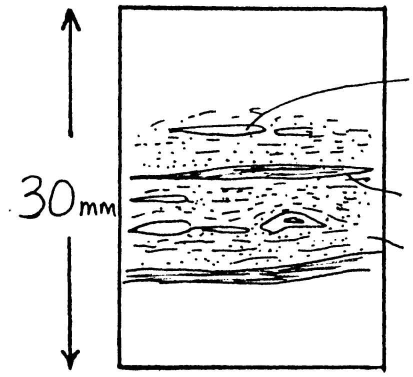
MUSCOVITE

VOID

60%	QUARTZ
30%	CALCITE CEMENT
5%	MUSCOVITE
5%	POROSITY
100%	

POROUS CALCAREOUS SILTSTONE

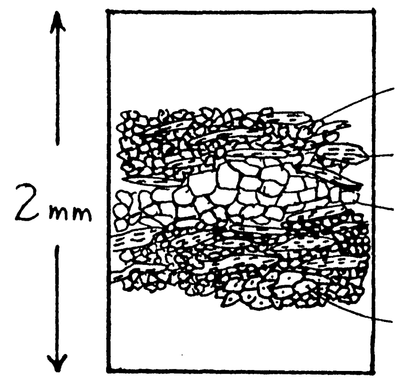
Silt to fine-grained quartz with minor muscovite in a cement of microcrystalline to microsparitic calcite, with a 5% porosity.



CARBONATE BOUDINS

CLAY LENSES

CALCAREOUS CLAY/SILT MATRIX



SILT-SIZE ANGULAR QUARTZ, clay/carbonate matrix

CHLORITE in quartz/clay/carbonate layers

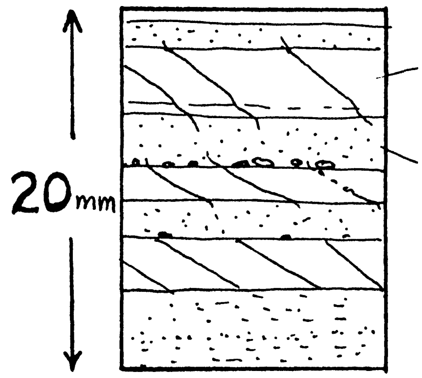
CARBONATE BOUDIN, sparry

CONCENTRATION OF QUARTZ (BOUDIN?)

35%	CALCITE	as sparry crystals in boudins and disseminated throughout clay/silt matrix
40%	QUARTZ	mostly silt-size in matrix, but also in lensoid concentrations (boudins?)
10%	CHLORITE	chlorite, in matrix
15%	CLAY	clay minerals, in matrix
Tr	OPAQUES	
100%		

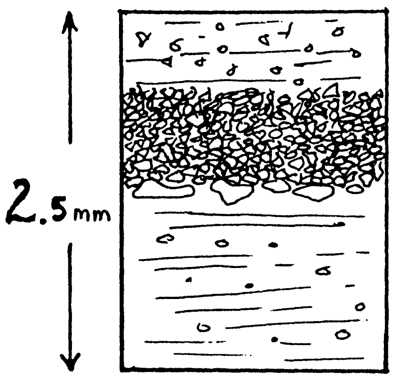
CALCAREOUS SILTSTONE

Boudinage of competent siliceous and calcitic layers in soft clay-silt matrix.



clay-rich layer, fractured

silt-rich layer, slightly coarser on bottom



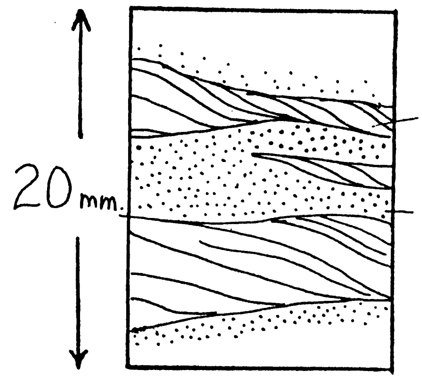
SILT BAND - angular quartz and feldspar fragments (silt-size) with chlorite and 20% calcareous clay matrix.

clay band - calcareous clay is in silt-matrix, angular quartz (silt-size) and chlorite grains scattered throughout

CYCLIC (VARVED?) CALCAREOUS CLAY

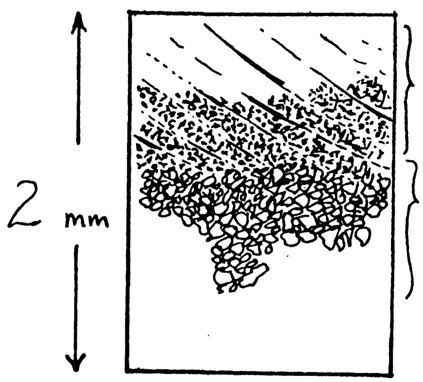
Bands or "varves"?, 2-5 mm average thickness of alternating calcareous clays, finely fractured and containing scattered chlorite and angular silt-size quartz, with layers of quartz silt containing scattered chlorite and a calcareous clay mixture.

SAMPLES P9, P14



Bands of fine-grained chloritic calcareous siltstone (showing fracture pattern)

Chloritic calcareous siltstone, containing muscovite and opaques



Fine silt band - fine quartz silt, disseminated carbonates, chlorite and a clay matrix which outlines the micro X-laminations

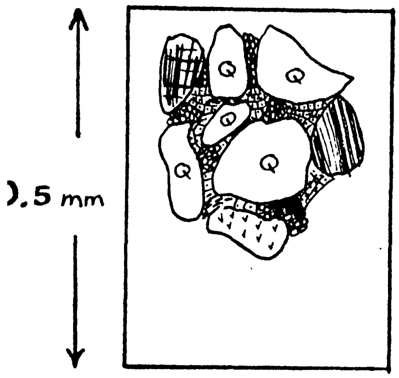
Coarser band - silt-fine quartz, angular, with calcite crystals (fine) and chlorite/muscovite (both present). No clay matrix, but opaques present.

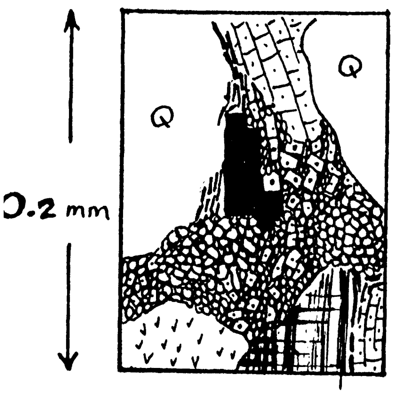
BANDED CALCAREOUS SILTSTONE

35%	QUARTZ, silt size, angular
30%	CHLORITE (+ MUSCOVITE)
25%	CARBONATES (CALCITE)
5%	CLAY MINS.
5%	OPAQUES
100%	

Similar to Sample B 15, but showing boudinage of finer-grained bands.

SAMPLE R4





35% QUARTZ GRAINS, subangular

10% FELDSPAR, simple and polysynthetic twinning

15% CHERT, microcrystalline

30% CARBONATES, some sparry crystals, mostly disseminated cement

2% OPAQUES

5% V. ROCK FRAGMENTS

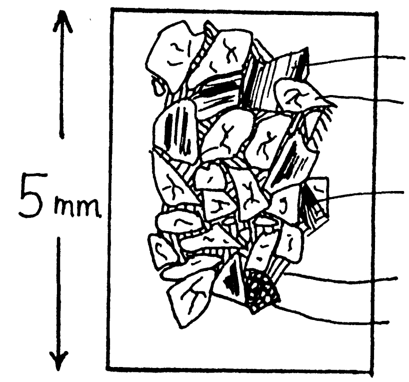
3% MUSCOVITE

100%

CHERTY CALCAREOUS SILTSTONE

Composed of silt or fine-grained quartz, feldspar with minor rock fragments in a matrix of predominantly carbonate and chert. The carbonate, sometimes as sparry grains and sometimes disseminated throughout the matrix, seems to be primary, whereas, the chert would appear to be diagenetic, occurring together with the disseminated carbonate and small amount of muscovite, between the grains of quartz and feldspar, which rarely touch. The opaque minerals present are euhedral cubes, and hence are probably not detrital.

SAMPLE R10



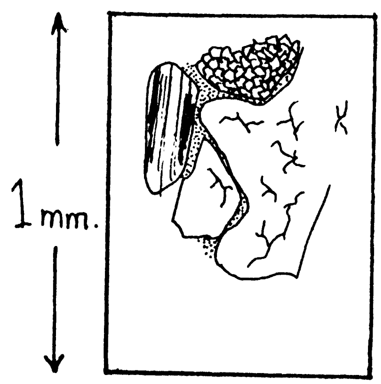
FELDSPAR (PLAGIOCLASE) CLASTS, angular, fractured

QUARTZ CLASTS, angular, fractured

MUSCOVITE

CALCITE CEMENT

CHERT CLAST



40% QUARTZ

25% FELDSPAR

2% MUSCOVITE

10% CHERT CLASTS

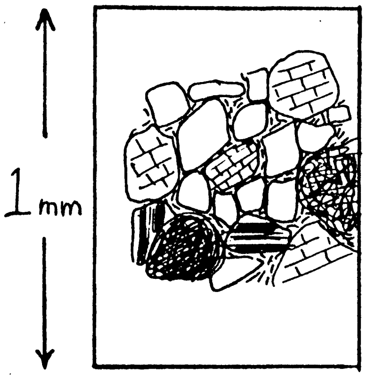
20% CALCITE CEMENT

3% OPAQUES

CALCAREOUS ARKOSE

Angular quartz, feldspar, and chert clasts of poor sorting with a calcite cement. The quartz and feldspar clasts are highly fractured.

SAMPLE E6

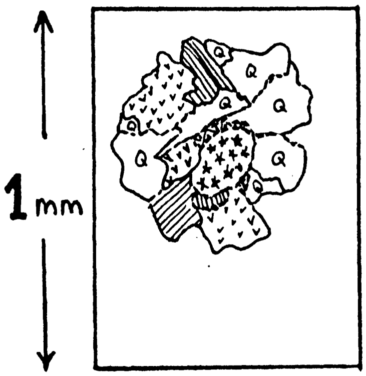


24%	QUARTZ		
15%	FELDSPAR		
15%	CARBONATE (CALCITE)		
1%	BIOTITE		
35%	MATRIX		
		Sericite	10%
		Carbonate	15%
		Muscovite	5%
		Phlogopyte	5%
10%	SERICITIZED ROCK FRAGMENTS		
100%			

CALCAREOUS WACKE

Fine grained, subangular quartz and feldspar crystals along with a minor amount of sericized rock fragments and apparently detrital carbonate grains, in a matrix of carbonate, sericite, muscovite, and phlogophyte. The overall carbonate content is close to 30%, and this could easily be called a limestone in hand specimen.

SAMPLE E10



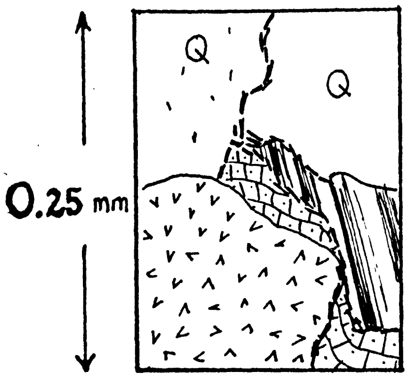
Quartz

Feldspar

V. Rock Fragments

Carbonates

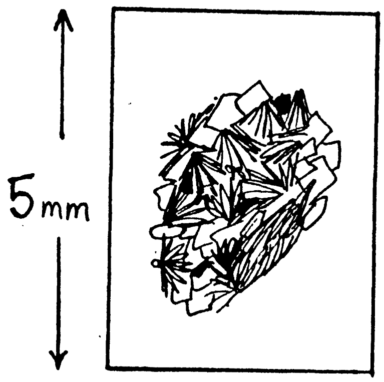
Muscovite



40%	QUARTZ; mostly single grains, some chert (8%)
20%	FELDSPAR; no polysynthetic twinning
25%	ROCK FRAGMENTS; volcanic
10%	CARBONATE; single grains, some cement
5%	MUSCOVITE; with carbonate as matrix
Tr	OTHER; (some Chlorite, Biotite)
100%	

CALCAREOUS LITHIC ARKOSE

Composed of quartz, feldspar, and volcanic rock fragments in a matrix of carbonate and muscovite. The grains are not rounded, but irregularly shaped and closely fitting with little matrix between. The irregular shape of the quartz grains may be due to diagenetic silica cement, but no overgrowths were noticed. The carbonate, apparently calcite, occurs in vuggy cavities between the grains, and disseminated with the muscovite needles between most of the grains at their boundaries. The muscovite is presumedly primary although the calcite appears to be secondary cement.



SERICITE

CALCITE

QUARTZ

OPAQUES

35%	CALCITE
25%	QUARTZ
35%	SERICITE
3%	MUSCOVITE/CHLORITE
2%	OPAQUES
100%	

SERICITIC LIMESTONE

This sample was from a faulted and slightly brecciated limestone. In this smaple, sericite is quite dominant over the original calcite and detrital quartz.

SAMPLE G6 (1)

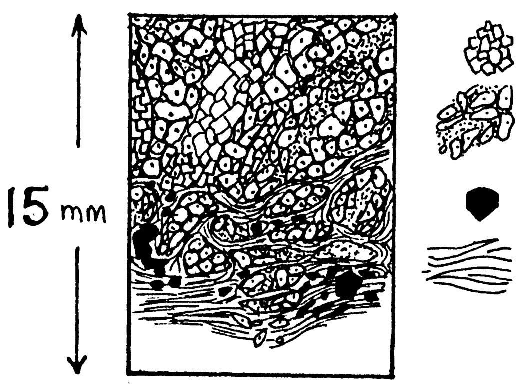
CALCITE VEINS

CALCAREOUS CHERTY SANDSTONE

BRECCIATED FRAGMENTS OF ABOVE

ARGILLACEOUS MATRIX

OPAQUES



CALCITE SPARS, some twinned

SUBANGULAR QUARTZ AND FELDSPAR GRAINS in a predominantly cherty and calcareous matrix

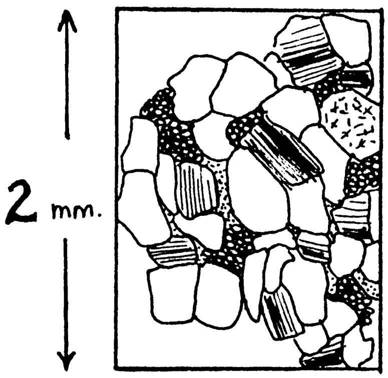
OPAQUES

ARGILLACEOUS MATRIX (MUD)

BRECCIA

This appears to have been a fine-grained sandstone with siliceous cherty cement that was later calcified (late diagenesis?) and at a much later stage, brecciated to its present state, the fine-grained matrix being muddy, siliceous, clayey, calcareous, and full of opaque minerals.

SAMPLE B4

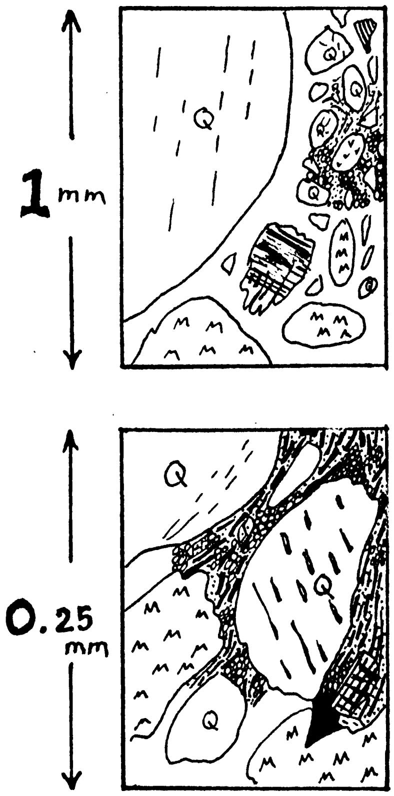


45%	QUARTZ (ANHEDRAL)	- some slightly strained - angular, no overgrowths
20%	(CHERT)	- not apparently diagenetic; perhaps clastic Chert grains
25%	FELDSPAR - mostly albite twinning	
5%	VOLCANIC ROCK FRAGMENTS	
5%	CHLORITE - RICH MATRIX	
Tr	OPAQUES	
100%		

CHERTY FEDLSPATHIC QUARTZITE

Fairly well sorted grains of quartz, chert, and feldspar, subangular, with occasional volcanic (fine-grained) rock fragment and a very small amount of matrix. No cement immediately noticeable, including quartz overgrowths, but perhaps some of the Chert is secondary.

SAMPLE B7



ARKOSIC WACKE

40% QUARTZ, metamporphic; strained, contains inclusions
rounded → angular,
silt size → gravel size (2mm)

10% FELDSPAR, mostly decomposed to Kaoline and Sericite

20% MMc/VOLC. ROCK FRAGMENTS

25% MATRIX
- Cherty cement
- Kaolin/Sericite
- Muscovite, Chlorite

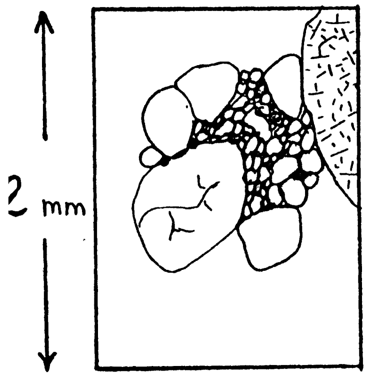
2% OPAQUES

Tr BIOTITE

3% CARBONATES

100%

Composed of unsorted, rounded to angular grains of quartz, feldspar, and rock fragments all less than 2 mm diameter. The grains had a metamorphic provenance, because of the nature of the rock fragments, the strained nature of the quartz, some grains of which contained linear inclusions (Schiller structure). The abundant matrix consisted of muscovite and chlorite needles, primary; Kaolin/ Sericite probably from the weathering of feldspar (Feldspar grains in the sample could be seen to be in the process of weathering) and diagenetic chert disseminated throughout the matrix. Opaques could be detrital because of their subrounded nature.



 QUARTZ SAND GRAINS, some fractured large, unsorted, subround to subangular, some Feldspar

 QUARTZ SILT AND MINOR CHERT

 CHLORITE

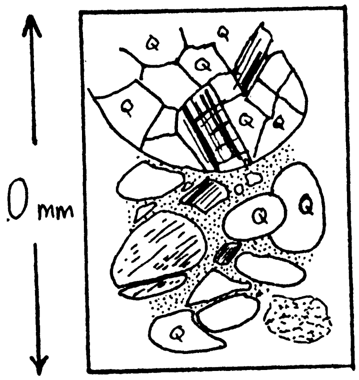
 ROCK FRAGMENT

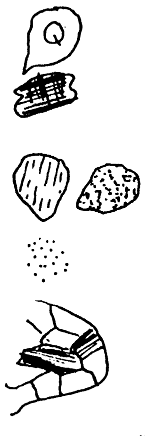
70%	QUARTZ (includes Silt and Chert)
10%	FELDSPAR
10%	ROCK FRAGMENTS
10%	CHLORITE
100%	

CHLORITIC QUARTZITE

Unsorted Quartz Sandstone with Chlorite.

SAMPLE R7





QUARTZ GRAINS, subrounded, poorly sorted

FELDSPAR GRAINS, subrounded, poorly sorted

STRAINED AND DISSEMINATED QUARTZ GRAINS

MATRIX, silt, clay, chlorite (secondary)

GRANITE PEBBLE, enhedral crystals

PALEOSOL

Formed from granite. Sample location was on the contact. Lack of volcanic and metamorphic rock fragments, presence of poorly-sorted but rounded quartz.

APPENDIX B

HAND SPECIMEN DESCRIPTIONS

Hand Specimens

L.1 mg granite, k-spar rich c̄ euhedral xstals of biotite

L.2 fg siltstone, med-grey, finely bedded, micaceous, non-calcareous

L.3 quartz ssr, muscovite-rich, non-calcareous

L.4 vfg qtz siltst, mica-rich, finely lam ll-beds

L.5 mg arkose, some graded bedding, non calcareous

L.6 fg sst (rounded qtz) silst and calcareous shales finely interbedded up to 5 or 10 mm.

L.7 massive DST c̄ minor shale parts (approximately 1 mm) some of which are siliceous.

L.8(1) Marble beds 5-30 mm c̄ shale parts (less than 5 mm). fg, pure, white, some hematite? staining (very minor).

L.8(2) mg, SST, grey, c̄ $CaCO_3$ cement (quite high), gelena? subrounded qtz (0.2 mm) weathers deeply white or buff.

L.9 fg Diabase (calcite in fractures)

L.10 fg SST grey, micaceous, slightly calc.

L.11 cg SST to gravel size, calcareous, micaceous

L.12 mg-cg SST, graded? non calc. grey, coarse laminated

L.13 mg-cg Arkose (less than 1 mm), calc, mica-free matrix

L.14 LST, finely bedded 1-5 mm c̄ micaceous shale parts 1-2 mm light grey to white (brown partings)

L.15 fg SST, qtz rich, finely laminated, slightly calc. along fractures

L.16 fg-mg SST, med grey as above c̄ some pyrite

L.17 vcg granite, qtz and feld.

L.18 siltst, calcareous, brecciated??

B.1(1) 2"-4" conglom pebs mostly granite, some argillitic c̄ striations? qtz-rich cg (subr-suba) med-grey matrix, unsorted pyrite, feldspar

B.1(2) fg qtz SST dark grey, weathers white, some mica, graded bedding calcareous along fractures.

B.1(3)	mg Arkose, qtz-rich (less than 1/2 mm, subr.) non calc.
B.1(4)	Slate, light grey-green, weathers buff-green
B.1(5)	Slates and siltst interbedded, calcareous
B.4	mg Arkose, light green-grey, well sorted, suba. to subr., non calc.
B.5	fg Arkose, light grey, qtz-rich, non calc.
B.6	fg Arkose, qtz (suba-subr), magnetite? or gelena?
B.7(1)	vfg-fg Arkose, grey, non calc., magnetite?
B.7(2)	fg Arkose, grey, micaceous, slightly calc.
B.7(3)	mg SST, grey-brown, slightly calc. micaceous
B.9	cg Arkose qtz-rich (approximately 1 mm) subang.
B.10	congl suba. qtz and feld less than 5 mm (average 2-3 mm) light green matrix, non calc.
B.11	mg-cg SST, qtz-rich, calc. matrix, slightly micaceous.
B.12	DST coarse bedded 10-30 mm, siliceous, pyrite, ll-laminated $\bar{c}$ shale partings
B.13	cg qtz SST less than 5% biotite, calcareous, some gravel.
B.14	cg Diabase
B.15	varbed clays bands approximately 5 mm of dark, micaceous argillite and light, mica-free argillite, distinct beds, non calc.
H.1(1)	mg qtz greywacke, coarsely bedded, subr. qtz and feld, micaceous matrix.
H.1(2)	mg-cg qtz greywacke, graded beds, feldspar, argillite beds, non calc. (turbidite?)
H.1(3)	varbed fg SST's. pure fg qtz SST and dirty fg greywacke $\bar{c}$ mica layers, calcareous along fractures.
H.3	cg SST, gravely, micaceous, coarsely interbedded $\bar{c}$ micaceous fg siltst, non calc.
H.4(1)	vfg siltst, coarse bedded, dark grey, non-calc., slightly micaceous

H.4(2) fg-mg SST poorly sorted qtz, micaceous c̄ pyrite.

F.1 1"-2" conglom, more sed. than gran. pebs., pyrite, larger pebs more rounded than smaller ones.

G.1 LST, med. bedded (5-10 cm) micropartings in some beds, but most with thick shale partings (10 cm).

G.2 fg Qtzite, sugary, dirty white, weathers buff, pyrite

G.4 vg argillite and slate ll-lam., lams of vfg qtz and silt (0.1 mm) slightly micaceous, light grey, weathers grey, siliceous, non calc.

G.5 as above, some laminae micaceous.

G.6(1) vfg silt and carb., lams 0.25 to 3 mm, pure siliceous layers and dirty calcareous layers (weather brown)

G.6(2) DST, some calcite, some silicates (qtz approximately 0.2 mm) sericite.

G.6(3) LST, 1-5 mm beds lst and dirty calcite, wavy lams light grey, weathers grey-buff.

G.6(4) LST and DST, shale partings contorted

G.6(5) LST, calcite sweats, lams approximately 1 mm, c̄ very fine shale parts.

G.7(1) dirty lsts and calc shales, finely bedded, wavy, lenticular, 1-5 mm lams. some qtz silt and clasts, grey weathers buff grey

G.7(2) granite, dark qtz-rich

G.8 mg to cg Arkose qtz and feld, non calc., some primary bedding

G.9 vfg SST, fairly well sorted, subang, some feld, some mica shale partings c̄ muscovite in bedding plane worm traces? mudcracks?

G.10 fg SST, sugary, slightly calc. or dolomitic, few large qtz and feldspar xstals.

G.11 1"-2" conglom unsorted, gran and sed. pebs, qtz-rich pebs, garnets? dark grey matrix

G.12 vfg argillite, non calc., finely bedded, dark grey, pyrite?

G.13 fg qtzite, pale br-gr, well sorted and rounded c̄ overgrowths

G.14	fg qtzite, some pink, pale green, staining, 10-20 mm pebs well rounded
G.15	fg qtzite (0.15 mm) pale br-gr, well sorted, well rounded c̄ overgrowths; no dust between xstal and overgrowth.
J.1	fg Arkose, grey to red grey, finely bedded, magnetite? gelena? non calc.
J.2	fg Arkose, subang to mg, non calc., qtz-rich.
J.2(2)	fg argillite c̄ arg-subang silt to sd clasts scattered throughout dark grey, finely-bedded, micaceous, pyrite
J.4	cg SST, micaceous, calcareous
J.5	fg siltst, med-grey, finely bedded, micaceous
R.4	siltst, calc., especially certain beds, mineralized, biot. and musc., siliceous, qtz clasts
R.7(1)	cg granite, pink, biot.-rich
R.7(2)	1" conglom, unsorted, graded? Lt. grey non calc. matrix of mica qtz feld.
R.9	massive DST massive Xstal growth, no qtz detritus, fine parts.
R.10	vcg SST - gravel, subr. qtz, some feld and mica, grains less than 10 mm calcareous matrix, some mineralization
R.11	fg-mg Arkose, lt grey, weathers white, subang qtz-rich, non calc.
R.12	siltst, muscovite, calcite-rich (shear zone?) qtz-rich subang.
R.13	mg SST, slightly arkosic, subang qtz.
R.14	Arkose? poorly sorted subang qtz and feld, light grey weathers tan, biotite?
R.14(2)	Arkose?, non calc., med grey, micaceous, non distinct grains
E.1	argillite, coarse laminated, dark and light grey, non calc. qtz detritus, biotite and muscovite??
E.3	mg, Arkose, qtz-rich, calcareous, c̄ hematite?
E.4	mg LST, dirty (argillaceous?)
E.5	vfg Arkose, almost glassy qtz and feld, some hematite?

E.6	DST, highly min'd, faintly layered, grey, weathers brown
E.7	calcareous siltstone, layered calc and non calc layers, moly? graphite? euhedral, calc. layers are sparry calcite cement c̄ quartz framework.
E.8	fg qtz SST, light grey, weathers white, calcite Xstals, pyrite
E.9	fg greywacke, finely lam'd, dark, weathers light, non calc.
E.10	fg massive DST, no shale parts, mineralized
E.11	mg qtzite, well sorted, 0.3 mm, hematite? stain = pink.
E.12	vf slate, ll-lam'd, (cg) pyrite nodules, qtz rich, micaceous, non calc., dark grey weathers grey.
E.13	vfg qtzite, almost glassy, pure white.
P.1	fg qtzite, dark
P.2	fg-mg arkose, qtz-rich, coarse bedding, slightly calc. mafic-rich layers (biotite, etc.)
P.2(2)	mg qtz SST, some mica, non calc. and fg arkose pink-green, well sorted, subang c̄ mica non calc.
P.2(3)	vfg argillite qtz-rich, non calc., sheared?
P.3	vcg qtzite (0.5 mm qtz) well sorted, round to surb. c̄ o/growth gelena? gold? clear weathers buff
P.4	calcareous argillite, flattened and bondinaged $CaCO_3$ layers (light colour) in darker, micaceous, matrix
P.5	as above
P.6	varved argillite, dark micaceous c̄ lighter siliceous lighter varves calcareous, finely lam'd, biotite and muscovite
P.7	fg siltst, fine bedded, light grey, some mica, qtz-rich
P.8	fg siltst, micaceous (biot. and musc.), dark grey, calc. in fracture
P.8(2)	fg LST, sugary approximately 0.1 mm, almost pure, wavy lams of silt and carbs, ll-lam, silt detritus, 1-2 mm lams muddy
P.9	Argillite, finely bedded, dark grey, calcareous along beds, wavy, lensoidal laminations, mineralized as in R.4.
P.10	fg-mg siltst, coarse lam'd, light grey, micaceous, calcareous

P.11 fg-mg SST, dark qtz-rich, carbonates, some mica

P.12 fg Qtz. (from sweat) almost pure.

P.13 fg Argillites, finely lam'd, dark grey, micaceous, non calc.

P.14 siltst, finely bedded, fine ll-lam, highly calc., dark grey to black micaceous matrix, mineralized as in R.4.

P.15 SST (dyke) o.3 suba qtz. in fg qtz. matrix, some mica, bit of matrix, calcareous in joints.

P.16 fg-mg qtzite, dark, no mafics, non calc.

D.1 Sugary, coarse grained, finely bedded limestone, abundant pyrite

D.2 Grey, cg lst and dst, coarse beds; contins minor amount of fg's and scattered angular qtz. sand-size grains

D.3 Dark grey-black, medium grained sparite, minor amounts of fg's (impurities).

D.4 Finely bedded slightly argillaceous siliceous dolomite and more coarsely bedded, clean micritic lst and dst.

D.5 Finely bedded (1-5 mm) pure white limestone (marble) with fine sericite/siliceous partings. Fractured.

D.6 Finely bedded, slightly argillaceous fg grey dolomite. vuggy and pinpoint porosity $\bar{c}$ red calcite crystals along bedding planes.

D.7 Faintly bedded massive silty microcrystalline dolostone

D.8 Cg, calcareous arkose.

D.9 Brecciated (intraformational?) dolostone; calcite crystalline in fracture zones. Sericite rich, argillaceous.

D.10(9) Calcareous arkose mg; has abundant pyrite and biotite mica.

D.10(6) Interbedded silty dolomitic arkose (cg) and fg microcrystalline dolomite.